# Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Stage 1 report on the findings from investigations into areas of significant ground damage (mass movements)

C. I. Massey M. D. Yetton J. Carey
B. Lukovic N. Litchfield W. Ries
G. McVerry

**GNS Science Consultancy Report 2012/317**
**1 August 2013 FINAL**

GNS
SCIENCE
TE PŪ AO

## BIBLIOGRAPHIC REFERENCE

Massey, C. I.; Yetton, M. J.; Carey, J.; Lukovic, B.; Litchfield, N.; Ries, W., McVerry, G. 2013. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Stage 1 report on the findings from investigations into areas of significant ground damage (mass movements), *GNS Science Consultancy Report* 2012/317. 37 p.

## REVIEW DETAILS

This report in draft form was independently reviewed by L. Richards (Rock Engineering Consultant) and T. Taig (TTAC Limited). Internal GNS Science reviews of drafts were provided by M. McSaveney and W. Saunders.

## CONTENTS

## FIGURES



## TABLES



## APPENDICES



## APPENDIX TABLES

# EXECUTIVE SUMMARY

## ES 1 INTRODUCTION

Following the 22 February 2011 earthquakes, members of the Port Hills Geotechnical Group (a consortium of geotechnical engineers contracted to Christchurch City Council (the Council) to assess slope instability in the Port Hills) identified several areas in the Port Hills where extensive cracking of the ground had occurred. In many areas these cracks were thought to represent localised relatively shallow inelastic deformation of the ground in response to the earthquake sequence. In other areas however, the density and pattern of cracking and the amounts of displacement across cracks clearly indicated that some areas had moved as a mass (mass movement).

Mass movement is defined as the geomorphic process by which material (rock and soil) move down-slope, typically as a mass, under gravity (Cruden and Varnes, 1996). The controls on the physical behaviour of these features in the Port Hills in future earthquakes or rainfall events is currently not well understood, and the current level of information held by the Council is not adequate to make reliable predictions of how these areas will respond to such events.

### ES 1.1 Scope and purpose of the work

Christchurch City Council contracted GNS Science to carry out further detailed investigations of these mass movements, in order to assess the nature of the hazard, the frequency of the hazard occurring, and whether the hazard, if it occurs, poses a risk to life, a risk to existing dwellings and/or a risk to critical infrastructure (defined as water mains, sewage mains, pump stations and substations and transport routes). Estimating risk requires detailed investigations, involving field mapping, ground investigations (comprising subsurface drilling and trenching), laboratory testing, numerical modelling and monitoring (of the features in the field and how they respond to earthquakes and rain), as well as the analyses of the collected information.

The main purpose of this work is to provide information on slope-stability hazards to assist the Council's land use and infrastructure planning to ensure development is managed in these areas, as well as to establish procedures to manage the on-going monitoring and investigation.

The work is to be undertaken in a series of stages (this report being Stage 1). Stages 2 to 4 will comprise the results from detailed investigations and assessments of selected mass movements.

### ES 1.2 Purpose of this Stage 1 report

Christchurch City Council is currently reviewing its District Plan, and to help with the development of the plan have requested GNS Science to: 1) provide a current list of the areas susceptible to significant mass movement; 2) provide the current interpreted boundaries of these areas; and 3) carry out a preliminary simple hazard exposure assessment to prioritise the areas with regards to future investigations and what type of investigations are required.

The purpose of this Stage 1 report is to provide the Council with interim results of the findings to date (July 2013) on items 1) to 3) above.

## ES 2 RELATIVE HAZARD EXPOSURE CATEGORIES

To prioritise the mass movements with regards to future investigations, each mass movement has been categorised (Class I, II or III) using a relative hazard exposure matrix, based on the nature of the hazard and the consequence of the hazard occurring.

The relative hazard exposure matrix does not quantify the frequency of the mass movement hazard occurring for each mass movement, as this is not possible based on current information. However, the return period of the earthquake peak ground accelerations (PGA) of 0.3 to 0.4g that could trigger reactivation of these mass movements is currently assessed as being less than 500 years at both rock and soil sites (NZS1170.5:2004 sub-soil classes B rock and C shallow soil). GNS Science has therefore, assumed for all mass movement hazards that the 0.3 to 0.4g PGA will occur more frequently than once in 500 years, which is the basis of ultimate limit state definitions given in AS/NZS 1170.0:2002. For renewed movements triggered by rain or snow melt, these return periods are likely to be smaller.

## ES 3 CONCLUSIONS

Based on the findings of this Stage 1 report, the following conclusions have been made:

- There are currently 36 mass movements identified in the Port Hills project area. Four of these have been further subdivided based on failure type giving a total of 46 mass movements including their sub areas:
  - 15 mass movements (including their sub areas) are assessed as being in the Class I (highest) relative hazard exposure category,
  - 18 mass movements (including their sub areas) are assessed as being in the Class II relative hazard exposure category,
  - 13 mass movements (including their sub areas) are assessed as being in the Class III (lowest) relative hazard exposure category.
- Mass movements assessed as being in the Class I relative hazard exposure category could, if the hazard were to occur, potentially result in the loss of life. Severe damage to dwellings and/or critical infrastructure, which may lead to the loss of services for many people, may also occur.
- Many of the mass movements in the Class I relative hazard exposure category are associated with cliff collapse and lie within existing cliff collapse risk maps (Massey et al., 2012a,b). However, in some of these areas (highlighted in yellow in Table A 3.1, Appendix 3), it is possible that larger volumes may fail and the resultant debris runout may extend further than previously assessed.
- Mass movements in the Class II relative hazard exposure category have potential to affect critical infrastructure, as well as severely damaging dwellings, if the hazard were to occur.
- Mass movements in the Class III relative hazard exposure category have potential to cause only minor damage to dwellings and local infrastructure, if the hazard were to occur.
- Given the magnitudes of displacement of the mass movements in the Class II and Class III relative hazard exposure categories and past performance during the 2010/11

Canterbury Earthquakes, it is unlikely that damage to dwellings would pose an immediate life risk to their occupants.

- Based on what happened during the 2010/11 Canterbury Earthquakes, earthquake-induced peak ground acceleration trigger levels for reactivation of these mass movements (those discussed in this report) are likely to be about 0.3g to 0.4g. The likely performance of these areas under longer duration shaking (such as an Alpine Fault scenario), however, has not yet been investigated.
- It is not yet understood how these mass movements will respond to exceptionally heavy or prolonged rainfall. Rainfall-induced movement of some of these features has been recorded in the past two years. However, the rainfalls have been unexceptional and the movements have been small.

## ES 4 RECOMMENDATIONS

1. Mass movements in the Class I relative hazard exposure category should be given a high priority by Christchurch City Council for detailed investigations and assessment. The level of risk needs to be quantified, including the frequency of the event occurring and the distance the debris may runout down a slope. As an interim measure before these investigations are concluded it is recommended that:
    a. Monitoring of surface movements should be carried out at frequent intervals and/or following significant earthquakes, rain events or if the Council otherwise becomes aware of possible renewed movement in these areas.
    b. Each area should have an emergency-management plan, which identifies the dwellings and critical infrastructure that could potentially be affected by renewed movement and runout.
    c. Investigations and assessment of these mass movements should comprise: field mapping; subsurface investigations (drilling and trenching); modelling of mass movement stability and runout potential; and assessment of the frequency of the hazard occurring and ultimately the risk to people occupying dwellings and road users.
2. For mass movements in the Class II relative hazard exposure category where the consequence of the hazard occurring is to critical infrastructure, it is recommended that:
    a. The Council and its infrastructure providers should be made aware of these areas and identify where their networks pass through them.
    b. Contingency plans should be put in place that consider renewed movement within these areas.
    c. Existing critical infrastructure should be redirected away from these areas where practicable. New infrastructure should not be placed in these areas.
3. For mass movements in the Class II relative hazard exposure category where the consequence of the hazard occurring is to dwellings, it is recommended that:
    a. Selected toe-slump features are investigated further (as per recommendation 1c.)
    b. In combination with these investigations, guidance (such as for foundation design and management of surface and sub-surface water flows, and reticulated water) should be provided for owners in these areas. It would be appropriate for Council to consult the Ministry of Business, Innovation and Employment (MBIE), who,

together with local suitably experienced engineering consultants, could provide guidance for rebuilding in these toe-slump areas.

4. For mass movements in the Class III relative hazard exposure category where the consequence of the hazard occurring is to dwellings, it is recommended that guidance should be provided for owners in these areas (as per recommendation 3b).

5. For existing and new dwellings on all identified mass movements it is recommended that:

    a. Filling and excavation (earthworks) within the mass-movements have appropriate geotechnical assessment.

    b. Surface and subsurface water flows are assessed and managed appropriately.

    c. Design and construction of water reticulation networks to take into account the potential for future ground displacement.

6. It is recommended that green field areas of the Port Hills are identified that exhibit similar topographical and geological characteristics as the mass movements discussed in this report. This information could be used as a guide to the potential for mass movement and to advise that appropriately qualified and locally experienced engineering geologists should assess the area prior to building.

## GLOSSARY OF TERMS

| Term | Description |
|---|---|
| Alluvium | A general name given to materials transported and deposited by streams and rivers. |
| Cliff top recession | The result of landslides from the top and face of cliffs, where the edge of the cliff moves back from the slope edge as material is removed (evacuated). |
| Colluvium | A general term applied to any loose, heterogeneous, and incoherent mass of soil material and/or rock fragments deposited by rainwash, sheetwash, or slow, continuous downslope creep, usually collecting at the base of gentle slopes or hillsides. |
| Crown | The highest point of the landslide source area. |
| Debris avalanche | A type of landslide comprising many boulders falling simultaneously from a slope. The rocks start by sliding, toppling or falling before descending the slope rapidly (> 5 m/sec) by any combination of falling, bouncing and rolling. |
| Debris flow | A type of landslide associated with long runout. They tend to be rapid (> 5 m/sec), liquefied landslides of mixed water and debris that can look like flowing concrete. |
| Debris inundation | The burial of land on or at the bottom of slope by debris from a source area further upslope. |
| Fall | A fall starts with the detachment of soil or rock from a steep slope. The material then descends mainly through the air by falling, bouncing or rolling. Movement is very rapid to extremely rapid (> 5 m/sec). |
| Ground bulging | Where the ground has shortened and the land surface has bulged by compression. |
| Loess | Predominantly silt-sized sediment, which is formed by the accumulation of wind-blown dust. |
| Loess slump | Localised deformation of soil material on slopes of about 20° to 30°, mainly comprising zones of tension. They differ from toe slumps in that they are not located at the bottom of low angle slopes. |
| Mass movement | The geomorphic process by which material (rock, debris and earth) moves down-slope, typically as a mass. |
| Orthophotos | Aerial photographs geometrically corrected ("orthorectified") such that the scale is uniform: the photo has the same lack of distortion as a map. Unlike an uncorrected aerial photograph, an orthophotograph can be used to measure true distances, because it is an accurate representation of the Earth's surface, having been adjusted for topographic relief, lens distortion, and camera tilt. |
| Peak ground acceleration (PGA) | The most commonly used measure of the severity of earthquake ground shaking. It is the largest (absolute) value of acceleration obtained usually from instrument records. |
| Return period | An estimate of the likelihood of an event, such as an earthquake, landslide, flood or a river discharge, to occur. It is a statistical measurement typically based on historical data denoting the average recurrence interval over an extended period of time between events of greater than or equal to a defined magnitude. Often referred to as recurrence interval in risk analysis. |

| | |
|---|---|
| Runout | The furthest distance that landslide debris travels down-slope beyond its source. It is measured as the distance from the downslope limit of the source area the toe of the debris, measured along the length of the debris trail. |
| Slide | Down-slope movement of a soil or rockmass occurring dominantly on single or multiple slip surfaces, where the moving mass tends to retain its general shape. On further movement, slides can develop into flows and avalanches as the mass breaks down. |
| Source area | Area of the landslide within which the displaced material originated. Often referred to as the “zone of depletion”. |
| Talus | An outward-sloping and accumulated heap or mass of rock fragments of any size or shape (usually coarse and angular) derived from and lying at the base of a cliff or very steep, rocky slope, and formed chiefly by gravitational falling, rolling, or sliding. |
| Tension crack | A crack in the ground, where the ground has pulled apart under tension. In mass movements these cracks typically indicate extensional movement in a down-slope direction. |
| Toe | The lower margin of displaced material of a landslide most distant from the crown. |
| Toe slump | Localised deformation of soil material near the base of low angle slopes and comprising zones of compression, translation and tension. |
| Topple | A type of fall, where the soil or rock mass rotates forward out of the slope about a point of axis below the centre of gravity of the displaced mass. |
| Tunnel gully | Tunnel gullies, also known as under-runners, occur in soils derived from loess. Tunnel gullies commonly occur on sites where deep loess has accumulated on moderately steep slopes. Tunnel gullies form when runoff water enters the subsoil through soil cracks, old tree root holes, or down rabbit burrows. Water carries the dispersed material away, scouring out ever-enlarging underground tunnels. Sections of the tunnel roof periodically collapse, creating the characteristic holes. |

# 1.0 INTRODUCTION

Christchurch City Council (the Council) has contracted GNS Science to: assess the hazard and risk to people (in residential dwellings and road users) and critical infrastructure (defined as water mains, sewage mains, pump stations and substations) from mass movement in the Port Hills Area. This project started in September 2012.

As part of this project GNS Science is to provide scientific advice to the Council in order to assist the Council to:

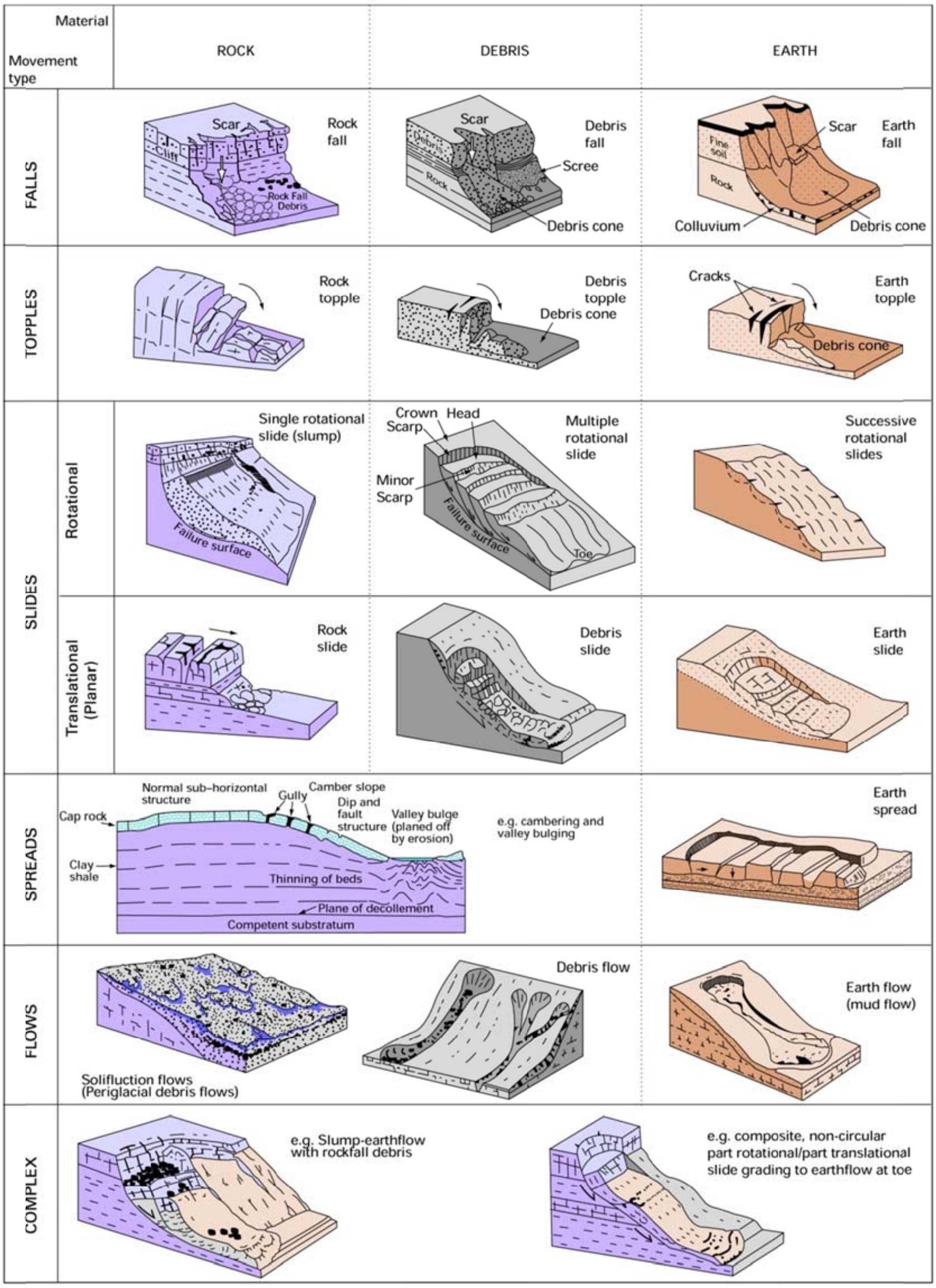
1. Systematically and consistently assess the nature of the hazard and level of risk to people, buildings and infrastructure in areas of significant mass movement in loess, fill, and bedrock as well as areas of cliff-top deformation; and
2. Provide information on hazards to assist the Council with its land-use and infrastructure planning to ensure appropriate development, as well as to establish procedures to manage the areas of significant mass movement, including the response to and assessment of new areas of mass movement that may occur in the future.

## 1.1 BACKGROUND

Following the 22 February 2011 earthquakes, members of the Port Hills Geotechnical Group (a consortium of geotechnical engineers contracted to Christchurch City Council to assess slope instability in the Port Hills) identified some areas in the Port Hills where extensive ground cracking had occurred. In many areas these cracks were thought to represent local shallow deformation of the ground in response to the earthquakes, e.g. around curbs, roads, retaining walls, dwellings and other structures. In other areas however, the density and pattern of cracking and the amounts of displacement across cracks clearly indicated that some areas had moved as a mass (mass movement).

Mass movement is defined as the geomorphic process by which material (rock, debris and earth) moves down-slope typically as a mass under gravity (Cruden and Varnes, 1996). Types of mass movement include falls, topples, slides, slumps, spreads and flows, each with its own characteristic features (Figure 1). Movement of such features can vary from a few millimetres to several metres, with potential to move many tens and hundreds of metres. The majority of the mass movement features discussed in this report were formed in response to earthquake ground motions caused by the 2010/11 Canterbury Earthquakes, and developed within a few seconds to several minutes.

The controls on the physical behaviour (possible renewed movement) of these areas in future earthquakes or rainfall is currently not well understood, and the current level of information held by the Council is not sufficient to make reliable predictions of how these areas will respond to such events.




**Falls** mass detached from steep slope/cliff along surface with little or no shear displacement, descends mostly through the air by free fall, bouncing or rolling.
**Topples** forward rotation about a pivot point.
**Rotational slides** sliding outwards and downwards on one or more concave-upward failure surfaces.
**Translational (planar) slides** sliding on a planar failure surface running more-or less parallel to the slope.
**Spreads** fracturing and lateral extension of coherent rock or soil materials due to liquefaction or plastic flow of subjacent material.
**Flows** slow to rapid mass movements in saturated materials which advance by viscous flow, usually following initial sliding movement. Some flows may be bounded by basal and marginal shear surfaces but the dominan movement of the displaced mass is by flowage.
**Complex slides** slides involving two or more of the main movement types in combination.

**Figure 1** A classification of mass movements widely used in practice (modified after DoE, 1990; Cruden and Varnes, 1996).

## 1.2 SCOPE AND PURPOSE OF THE WORK

Christchurch City Council contracted GNS Science to carry out further detailed investigations of these mass movements, in order to assess the nature of the hazard, the frequency of the hazard occurring, and whether the hazard, if it occurs poses a risk to life, a risk to existing dwellings and/or a risk to critical infrastructure (defined as water mains, sewage mains, pump stations and substations and transport routes). Estimating risk requires detailed investigations, involving field mapping, ground investigations (comprising subsurface drilling and trenching), laboratory testing, numerical modelling and monitoring (of the features in the field and how they respond to earthquakes and rain), as well as the analyses of the collected information.

The main purpose of this work is to provide information on slope-stability hazards to assist the Council's land use and infrastructure planning to ensure development is managed in these areas, as well as to establish procedures to manage the on-going monitoring and investigation.

The work is to be undertaken in a series of stages (this report being Stage 1). Stages 2 to 4 will comprise the results from detailed investigations and assessments of selected mass movements.

## 1.3 PURPOSE OF THIS STAGE 1 REPORT

Christchurch City Council is currently reviewing its District Plan, and to help with the development of the plan have requested GNS Science to: 1) provide a current list of the areas susceptible to significant mass movement; 2) provide the current interpreted boundaries of these areas; and 3) carry out a preliminary simple relative hazard exposure assessment to prioritise the areas with regards to future investigations and what type of investigations are required.

The purpose of this Stage 1 report is to provide the Council with interim results of the findings to date (June 2013) on items 1) to 3) above.

## 2.0 METHOD

### 2.1 DESKTOP STUDIES AND WORKSHOPS

A list of 24 known or suspected areas of significant mass movement was compiled during a workshop held between GNS Science, Tonkin & Taylor (T&T), Aurecon NZ Ltd and Christchurch City Council on 20 June 2012. This workshop considered information collected during earlier geotechnical investigations carried out since February 2011.

### 2.2 FIELD MAPPING

Field mapping of the 24 areas on the list commenced in October 2012 and was completed in January 2013. As a result of the field mapping, a further 10 areas were identified, bringing the total number of identified significant contiguous mass movements to 36 (some areas were split into 'sub-areas'). These areas are shown in Appendix 1. The mapping was limited to the urban areas in Appendix 1.

Field mapping was carried out by GNS Science. The mapping carried out by a particular person was cross-checked in the field by another person to ensure mapping reliability and consistency.

The fieldwork comprised mapping the surface features developed by mass-movement processes that were apparent at the time. Mapping was extended around the identified mass movements to ensure the boundaries were defined accurately. These mapped surface features included: 1) open (tension) cracks and the magnitude of opening (crack apertures – see below); 2) ground bulging (compressional features) where the ground has shortened and the land surface bulged by compression; 3) springs and areas of water seeps; 4) tunnel gullies and 5) damaged/rotated retaining walls.

Crack apertures – relative displacements across cracks in both the horizontal and vertical directions – were measured using a tape measure at locations that were thought to best represent the overall displacement across the crack. Cracks with apertures of less than 2-5 mm were typically not mapped.

Features identified were mapped at a scale of 1:500 onto orthophotos taken by New Zealand Aerial Mapping following the 22 February 2011 earthquakes. The photographs used as background on the field maps had a ground resolution of about 10 cm. The mapped shape and position of the features may differ from the absolute shape and position of the same features on the ground due to mapping inaccuracies. An estimate of the line-work precision presented on the maps is about ±5 m on the ground.

During the field mapping the results to date were discussed at a workshop held in Christchurch between 28 and 30 November 2012. The purpose of the workshop was to discuss the results with GNS Science project staff Dr Mauri McSaveney and external peer reviewers Dr Laurie Richards and Tony Taig. The workshop was also attended by Dr Marlene Villeneuve on behalf of the University of Canterbury.

## 2.3 BOUNDARIES TO THE MASS MOVEMENTS

GNS Science has delineated the current boundaries of the mass movements based on an interpretation of the results from field mapping.

These boundaries encompass the area between the upslope extent of open cracks and the down-slope extent of zones of compression (ground bulging).

For this report a significant mass movement is defined as one with a total relative displacement (inferred from cumulative crack apertures) estimated to be of greater than 100 mm with respect to its surrounding land. A cumulative displacement of greater than 100 mm was chosen for two reasons: 1) it was an amount of displacement that could be measured with a reasonable level of accuracy in the field; and 2) it was an amount that had been used by others as a qualitative reflection of the impact that earthquakes would have on the stability of the slope (e.g. Abramson et al., 2002; Keefer and Wilson, 1985; Jibson and Keefer 1993).

Where possible the mass movements were subdivided into:

1. Extensional areas – where the ground surface comprised multiple open cracks, indicating that the ground had predominantly opened in response to movement. Typically found near the upper (upslope) part of the feature.
2. Translational areas – where the ground had predominantly moved as an intact block (raft) of material. These areas also contain localised open cracks (indicating extension) and bulging (indicating compression). Typically found in the central part of the feature.
3. Compressional areas – where the ground had predominantly bulged (buckled) due to compression. These areas also contain localised open cracks indicating extension. Typically found in the toe area (lower part) of the feature.

Not all observed open cracks indicated land instability and mass movement. Narrow cracks also form as the moisture content of soil decreases and increases (a process referred to as shrink swell). Cracks may also form through settlement of fill around structural features such as retaining walls, dwellings and other engineered structures and from an inelastic response of a material to ground shaking.

The mapped surface features were used to infer mass movement boundaries that best separated areas showing coherent and consistent mass movement “signals” from minor cracks and compression that form a background of apparent “noise” in many strongly shaken areas. With further investigations, and possible changes in the behaviour of the slopes themselves, the current inferred boundaries of these features may change and possibly enlarge.

A 10 m wide area has been added to the inferred boundaries where the area of movement, cracking and bulging could potentially in the future enlarge in an up-slope, lateral or down-slope (to take into account compression at the toe of the loess slumps) direction beyond the currently recognised boundary. This has been termed a “10 m enlargement area”.

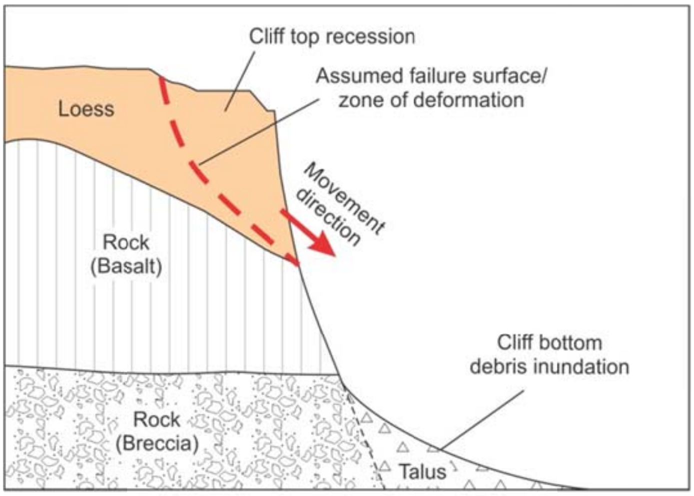
## 2.4 MASS MOVEMENT TYPES

Each identified mass movement has been classified by movement (failure) type. These failure types are illustrated in schematic cross-sections in Figure 2 and are briefly described in Table 1. The failure type is inferred primarily from the nature of the materials and the inferred movement style, and generally follows the landslide classification scheme of Cruden and Varnes (1996).

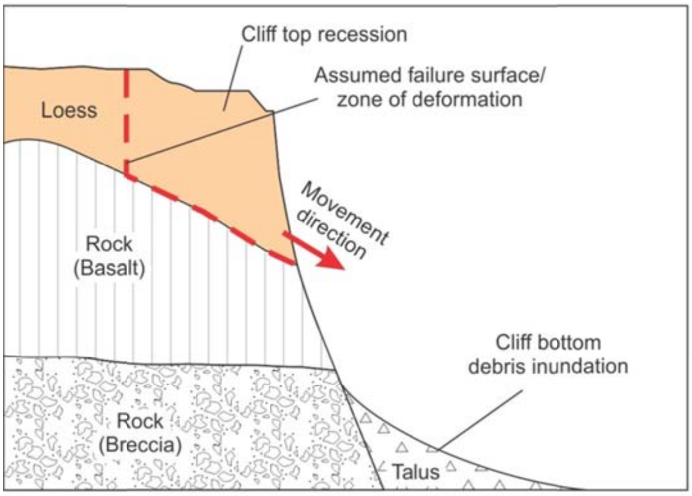
It should be noted that failure types 1 to 4 involve some potential for debris to run-out some distance down-slope. It is unlikely that the toe slumps (failure type 5) will runout any significant distance as the toe is already at the base of the slope. Where loess slumps have sloping ground extending below them, there is a possibility that such areas may be more prone to tunnel gully formation and debris flows than other adjacent but non-cracked areas in similar materials.

**Table 1** Mass movement failure types in the Port Hills. Failure types 1 to 4 are the same as the cliff-collapse processes discussed in Massey et al. (2012a,b).

| **Failure type** | **Description** (see also Figure 2) |
|---|---|
| 1. Loess failures | Slides, falls, flows and avalanches of loess (including colluvium and fill) where movement is confined within the loess and is not influenced by the rock beneath. Typically occurs where thick (> 5 m) loess mantles the tops of steep slopes (cliffs – typically greater than 60°) formed in rock. Potential for debris to run-out (down-slope), inundating dwellings and critical infrastructure along its path. Potentially triggered mainly by earthquakes and periods of rain. There is much historical evidence of loess failures damaging property in the Port Hills. Small loess failures occur every year mostly associated with heavy rain. |
| 2. Loess on rock failures | Slides, falls, flows and avalanches of the loess (including colluvium and fill) along the top of the rock (rock head). Typically occurs where thick (> 5 m) loess mantles the tops of steep slopes formed in rock. Tend to be larger in area (and volume) than failure type 1. Potential for debris to run-out (down-slope), inundating dwellings and infrastructure along its path. Potentially triggered mainly by earthquakes and periods of rain. There have been three recorded deaths on Banks Peninsula from rainfall-induced loess-on-rock failures, but none have occurred in the Port Hills. |
| 3. Loess and rock failures | Slides, falls, flows and avalanches of the loess (including colluvium and fill) possibly due to failure of the underlying rock. Failure may be along persistent material boundaries or discontinuities and/or through weaker materials forming the rock mass. Typically occurs on steep and high coastal and relict coastal cliffs mantled by thick (> 5 m) loess. Tend to be larger in area (and volume) than failure types 1 and 2. Potential for debris to run-out (down-slope), inundating dwellings and infrastructure along its path. Potentially triggered mainly by earthquakes and periods of rain. These historically have not been differentiated from failure types 1 and 2. Most of the loessial soils on steep slopes in the Port Hills are loess colluviums, frequently containing colluvial boulders. |
| 4. Rock failures | Slides, topples, falls and avalanches of the rock along persistent material boundaries, discontinuities or through the rock mass. Mostly occurs on steep and high coastal and relict coastal cliffs. Tend to be similar in area (and volume) to failure type 3. Potential for debris to run-out (down-slope), inundating dwellings and infrastructure along its path. Potentially triggered mainly by earthquakes and periods of rain. Very small rock failures fall from the steeper cliffs many times a year, triggered mostly by rain and sometimes by earthquakes, or without any detectable trigger. Larger damaging rock failures historically have occurred every few years or so. |
| 5. Loess slumps (a type of slide as per the classification of Cruden and Varnes, 1996) | Slumping of loess, colluvium, alluvium and fill. Occurs mainly on low angle (typically less than 25°) slopes where the Port Hills slopes, typically underlain by volcanic rocks, loess and colluvium, grade into the flatter areas at the valley bottoms with permanent relatively high water tables. Formed where colluvium has often run-out onto and mixed with alluvium on the valley floor. These gentle valley slopes are referred to as "toe slopes" and these mass movements are referred to as "toe slumps" (failure type 5a in Figure 2). Movement mechanisms are likely to involve un-drained loading of locally saturated loess, colluvium and alluvium and generation of excess pore pressures during earthquakes. Recorded movement magnitudes less than 1.5 m to date; triggered mainly by earthquakes, although some minor non-earthquake reactivations have been recorded in the last two years for some of these features. There is geomorphic evidence (pre-2010/11 Canterbury Earthquakes) of movement of several toe slumps, but there are no recognised historical records of damage to dwellings from them. The toe-slump areas were entirely green field prior to the mid-1920s, and most development of urban subdivision on them is post-1970.<br><br>Slumping of loess, colluvium and fill on low angle (typically around 20 to 30°) slopes not located on toe slopes has also occurred (failure type 5b in Figure 2). Possibly similar movement mechanism to the toe slumps. There is a possibility that such areas may be more prone to tunnel gully formation and debris flows than other adjacent but non-cracked areas in similar materials. The significance of these features is currently not understood. These features have not previously been recognised in the Port Hills, suggesting their formation is typically due to earthquake ground shaking. |

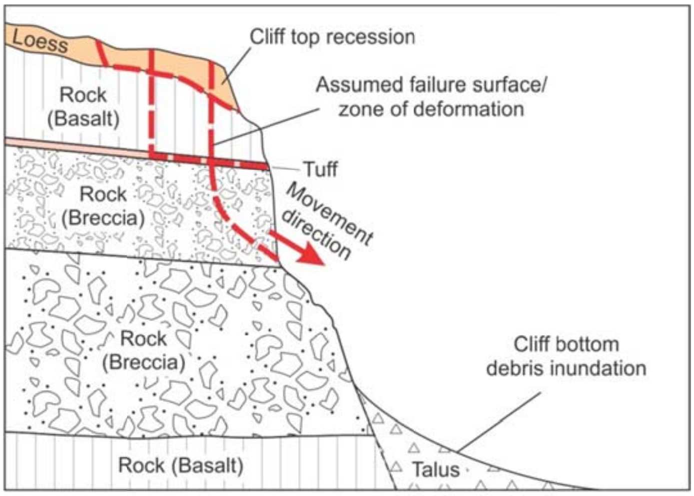



**1. Loess*** (slides, falls, flows and avalanches).

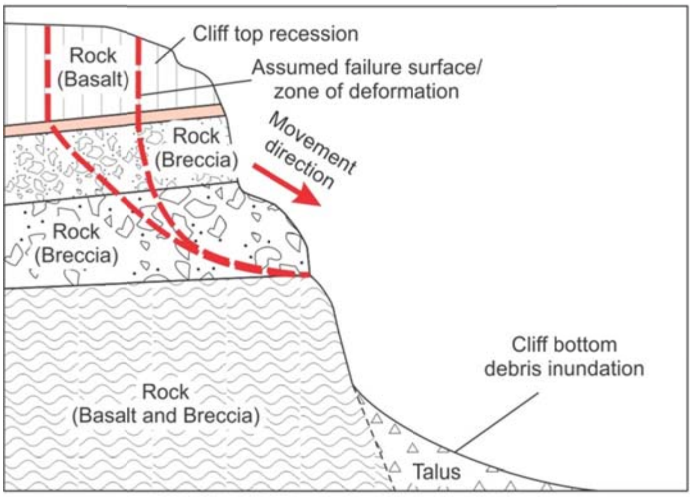



**2. Loess* on rock** (slides, falls, flows and avalanches).

**Figure 2** Simplified characterisation of mass movement mechanisms in the Port Hills.

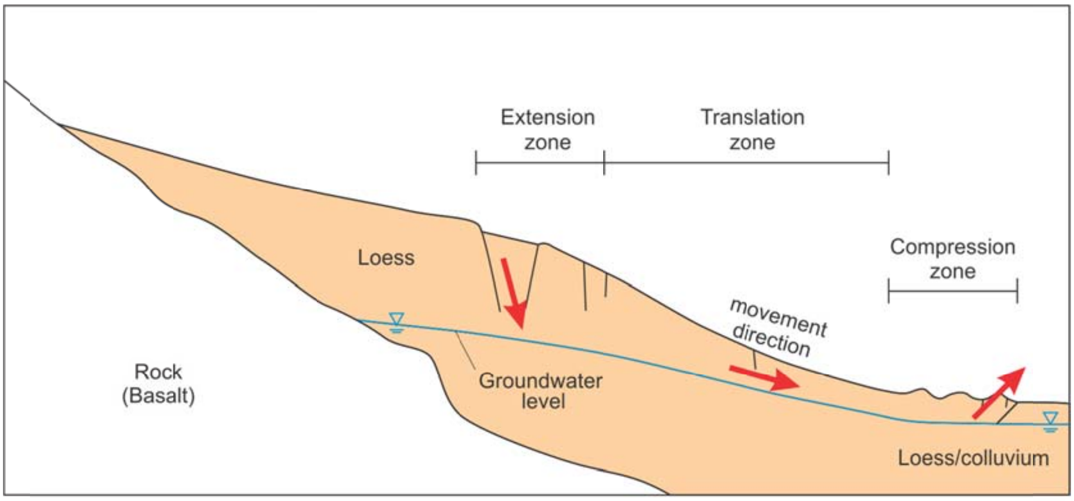



3. **Loess* and Rock** (slides,falls, flows and avalanches).

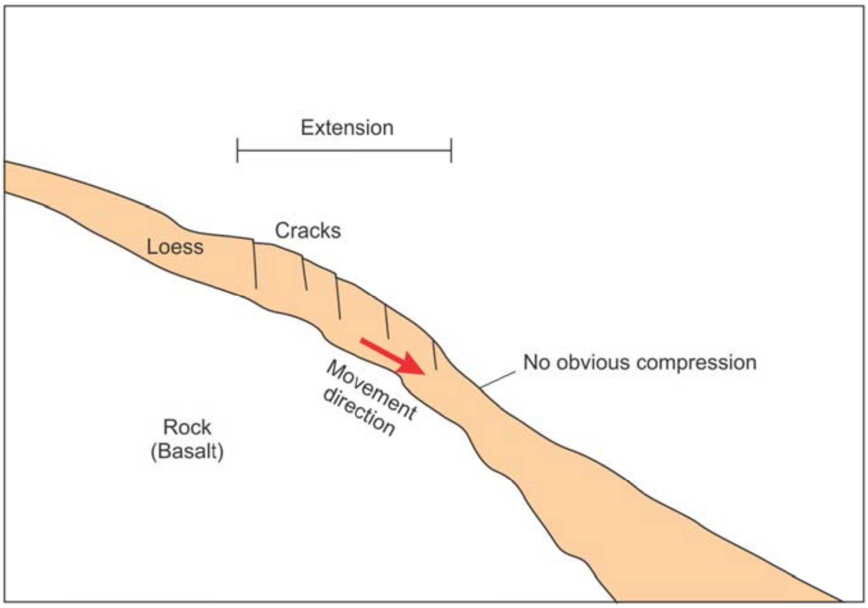



4. **Rock** (slides, topples, falls and avalanches).

**Figure 2** Cont.




5a. Loess* slump (Toe slump)




5b. Loess* slump

**Figure 2** Cont.

*Note: Where loess is stated or shown, this can be loess, colluvium or fill.

### 2.4.1 Movement styles

Different failure types exhibit different styles of movement. For example, in some landslide movements such as falls, spreads, flows and avalanches (Figure 1), the debris may travel considerable distances down-slope with speeds ranging from rapid (>1.5 m/day) to extremely rapid (5 m/sec e.g. debris flow), based on the scheme by Cruden and Varnes (1996). In contrast, some landslides such as the loess and toe slumps have minimal runout. The runout potential of a landslide is mostly controlled by the steepness of the slope below the source, the extent to which the debris is fluidised and the slope materials along the path of the debris.

Runout distance is defined as the furthest distance that landslide debris travels down-slope beyond its source area. For this report the runout distance is expressed as the distance measured from the downslope limit of the source to the toe of the debris. In the Port Hills, long runout is mostly associated with debris avalanches falling from the steep cliffs (these are discussed in more detail in Massey et al. 2012a,b), and from debris flows from areas of loess, colluvium and fill located on slopes (Bell and Trangmar, 1987).

For debris to run-out there generally needs to be space below the source area to run-out onto. Estimating the runout distance of landslide debris requires detailed investigations and modelling. For many of the cliffs in the Port Hills the potential runout distance of debris has already been assessed and risk maps have been generated (refer to Massey et al., 2012a,b). The risk maps contained in these reports were based on empirical models relying on the runout distances of debris avalanches triggered by the 2010/11 Canterbury Earthquakes. In some instances, it is now recognised that much larger volumes of debris could fall from the same cliffs, and the larger volumes have potential to run-out further than previously recorded, these areas are now identified and highlighted (Appendix 3).

In this Stage 1 report those mass movements where the debris is assessed as having potential to run-out have been identified, and arrows have been shown on the maps to indicate the general part of the mass movement where runout may originate. For the reasons discussed above, the arrows do not indicate the distance the debris might travel.

It should be noted that not all of the currently identified mass movements may move and run-out in the future, and it may only be parts of a particular mass movement that undergo renewed activity.

### 2.5 RELATIVE HAZARD EXPOSURE MATRIX

A simple relative hazard exposure matrix has been developed to help the Council prioritise the mass movements in terms of future investigations and the possible requirements needed to manage them. The relative hazard exposure matrix is broadly based on the risk management framework contained in the original Risk Management Guidelines Companion to AS/NZS 4360:2004, which is now superseded by 31000:2009.

The matrix consists of three hazard and three consequence classes (Table 2). The hazard exposure matrix does not quantify the frequency (likelihood) of the hazard occurring, as this is not possible based on current information (refer to Section 2.5.1 for more detail).

The hazard classes are based on the assessed dominant type of movement and magnitude of inferred displacement of the mass movement; these are shown schematically in Figure 3. The hazard classes are defined as follows:

1. Displacement and debris runout – areas where displacement could cause the mass to break up (disintegrate) and travel a considerable distance (e.g. tens of metres) down the slope at significant speed, inundating dwellings and roads. Given the likely speed of the debris, there is little time for people to get out of the way. This hazard class may also be associated with cliff top recession. Typically failure types 1 to 4.
2. Land movement with displacement greater than 0.3 m (see below) and where the debris is assessed as having limited runout potential. Typically failure type 5.
3. Land movement with displacement less than 0.3 m (see below) and where the debris is assessed as having limited runout. Typically failure type 5.

Displacements for each mass movement are inferred by adding together the mapped crack apertures (openings) along sections through the mass movement (Figure 3B and C). They are a lower bound estimate of the total displacement, as no account is given for plastic deformation of the mass (i.e. thinning of the mass without cracking) and not every crack was mapped. It should also be noted that where loess or other soil overlies rock and where there has been failure of the rock (failure types 3 and 4), the cracks in the surface loess/soil may not represent the true displacement of the underlying rock.

Displacement may also result in bulging (compression) of the land surface.

The consequence classes are based on who or what could be impacted:

1. Life risk – if the hazard were to occur it could lead to a loss of life, e.g. where debris could run-out and severely impact dwellings and people in them, and in gardens or walking, cycling (pedal or motorised) and driving along roads.
2. Critical infrastructure – if the hazard were to occur it could lead to the loss of critical infrastructure and access.
3. Dwellings – if the hazard were to occur it could cause damage to dwellings, ranging from minor deformation and cracking (with no associated life risk) to significant deformation, inundation and collapse (associated with a life risk).

Critical infrastructure is defined, by Christchurch City Council for the purpose of this report, as infrastructure vital to public health and safety. It includes transport routes (where there is only one route to a particular destination), telecommunication networks, all water related mains and power networks (where there is no redundancy in the network), and key medical and emergency service facilities. Networks include both linear features such as power lines or pipes and point features such as transformers and pump stations.

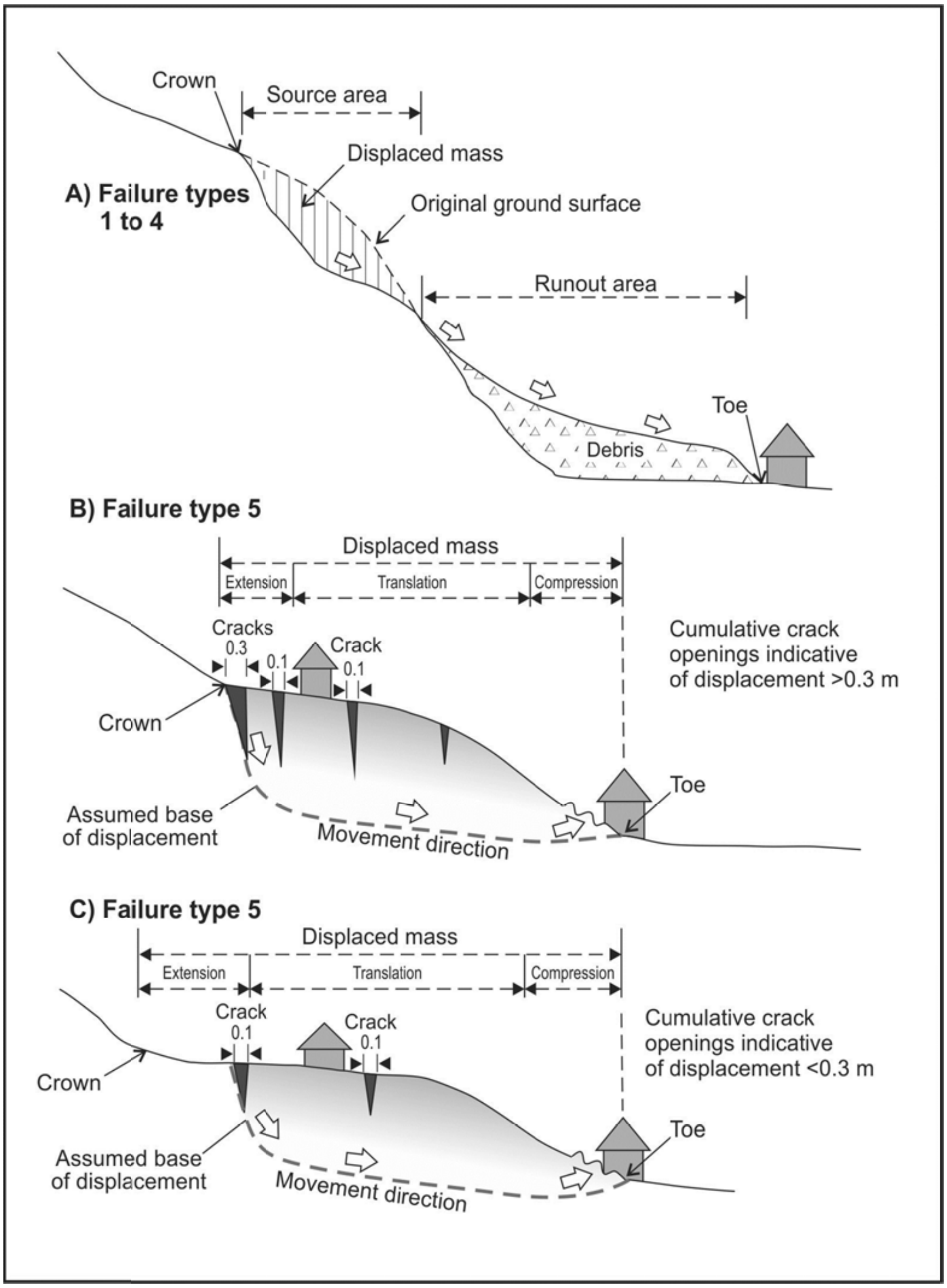



**Figure 3** A) A mass movement with displacement greater than 0.3 m and debris runout (failure types 1 to 4). B) A mass movement with an inferred cumulative displacement greater than 0.3 m, which is a value used in the relative hazard exposure matrix (failure type 5). C) A mass movement with an inferred cumulative displacement less than 0.3 m, a value used in the relative hazard exposure matrix (failure type 5).

**Table 2** Mass movement relative hazard exposure matrix (described further in Table 3).

| | | Hazard Class | | |
|---|---|---|---|---|
| | | 1. Displacement* greater than 0.3 m and debris runout | 2. Displacement* greater than 0.3 m; no runout | 3. Displacement* less than 0.3 m; no runout |
| **Consequence Class** | 1. Life – potential to cause loss of life if the hazard occurs | **CLASS I** | **CLASS III** | **CLASS III** |
| | 2. Critical infrastructure[1] – potential to disrupt critical infrastructure if the hazard occurs | **CLASS I** | **CLASS II[2]** | **CLASS II** |
| | 3. Dwellings – potential to destroy dwellings if the hazard occurs | **CLASS I** | **CLASS II** | **CLASS III** |

*Note: Displacements for each mass movement are inferred by adding together the mapped crack apertures (openings) along sections through the mass movement (Figure 3B and C). They are a lower bound estimate of the total displacement, as no account is given for plastic deformation of the mass and not every crack has been mapped.

[1] Critical infrastructure is defined, for the purpose of this report, as infrastructure vital to public health and safety. It includes transport routes (where there is only one route to a particular destination), telecommunication networks, all water related mains and power networks (where there is no redundancy in the network), and key medical and emergency service facilities. Networks include both linear features such as power lines or pipes and point features such as transformers and pump stations.

[2] This relative hazard exposure category is based largely on an assumption that ‘critical infrastructure’ exists within these areas. Until further assessments are made on the nature of toe slumps and the existence of critical infrastructure in these areas, the relative hazard exposure category of these mass movements has been appropriately assessed as “Class II”. It is likely that many of the mass movements in the Class II relative hazard exposure category (where the hazard class is 2 and the consequence class is 2) would be more appropriately classified as “Class III” following further assessments.

The relative hazard exposure categories (Class I, II & III) are defined in Table 3. These relative hazard exposure categories bring together the hazard types (failure types and movement styles, e.g. the nature of the failure and the runout potential of the debris) with the consequences of the hazard if it were to occur. These relative hazard exposure categories are provided to help the Council prioritise future investigation works.

**Table 3** Mass movement hazard exposure matrix description.

| Relative hazard exposure category | Hazard class | Consequence class | Description |
|---|---|---|---|
| Class I has highest priority for further assessment as there is a potential risk to life and where runout and rapid movement of debris may cause severe damage to dwellings and critical infrastructure with the potential to affect many people. | 1 | 1 and 3 | Slides, falls, topples, flows and avalanches of loess, loess and rock or rock, with associated displacement in the source area of greater than 0.3 m leading to cliff top recession. Once triggered the debris has potential to run-out long distances down-slope. In these locations there is potential for dwellings in the source area to be undercut and severely damaged by displacement, and for debris to impact and inundate dwellings, their occupants or road users lower down the slope. Given the velocity and long runout it is possible these types of mass movement could result in the loss of life. |
| | 1 | 2 | As above, but where cliff top recession and debris runout has potential to severely impact critical infrastructure, which may lead to the loss of services for many people. |
| Class II has an intermediate priority for further assessment, as there is potential for any affected critical infrastructure to be impacted, which could potentially affect many people. Magnitudes of displacement could severely damage dwellings. | 2 | 2 and 3 | Loess and toe slumps with associated cumulative inferred displacement of the mass of greater than 0.3 m, where dwellings and critical infrastructure is present within the moving mass. Runout of debris is assessed to be minimal. Possible that renewed movement may severely impact critical infrastructure and dwellings. The level of disruption to critical infrastructure and dwellings is likely to be a function of where they are within the feature. The most hazardous places are the mainly extensional and compressional areas. Given the magnitudes of displacement it is unlikely that damage to dwellings would pose an immediate life risk to their occupants. |
| | 3 | 2 | Loess and toe slumps with associated cumulative inferred displacement of the mass of less than 0.3 m but where critical infrastructure is present within the moving mass. Runout of debris is assessed to be minimal. Although the magnitudes of displacement are relatively minor it is possible that renewed movement may impact critical infrastructure. The level of disruption to critical infrastructure is likely to be a function of where they are within the feature. The most hazardous places are the mainly extensional and compressional areas. |
| Class III has the lowest priority for further assessment, as magnitudes of displacement are small and only dwellings and local infrastructure are likely to be affected. | 2 | 1 | Loess and toe slumps with associated cumulative inferred displacement of the mass of greater than 0.3 m and where dwellings are located on the moving mass. Runout of debris is assessed to be minimal. Given the magnitudes of displacement it is unlikely that damage to dwellings would pose an immediate life risk to their occupants. |
| | 3 | 1 and 3 | Loess and toe slumps with associated cumulative inferred displacement of the mass of less than 0.3 m and where dwellings are present on the moving mass. Runout of debris is assessed to be minimal. It is possible that renewed movement may cause some damage to dwellings, particularly if dwellings are located in the mainly extensional areas. Given the magnitudes of displacement it is unlikely that damage to dwellings would pose an immediate life risk to their occupants. |

### 2.5.1 Likelihood of the event occurring

The potential future behaviour of each identified mass movement is a function of: 1) the failure type (Table 1); and 2) the triggering factor(s) that could initiate movement. Currently there is insufficient information to accurately assess the future behaviour of each mass movement individually.

The main triggering factors are assessed as being either: A) earthquake-induced peak ground acceleration; and B) rainfall or snow melt. In some cases mass movements may be triggered by other factors such as slope modification (e.g. earthworks and drainage), or there may be no apparent triggering event.

For earthquake triggers the frequency of a given peak ground acceleration occurring can be obtained from the National Seismic Hazard Model (see below). In general, the hazard calculations within this model are based on time-independent earthquake probabilities, which is standard practice for probabilistic hazard analysis for engineering design. Time-independent earthquake probabilities are based on the average rate of occurrence of earthquakes on a source, but do not take account of the elapsed time since the last event or enhanced activity associated with earthquake sequences following major events.

As a result of the 4 September 2010 Darfield Earthquake and its associated aftershocks, the current level of seismic activity in the Christchurch area is considerably higher than the long-term average, and is likely to remain enhanced for several decades (Webb et al., 2011), but with decreasing rates with time. Given this current enhancement of seismicity, it is necessary to develop earthquake probabilities that vary over time to represent the on-going earthquake sequence in the region.

This increased level of seismicity is incorporated in a modified form of the 2010 version of the National Seismic Hazard Model (Stirling et al., 2012), which incorporates the now-increased probabilities of rupture for major faults in the region (Gerstenberger, 2011), and more importantly, a greatly enhanced but gradually decreasing rate of earthquakes distributed through the Christchurch area that have not been assigned to specific faults (distributed seismicity). The distributed seismicity component of the model combines multiple models from each of three classes according to an expert elicitation process carried out by GNS Science in November 2011. The three classes were time-dependent models for short- and medium-term clustering, and long-term modelling. This is hereafter referred to as the Composite Seismic Hazard Model and is a further development of the classes of models described in Webb et al. (2011) and Gerstenberger et al. (2011). The same model was used to determine the current values of peak ground accelerations for deep or soft soil sites required to be used for liquefaction assessment in Christchurch (Ministry of Business, Innovation and Employment, 2012), and it was also used for the cliff collapse (Massey et al., 2012a,b) and rockfall (boulder roll) risk assessments (Massey et al., 2012c,d).

The return periods of varying levels of peak ground acceleration have been generated for the Port Hills using the Composite Seismic Hazard Model for site sub-soil classes B (rock) and C (shallow soil) according to AS/NZS 1170.0:2002, which best represent the materials in the Port Hills. It should be noted that this model does not take into account large amplification of ground shaking caused by steep topography and/or soil/rock material contrasts, which occurred in the Port Hills during the 2010/11 Canterbury Earthquakes.

Unlike the above-mentioned cliff collapse and rockfall reports, the peak ground accelerations and their associated return periods used for this report assume no earthquake magnitude weighting and all aftershocks (100% seismicity) are included above magnitude M5.25 in the model. Magnitude 5.25 is chosen as no mass movements were triggered in the Port Hills by earthquakes less than Magnitude 5.25. All the liquefaction assessments have used 100% seismicity but considerable magnitude-weighting (Ministry of Business, Innovation and Employment, 2012).

## 3.0 RESULTS

Each mass movement has been classified by failure type, field-observed mass movement characteristics (based on observations made after the 2010/11 Canterbury Earthquakes) (Table 1), hazard class, consequence class and relative hazard exposure category (Tables 2 and 3). These are summarised in Table A 3.1 in Appendix 3.

### 3.1 RELATIVE HAZARD EXPOSURE MATRIX

There are currently 36 mass movements identified in the Port Hills project area. Four of these have been further subdivided based on failure type, resulting in a total of 46 mass movements including their sub areas. A map showing the mass movements colour-coded by their relative hazard exposure categories (Class I, II & III)) is contained in Appendix 1. Detailed maps of these mass movements are contained in Appendix 2.

The numbers of mass movements (including sub areas) in each relative hazard exposure category are summarised in Table 4.

**Table 4** Summary of the relative hazard exposure assessment.

| Relative hazard exposure Category (priority)[1] | Number of mass movements (including sub areas) | Failure type[2] |
|---|---|---|
| CLASS I | 15 | 1 to 4 |
| CLASS II | 18 | 5 |
| CLASS III | 13 | 5[3] |

[1] From Tables 2 and 3.

[2] From Table 1.

[3] One of the category CLASS III mass movements (ID 20, Lucas Lane) would have been CLASS I but it has now been mitigated.

Four of the mass movements in the Class II relative hazard category require further assessment because of uncertainty about the significance of the infrastructure that is located within them. Further assessment may mean that some or all of these mass movements may be reclassified to being in the Class III relative hazard exposure category.

Based on the results of the hazard exposure assessment, mass movements in the Class I relative hazard exposure category are considered high priority for future assessment. This is because, if the hazard were to occur, there is potential for dwellings in the source area to be undercut and severely damaged by ground displacement, and for debris to impact and inundate dwellings and their occupants or road users lower down the slope. Given the velocity and long runout it is possible these types of mass movement could result in the loss of life and/or impact critical infrastructure, which may lead to the loss of services for many people.

Mass movements in the Class II relative hazard exposure category are considered to be of intermediate priority for future assessment. This is because, if the hazard were to occur, there is potential for critical infrastructure to be impacted, which could affect many people.

Dwellings on these mass movements are also likely to be significantly damaged as a result of renewed movement. However, given the magnitudes of displacement it is unlikely that damage to dwellings would pose an immediate life risk to their occupants. If renewed movement were to occur it is possible that some dwellings may be severely structurally damaged.

Mass movements in the Class III relative hazard exposure category are considered to be of low priority for future assessment. This is because, if the hazard were to occur, there is potential that only dwellings and local infrastructure are likely to be affected. Given the very low magnitudes of displacement it is unlikely that damage to dwellings would pose an immediate life risk to their occupants. If renewed movement were to occur it is possible that some dwellings may be structurally damaged.

## 3.2 FREQUENCY OF THE EVENT OCCURRING

Based on current information it is not possible to quantify the frequency of the mass movement hazard occurring, for each mass movement. For this Stage 1 report it is simply assumed that the frequency of the hazard occurring, for all mass movement hazards, is greater than 1 in 500 years (a return period of 500 years), whether triggered by a rainstorm, earthquake or other event. 500 years is the basis of the ultimate limit state definitions for a residential dwelling (building importance class 2) as set out in AS/NZS 1170.0:2002.

This is because for earthquake triggers alone, the return period of the earthquake peak ground accelerations (PGA) of 0.3 to 0.4g that could trigger reactivation of these mass movements is currently assessed as being less than 500 years at both rock and soil sites (NZS1170.5:2004 sub-soil classes B rock and C shallow soil). These estimates are from post-earthquake hazard models that take account of the increased seismicity rates since the initiation of the Canterbury earthquake sequence, while allowing for the gradual decay of the seismicity with time.

For renewed movements triggered by rain or snow melt, these return periods are likely to be smaller.

### 3.2.1 Earthquake triggers

Based on what happened during the 2010/11 Canterbury Earthquakes, earthquake-induced peak ground acceleration trigger levels for reactivation of these mass movements (those discussed in this report) are likely to be 0.3g to 0.4g or above (equivalent to 30 and 40% of gravity, where gravity is 9.81 m/s/s). The magnitude of displacement is likely to increase with increasing peak ground accelerations for motions of similar duration and with increased duration of strong ground acceleration. The performance of these specific mass movements under long-duration but perhaps lower-amplitude shaking such as an Alpine Fault earthquake (i.e., longer than that recorded during the 2010/11 Canterbury Earthquakes), is not known at this stage.

The 22 February 2011 earthquakes (all earthquakes on the day) generated the greatest number of mass movements in the Port Hills. Subsequent aftershocks have also generated mass movements, most notably the 13 June 2011 earthquake.

The horizontal peak ground accelerations (the maximum single directional component) recorded in the Port Hills by the GeoNet strong motion network from the 22 February 2011 earthquakes range between 0.3g to 1.7g, with a mean of about 0.8g; for the 13 June 2011 earthquake the range is between 0.2g and 2.0g, with a mean of about 0.7g, however, it should be noted that these records include site-amplification effects.

The return periods of the horizontal PGAs of 0.4 to 1.6g in the Port Hills are listed in Table 5 for rock sites and shallow soil sites (site classes B and C respectively based on NZS 1170.5:2004). The estimated 500-year return period PGAs are about 0.8g for rock and just over 1g for shallow soil site conditions. These estimates are derived using the Composite Seismic Hazard Model. The return periods of the recorded motions were much longer for the pre-September 2011 model, from several thousand years to over 10,000 years. Note that the seismic hazard model for the Christchurch area is frequently updated due to the on-going nature of the seismicity in the region and so the numbers given in Table 5 may change. The 50-year average model does, however, account for an expected decay in the rate of earthquakes with time.

**Table 5** Return periods of a given PGA in the Port Hills – Site Class B Rock and C Shallow soil. From the Composite Seismic Hazard Model.

| | **Approximate return periods (years) of 22 February and 13 June 2011 earthquake-ground motions in the Port Hills** | | | |
|---|---|---|---|---|
| **Date** | PGA 0.4g | PGA 1g | PGA 1.4g | PGA 1.6g |
| | ***Site Class B Rock*** | | | |
| 2012 (year 1) | 14 | 219 | 980 | 2012 |
| 2012 to 2061 (50 year average) | 82 | 1,311 | 5,747 | 11,628 |
| | ***Site Class C Shallow soil*** | | | |
| 2012 (year 1) | 7 | 73 | 252 | 444 |
| 2012 to 2061 (50 year average) | 44 | 438 | 1,504 | 2,639 |

*Notes: PGAs were derived using the composite seismic hazard model for year 1 to year 50, from January 2012. Derived using a minimum earthquake magnitude ($M_{min}$) of $M_W$ 5.25, for site classes B and C (NZS 1170.5:2004), which are most typical of the materials found in the Port Hills. These do not include site amplification effects (caused by topography and/or material contrasts) or any magnitude weighting. The shallow soils PGAs, however, are modelled as 4/3 (four thirds) times those expected on a flat rock site, to take into account some amplification. Highlighted PGAs have return periods of less than 500 years. Only the first digit in the number is significant.*

*Mass movements in rock may be triggered by each exceedance of the ground acceleration trigger level, rather than those mass movements in soil, which may require several cycles of acceleration. For this reason the PGA/return period estimates do not use magnitude-weighting factors that considerably reduce the effective PGAs for a given return period. It should be noted that magnitude weighting factors have been used for liquefaction assessment and structural design and assessment.*

### 3.2.2 Rain, snowmelt and other triggers

Historical landslides in the Port Hills have mainly been triggered by rainfall (Bell and Trangmar, 1987). Several short historical records of property damage from landslides suggest at least one a year on average. One notable storm in August 1975 caused about 600 landslides (Harvey, 1976), mainly debris flows. Rainfall magnitudes/durations and their associated annual frequencies (probabilities) of occurrence in Christchurch have been well studied (e.g. Griffiths et al. 2009) but the data on landslide occurrences are inadequate to relate a given amount of rain with the frequency and magnitude of landslide occurrence.

Evidence from ground surveys carried out in the Port Hills over the past two years does suggest that renewed displacement of some of the initially earthquake-induced mass movements may be linked to periods of prolonged wet weather. However, evidence from the record before 2010 does not support that as a generality. In the historical record, damaging landslides of types 1 and 3 have occurred in most years, after daily rainfalls of as little as 30 mm (an amount of rainfall expected in Christchurch several times a year). In contrast, daily rainfalls in excess of 100 mm sometimes have had no associated damaging landslides. This does not however, imply that no landslides occurred; because landslides in the Port Hills occur so commonly during rain, many are not considered newsworthy and pass unrecorded. For example, Christchurch's highest daily rainfall in nearly 140 years of record was 124.2 mm on 17 April 1974, a date noted for the widespread flooding in Christchurch, but not for any landslides triggered. Another example is the heavy rainfall of August 1945 which caused severe flooding in Sumner with widespread deposition (up to 0.5 m thick) of loess soil in Sumner, but there is no record of specifically where the loess washed from.

It is also possible that movement of these initially earthquake-induced mass movements may occur in response to changes in the moisture content of the materials during the seasons. Such seasonal changes can lead to shrinkage and swelling of the soil, which can result in noticeable deformation of structures such as walls and footpaths. This type of movement is likely to be more localised and unrelated to displacement of the larger mass movement as triggered during the 2010/11 Canterbury Earthquakes.

# 4.0 DISCUSSION

## 4.1 PREVIOUS ASSESSMENTS AND OBSERVATIONS

For many of the mass movements in the Class I relative hazard exposure category the risk to life has already been estimated, where this risk is from cliff-collapse hazards, failure types 1 to 4 (Table 1). The risk assessments for these features are contained in Massey et al. (2012a,b). However, for some of these mass movements (highlighted in yellow in Table A 3.1, Appendix 3), there is potential for larger volumes to fail with the resultant debris runout travelling further than previously assessed. For this reason these mass movements are included with the other Class I (high priority for further investigation) mass movements.

Most of the mass movements in the Class II and Class III relative hazard exposure categories are loess slumps (mainly toe slumps). Although the movement of the toe slumps during earthquakes may be rapid, the short duration of earthquake shaking (typically less than a minute during the 2010/11 Canterbury Earthquakes) resulted in total maximum inferred displacements of less than 1.5 m. The main risks in such areas are to dwellings and infrastructure. While it is possible that part of a dwelling on such a feature could collapse, endangering its occupants, there were no such injuries reported during any of the 2010/11 Canterbury Earthquakes.

## 4.2 KNOWLEDGE GAPS AND OTHER POTENTIAL FUTURE WORK

For this Stage 1 report only the current urban areas of the Port Hills have been mapped, as it is in these areas that Christchurch City Council is concentrating its efforts to manage the risks. It is not feasible to map the green field areas of the Port Hills in the same level of detail as those urban areas identified and discussed in this report.

It should be noted that other mass movements – not identified in this report – could exist in green field areas within the Port Hills project area that exhibit similar characteristics to the mass movements discussed in this report. It is also possible that a future local earthquake (located elsewhere in the Port Hills), or that longer duration shaking, from for example an Alpine Fault earthquake, could trigger new mass movements as well as reactivating the mass movements identified in this report.

On completion of this mass-movement project however, it should be possible to recognise simple geomorphological (and topographical) features/relationships associated with the different mass movement failure types. These features may then be used to identify additional areas where such failure types might occur.

For example, the mapped toe-slump failure types occur near the toe of slopes formed of mixed colluvium and loess inclined between 5° and 30°, at elevations between 1 and 30 m above sea level and where the groundwater levels in the toe areas are close to the surface. The approximate plan area of the Port Hills slopes that fall within these combined material and topographic criteria – in the project area – is about 4.5 $km^2$. The identified toe slumps occupy 0.3 $km^2$ of this area and therefore represent only about 7% of the total area potentially susceptible to toe slumps. The maximum recorded cumulative displacement (inferred from crack apertures) of a toe slump is about 1.5 m, however, this represents only one mass movement. The average cumulative displacement of all toe slumps (estimated along section lines through each mass movement) is in the order of 0.5 m, but the majority of toe slumps moved less than 0.3 m.

At present there is only a limited understanding of the mechanisms of movement of the toe slumps. As a result of this lack of knowledge it is not currently possible to identify how they would likely respond to events such as an Alpine Fault earthquake, where the duration of strong shaking would be much longer (minutes) than occurred during the 2010/11 Canterbury Earthquakes (tens of seconds), although probably of lower peak amplitude (peak ground acceleration). Geomorphological evidence indicates that these features are not new, and therefore ground motions from earlier strong earthquakes may have triggered some movement prior to the more recent events.

The only available monitoring records from a toe slump (Vernon Terrace) suggest that large movements of these features are not likely to be caused by increased pore pressures linked to rainfall although some minor post-earthquake movement (less than 20 mm) has been detected by monitoring equipment. It should be noted however, that no systematic assessment has been carried out of the toe-slump features and the Vernon Terrace monitoring records extend back only two years.

Another potential issue in the loess- and toe-slump areas, particularly in the extensional zones, may be tunnel gullying and erosion caused by water entering the cracks during rain.

## 5.0 CONCLUSIONS

Based on the findings of this Stage 1 report, the following conclusions have been made:

- There are currently 36 mass movements identified in the Port Hills project area. Four of these have been further subdivided based on failure type giving a total of 46 mass movements including their sub areas.
- Based on a simple preliminary hazard exposure assessment:
  - 15 mass movements (including their sub areas) are assessed as being in the Class I relative hazard exposure category. These are considered to be of high priority for further assessment because, if the hazard were to occur, there is potential for dwellings in the source area to be undercut and significantly damaged by displacement, and for debris to impact and inundate dwellings and their occupants or road users lower down the slope. Given the velocity and long runout it is possible these types of mass movement could result in the loss of life. Dwellings and/or critical infrastructure, which may lead to the loss of services for many people, may also be severely damaged.
  - 18 mass movements (including their sub areas) are assessed as being in the Class II relative hazard exposure category. These are considered to be of intermediate priority for further assessment because, if the hazard were to occur, there is potential for critical infrastructure (affecting many people), and dwellings to be severely damaged. Given the magnitudes of displacement and past performance during the recent earthquakes, it is unlikely that in renewed movement episodes damage to dwellings would pose an immediate life risk to their occupants.
  - 13 mass movements (including their sub areas) are assessed as being in the Class III relative hazard exposure category. These are considered to be of low priority for further assessment because, if the hazard were to occur, there is potential for dwellings and local infrastructure to suffer only minor damage. Given the low magnitudes of displacement and past performance during the recent earthquakes, it is unlikely that in renewed movement episodes damage to dwellings would pose an immediate life risk to their occupants.
- Many of the mass movements in the Class I relative hazard exposure category are associated with cliff collapse and lie within existing cliff collapse risk maps (Massey et al., 2012a,b). However, in some of these areas (highlighted in yellow in Table A 3.1, Appendix 3), it is possible that larger volumes may fail and the resultant debris runout may extend further than previously assessed.
- The majority of the mass movements in the Class II and Class III hazard exposure categories are toe slumps. The mapped toe slumps represent only about 7% of the total area potentially susceptible to toe slumps. Although the movement of the toe slumps during earthquakes may be rapid, the short duration of earthquake shaking (typically less than a minute during the 2010/11 Canterbury Earthquakes) resulted in total maximum inferred displacements of about 1.5 m, with an average of 0.5 m, but the majority moved less than 0.3 m. In such areas the risk is to dwellings and infrastructure. While it is possible that people in affected dwellings could be injured by collapse of the dwelling, there were no such injuries reported during the 2010/11 Canterbury Earthquakes.

- Based on what happened during the 2010/11 Canterbury Earthquakes, earthquake-induced peak ground acceleration trigger levels for reactivation of these mass movements (those discussed in this report) are likely to be about 0.3g to 0.4g. The likely performance of these areas under longer duration shaking (such as an Alpine Fault scenario), however, has not yet been investigated.
- It is not yet understood how the mass movements will respond to exceptionally heavy or prolonged rainfall. Rainfall-induced movement of some of these features has been recorded in the past two years. However, the rainfalls have been unexceptional and the movements have been small.

## 6.0 RECOMMENDATIONS

1. Mass movements in the Class I relative hazard exposure category should be given a high priority by Christchurch City Council for detailed investigations and assessment. The level of risk needs to be quantified, including the frequency of the event occurring and the distance the debris may run-out down a slope. As an interim measure before these investigations are concluded it is recommended that:

    a. Monitoring of surface movements should be carried out at frequent intervals and/or following significant earthquakes (associated with peak ground accelerations greater than 0.3g), rain events (greater than 30 mm cumulative rainfall in any 24-hour period or 50 mm in 48 hours), or if the Council otherwise becomes aware of possible renewed movement in these areas.

    b. Each area should have an emergency-management plan, which identifies the dwellings and critical infrastructure that could potentially be affected by renewed movement and runout, and outlines a strategy to deal with such eventualities.

    c. Investigations and assessment of these mass movements should comprise: field mapping; subsurface investigations (drilling and trenching); modelling of mass movement stability and runout potential; and assessment of the frequency of the hazard occurring and ultimately the risk to people occupying dwellings and road users.

2. For mass movements in the Class II relative hazard exposure category where the consequence of the hazard occurring is to critical infrastructure, it is recommended that:

    a. The Council and its infrastructure providers should be made aware of these areas by comparing their network maps with the mass movements discussed in this report, and identify where their networks pass through them.

    b. Contingency plans should be put in place that consider the possible impact on the networks that would be caused by future displacements within these areas.

    c. Existing critical infrastructure should be redirected away from these areas where practicable. If this is not practicable, then a level of robustness should be built into the critical infrastructure e.g. engineering works that take into account future movement in these areas. New infrastructure should not be placed in these areas.

3. For mass movements in the Class II relative hazard exposure category where the consequence of the hazard occurring is to dwellings, it is recommended that:

    a. Selected toe-slump features be investigated further (as per recommendation 1c.) to assess how they are likely to perform during earthquakes which produce longer duration strong ground shaking (such as the Alpine Fault scenario), and higher ground water levels (increased pore pressures) linked to rainfall. These assessments are needed to address whether displacement of these features is something that can, or should be taken into account when constructing dwellings.

    b. In combination with these investigations, guidance (such as for foundation design and water reticulation) should be provided for owners in these areas. There are similarities between the toe slumps and the lateral spreading identified on the flat-land areas of Christchurch. Therefore, it would be appropriate for Council to consult the Ministry of Business, Innovation and Employment (MBIE), who, together with local suitably experienced engineering consultants, could provide guidance for rebuilding in these toe-slump areas.

4. For mass movements in the Class III relative hazard exposure category where the consequence of the hazard occurring is to dwellings, it is recommended that guidance (such as for foundation design, surface and subsurface water flows and reticulated water) should be provided for owners in these areas (as per recommendation 3b).

5. For existing and new dwellings on all identified mass movements it is recommended that:

    a. Filling and excavation (earthworks) within the mass-movements have appropriate geotechnical assessment. Filling and/or excavating material within these areas could change the surface/subsurface drainage and stresses (loading conditions), which could lead to renewed movement, localised subsidence, inundation by debris and/or erosion.

    b. Design and construction of local surface and sub-surface water reticulation networks (such as sewer, storm and potable) that take into account the potential for future ground displacement.

6. It is recommended that green field areas of the Port Hills are identified that exhibit similar topographical and geological characteristics as the mass movements discussed in this report. This information could be used as a guide to the potential for mass movement and to advise that appropriately qualified and locally experienced engineering geologists should assess the area prior to building.

## 7.0 ACKNOWLEDGEMENTS

The authors would like to acknowledge Laurie Richards (Rock Engineering Consultant), Tony Taig (TTAC Ltd.) and Mauri McSaveney (GNS Science), who have all contributed significantly to the information presented in this report. This report was reviewed by M. McSaveney and W. Saunders (GNS Science) and by L. Richards (Rock Engineering Consultant) and T. Taig (TTAC Ltd.).

## 8.0 REFERENCES

Australia New Zealand Standard (AS/NZS) 1170.0:2002.

Australia New Zealand Standard (AS/NZS) 4360:2004 companion guide.

Abramson, L.W., Lee, T.S., Sharma, S., Boyce, G.M. 2002. Slope stability and stabilisation methods, Second edition. A Wiley Interscience publication. Pub. John Wiley and Sons.

Bell, D.H., Trangmar, B.B. 1987. Regolith materials and erosion processes on the Port Hills, Christchurch, New Zealand: Fifth International Symposium and Field Workshop on Landslides. Lausanne, A.A. Balkema. Volume 1: 77-83.

Cruden, D.M., Varnes, D.J. 1996. Landslide types and processes. Landslide: investigation and mitigation. Turner, K.A.; Schuster, R.L. (eds.). Special report, Transportation Research Board, National Research Council, 247. Chapter 3, 36–75.

Department of the Environment (DoE). 1990. Planning Policy Guidance: Development on Unstable Land, PPGl4. London, HMSO.

Griffiths, G., Pearson., McKerchar, A. 2009. Review of the frequency of high intensity rainfalls in Christchurch. NIWA Client Report: CHC2009-139. September 2009.

Gerstenberger, M., Cubrinovski, M., McVerry, G., Stirling, M., Rhoades, D., Bradley, B., Langridge, R., Webb, T., Peng, B., Pettinga, J., Berryman, K., Brackley, H. 2011. Probabilistic assessment of liquefaction potential for Christchurch in the next 50 years. GNS Science Report 2011/15.

Harvey, M.D. 1976. An analysis of the soil slips that occurred on the Port Hills, Canterbury, between 10-25 August 1975. Soil Science Society of New Zealand, Palmerston North, August 1976.

Jibson, R.W., Keefer, D.K. 1993. Analysis of the seismic origin of landslides: Examples from the New Madrid Seismic Zone. Geological Society of America Bulletin, Vol. 21, No. 4, pp. 521-536.

Keefer, D.K., Wilson, R.C. 1989. Predicting earthquake-induced landslides, with emphasis on arid and semi-arid environments. Proceedings of landslides in semi-arid environment. Vol. 2. Inland Geological Society, Riverside, California. pp. 118-149.

Massey, C.I., McSaveney, M.J., Yetton, M.D., Heron, D., Lukovic, B., Bruce, Z.R.V. 2012a. Canterbury Earthquakes 1020/11 Port Hills Slope Stability: Pilot study for assessing life-safety risk from cliff collapse. GNS Science Consultancy Report 2012/57.

Massey, C.I., McSaveney, M.J. and Heron, D. 2012b. Canterbury earthquakes 2010/11 Port Hills Slope Stability: Life-safety risk from cliff collapse in the Port Hills, GNS Science Consultancy Report 2012/124. 35 p + Appendices.

Massey, C.I., McSaveney, M.J., Heron, D., Lukovic, B. 2012c. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Pilot study for assessing life-safety risk from rockfalls (boulder rolls). GNS Science Consultancy Report 2011/311.

Massey, C.I., McSaveney, M.J., Lukovic, B., Heron, D., Ries, W., Moore, A., Carey, J. 2012d. Canterbury Earthquakes 2010/11 Port Hills Slope Stability: Life-safety risk from rockfalls (boulder rolls) in the Port Hills, GNS Science Consultancy Report 2012/123.

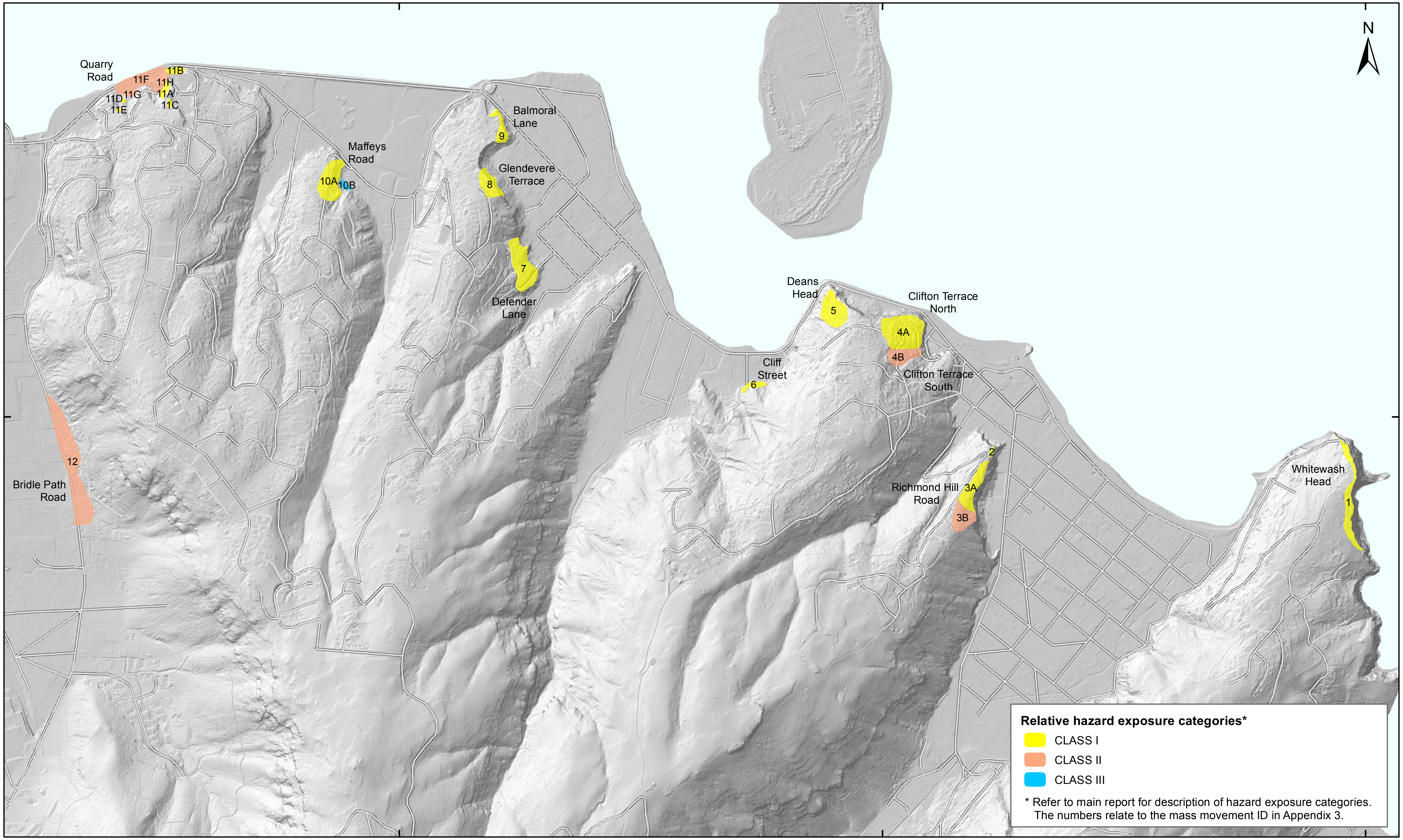
Ministry of Business, Innovation and Employment 2012.http://www.dbh.govt.nz/UserFiles/File/Publications/Building/Guidance-information/pdf/canterbury-technical-guidance-foundations-part-c.pdf, Appendix C2: Guidance on PGA values for geotechnical design in Canterbury.

New Zealand Standard NZS1170.5:2004.

Webb, T.H. (compiler), Bannister, S., Beavan, J., Berryman, K., Brackley, H., Fry, B., Gerstenberger, M., Holden, C., Kaiser, A., McVerry, G., McSaveney, E., Pettinga, J., Reyners, M., Rhoades, D., Somerville, P., Stirling, M., Van Dissen, R., Villamor, P., Wallace, L., Zhao, J. 2011. The Canterbury Earthquake Sequence and Implications for Seismic Design Levels. GNS Science Consultancy Report 2011/183.

# APPENDICES

## APPENDIX 1: STAGE 1 LOCATIONS OF IDENTIFIED SIGNIFICANT MASS MOVEMENTS IN THE PORT HILLS PROJECT AREA




SCALE BAR: 0 0.5 1 km

EXPLANATION:

Refer to Appendices 2 and 3 for maps and more details of each mass movement.

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution.
Roads provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

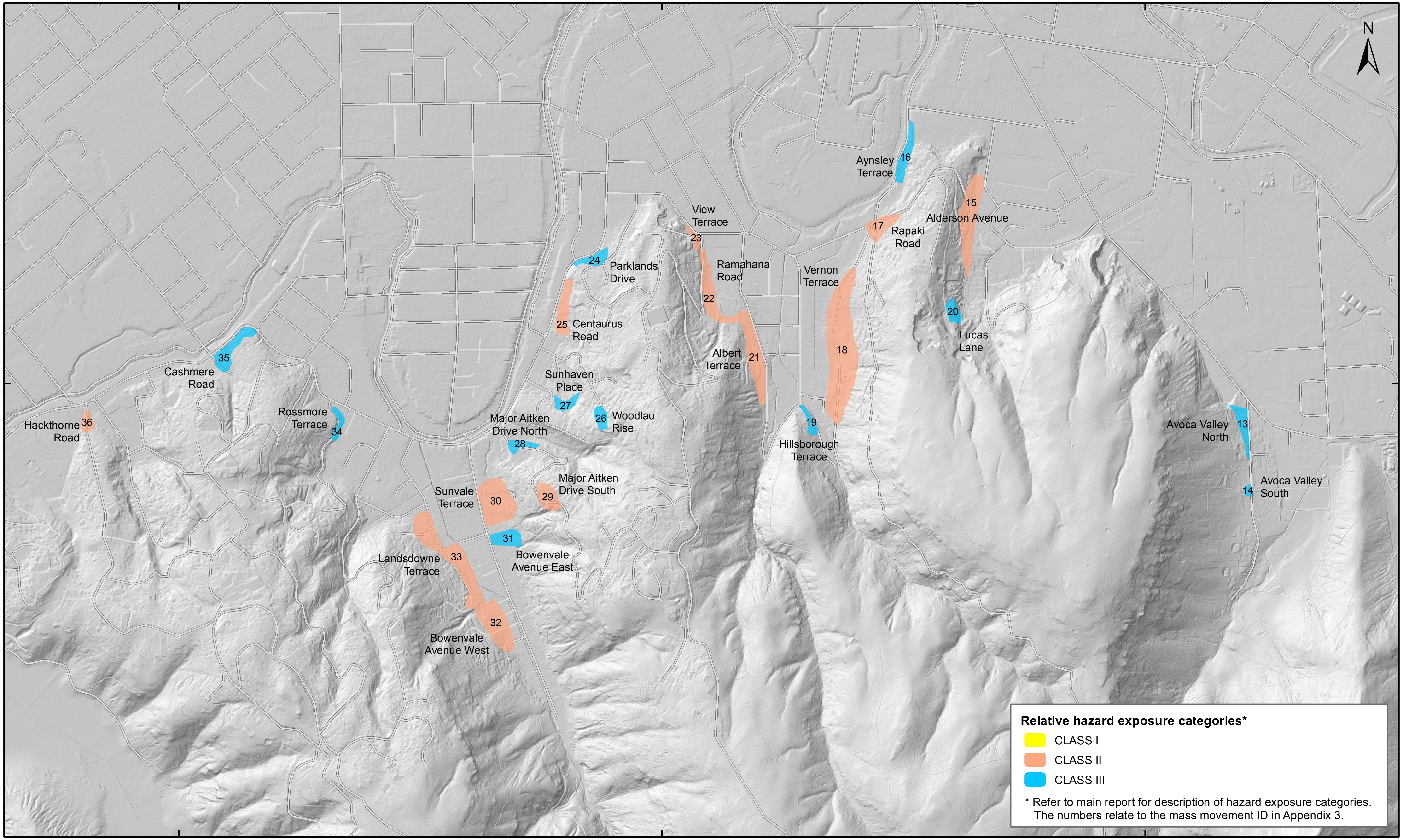
**Appendix 1**

**FINAL**

**Map 1**

REPORT: CR2012/317

DATE: July 2013




SCALE BAR: 0 0.5 1 km

EXPLANATION:

Refer to Appendices 2 and 3 for maps and more details of each mass movement.

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution.
Roads provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills**
**Christchurch**

**Appendix 1**

**FINAL**

**Map 2**

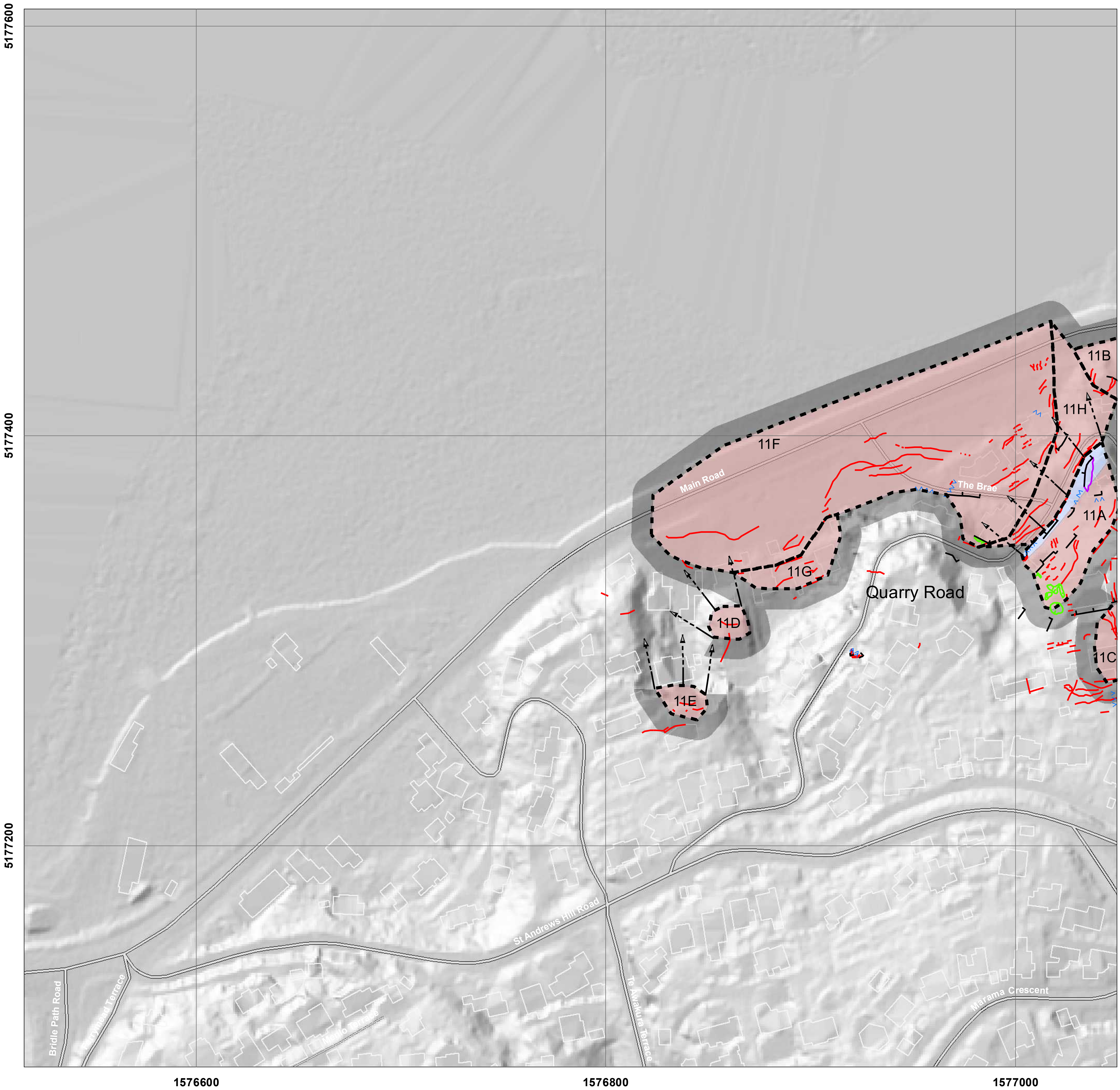
REPORT: CR2012/317

DATE: July 2013

## APPENDIX 2: STAGE 1 MASS MOVEMENT MAPS

# MAP INDEX

| Name of mass movement | Map Number |
|---|---|
| Albert Terrace | C6, D6 |
| Alderson Avenue | B8, C8 |
| Avoca Valley North | D10, E10 |
| Avoca Valley South | E10 |
| Aynsley Terrace | B7, B8 |
| Balmoral Lane | A18 |
| Bowenvale Avenue East | E4 |
| Bowenvale Avenue West | F4 |
| Bridle Path Road | D15, E15 |
| Cashmere Road | D2 |
| Centaurus Road | C5, D5 |
| Cliff Street | D20 |
| Clifton Terrace North | C21, C22 |
| Clifton Terrace South | C21, C22 |
| Deans Head | C21 |
| Defender Lane | B18, B19, C18, C19 |
| Glendevere Terrace | B18 |
| Hackthorne Road | D1 |
| Hillsborough Terrace | D7 |
| Landsdowne Terrace | E3, E4, F4 |
| Lucas Lane | C8 |
| Maffeys Road | B17 |
| Major Aitken Drive North | E4 |
| Major Aitken Drive South | E4, E5 |
| Parklands Drive | C5 |
| Quarry Road | A15, A16 |
| Ramahana Road | C6 |
| Rapaki Road | B7, C7 |
| Richmond Hill Road | D22, E22 |
| Rossmore Terrace | D3 |
| Sunhaven Place | D5 |
| Sunvale Terrace | E4 |
| Vernon Terrace | C7, D7 |
| View Terrace | C6 |
| Whitewash Head | D25, E25 |
| Woodlau Rise | D5 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

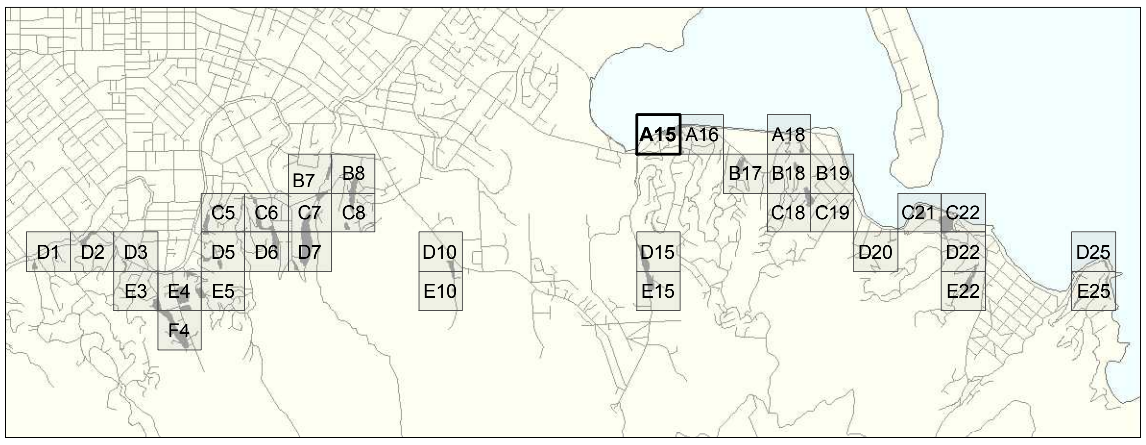
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | | STAGE 1: MASS MOVEMENTS | **Appendix 2** |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL | GNS SCIENCE TE PŪ AO | | **FINAL** |
| | CHK: CM, JC, MY | | **Port Hills Christchurch** | **Map A15** |
| | | | | REPORT: CR2012/317 · DATE: July 2013 |


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

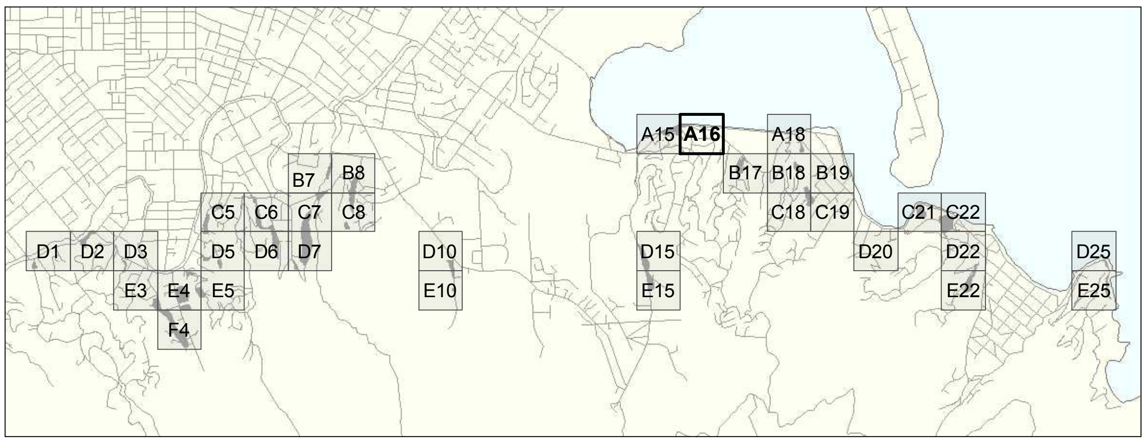
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

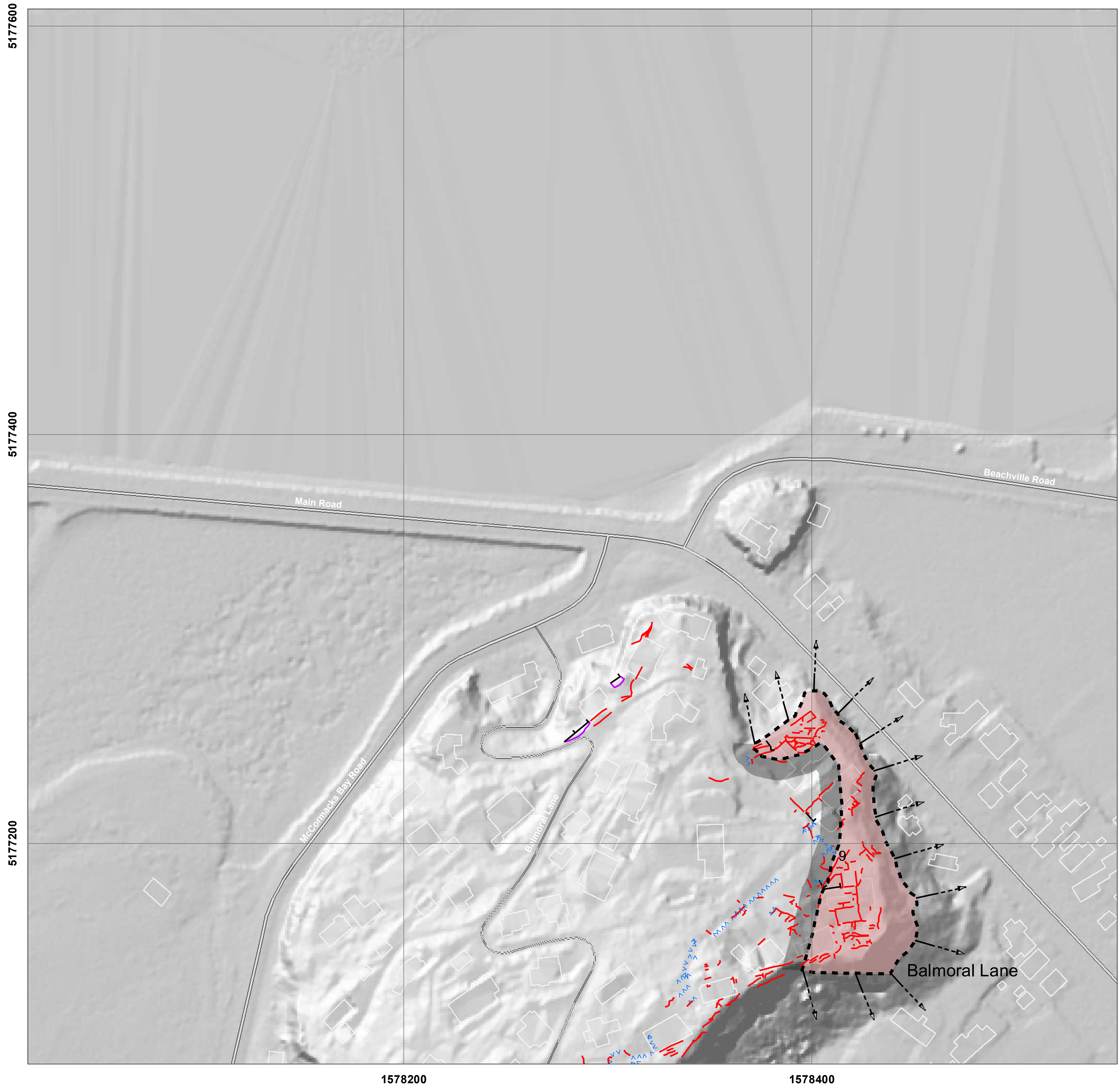
**Appendix 2**

**FINAL**

**Map A16**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

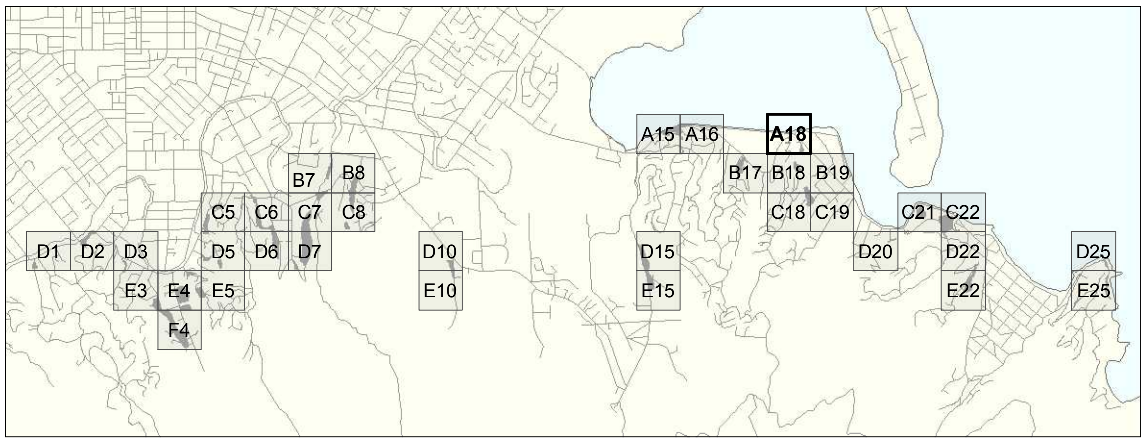
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map A18**

REPORT: CR2012/317

DATE: July 2013


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

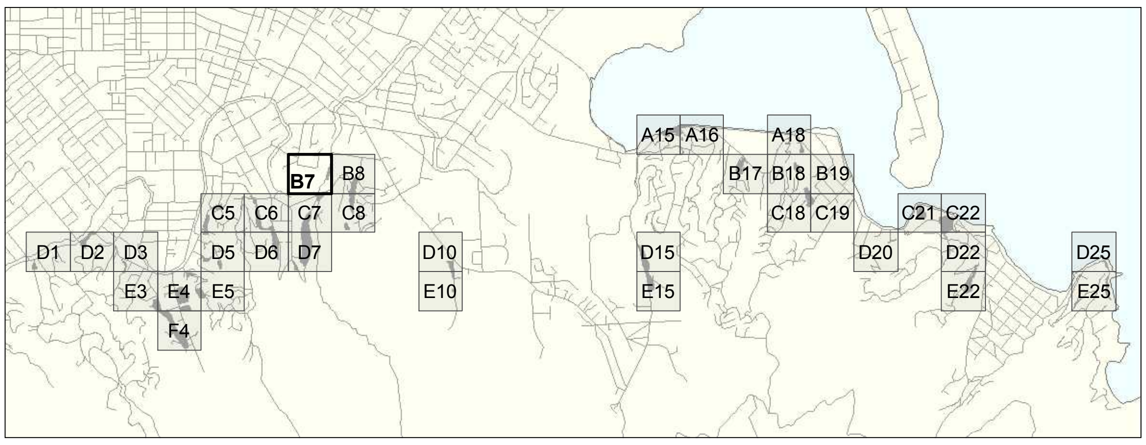
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

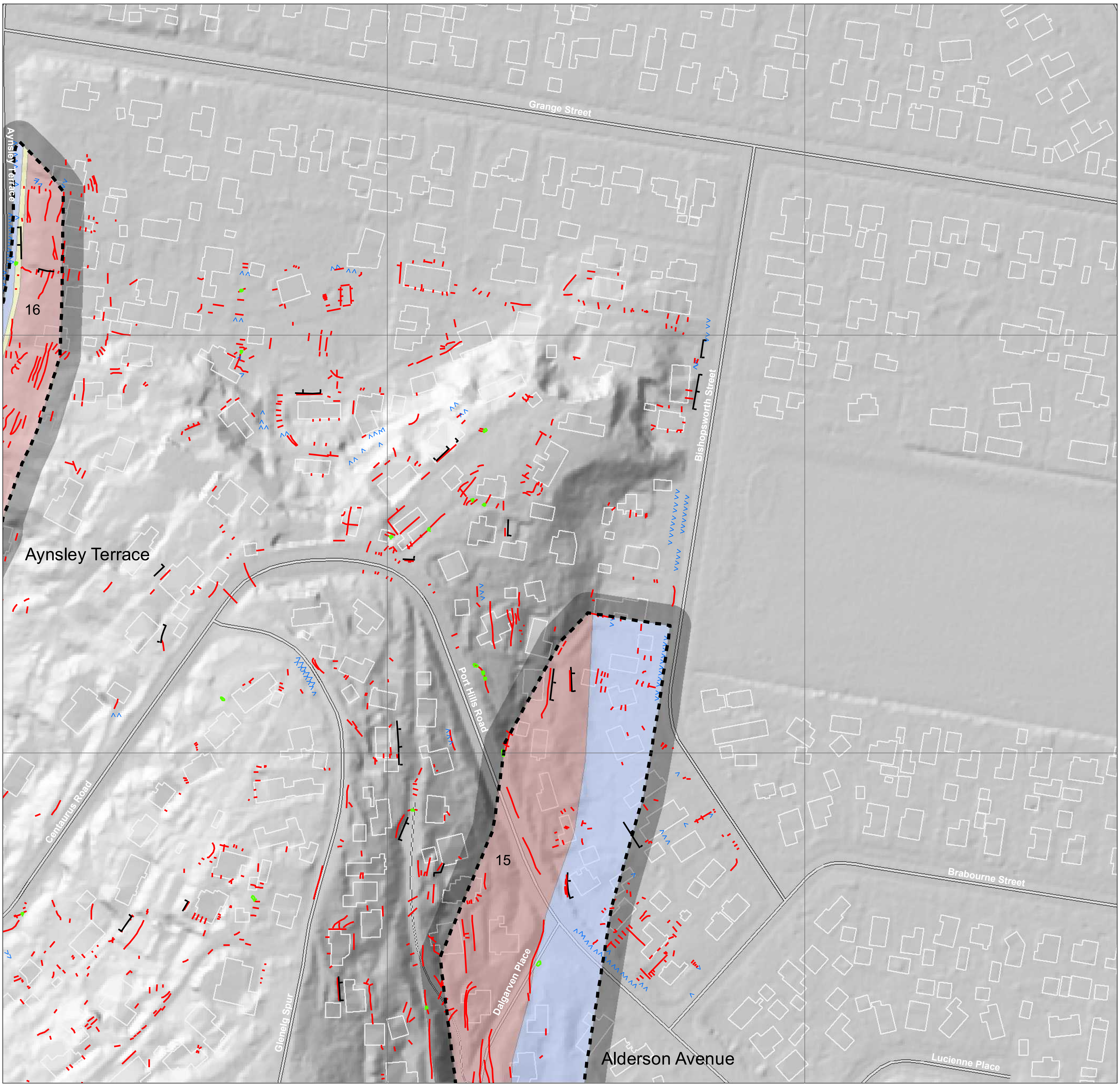
N

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| | | | | **FINAL** |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL / CHK: CM, JC, MY | | **Port Hills Christchurch** | **Map B7** |
| | | | | REPORT: CR2012/317 DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

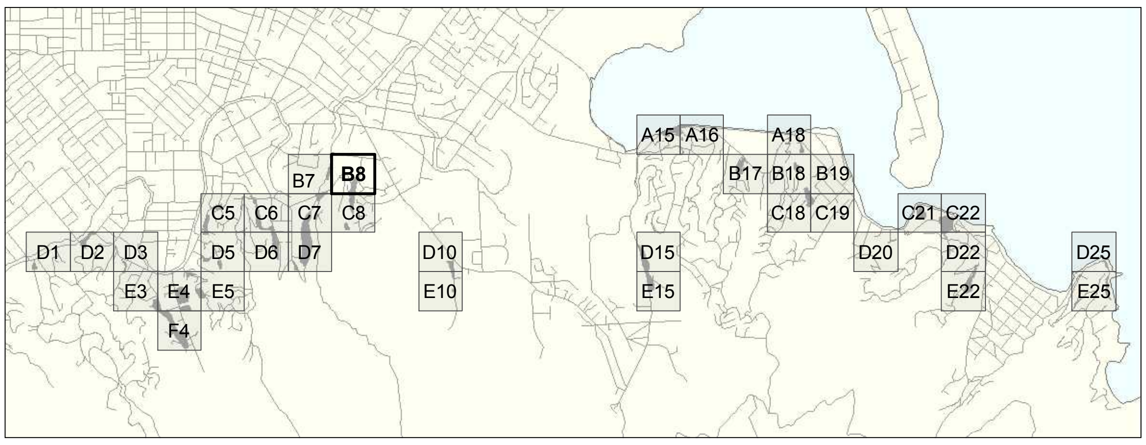
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map B8**

REPORT: CR2012/317

DATE: July 2013


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

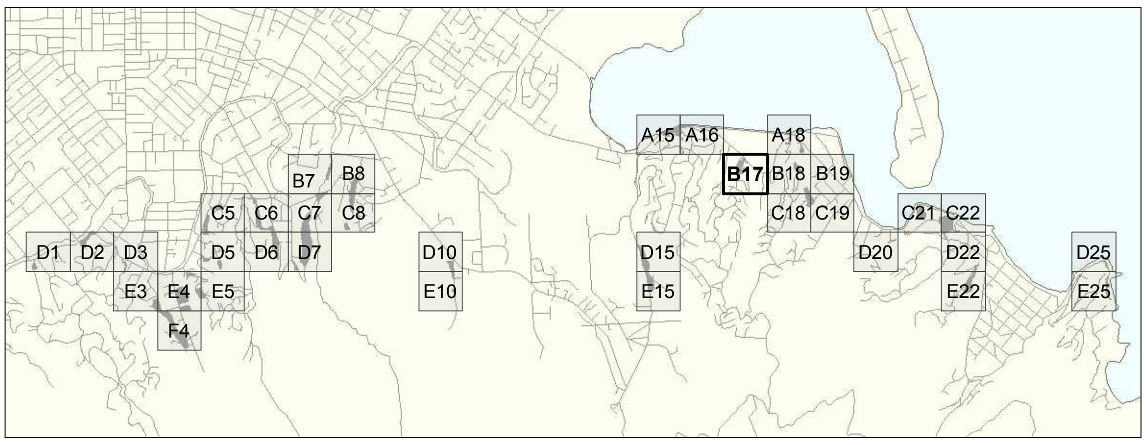
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

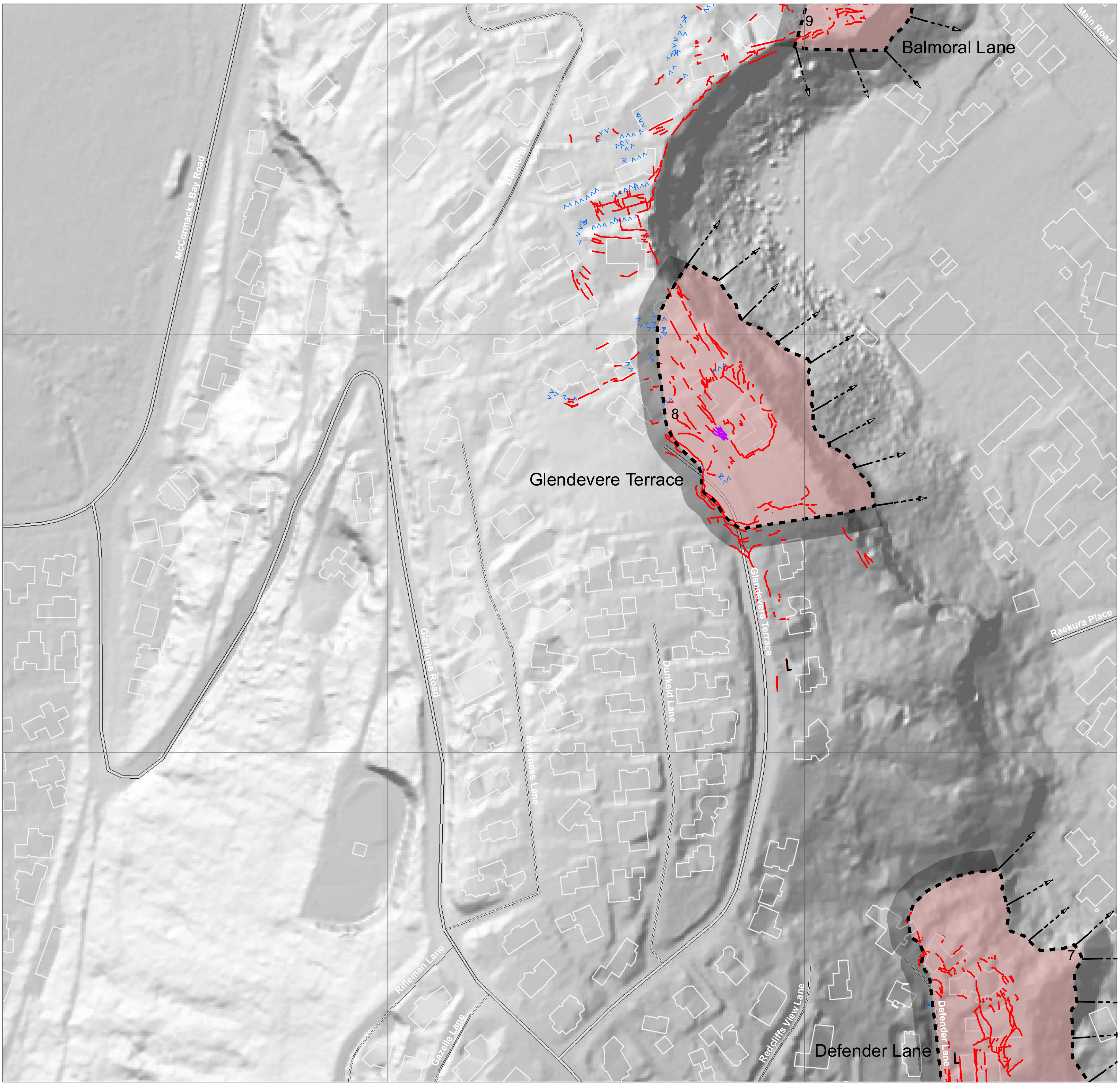
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL | | | FINAL |
| | CHK: CM, JC, MY | | Port Hills Christchurch | Map B17 |
| | | | | REPORT: CR2012/317 — DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

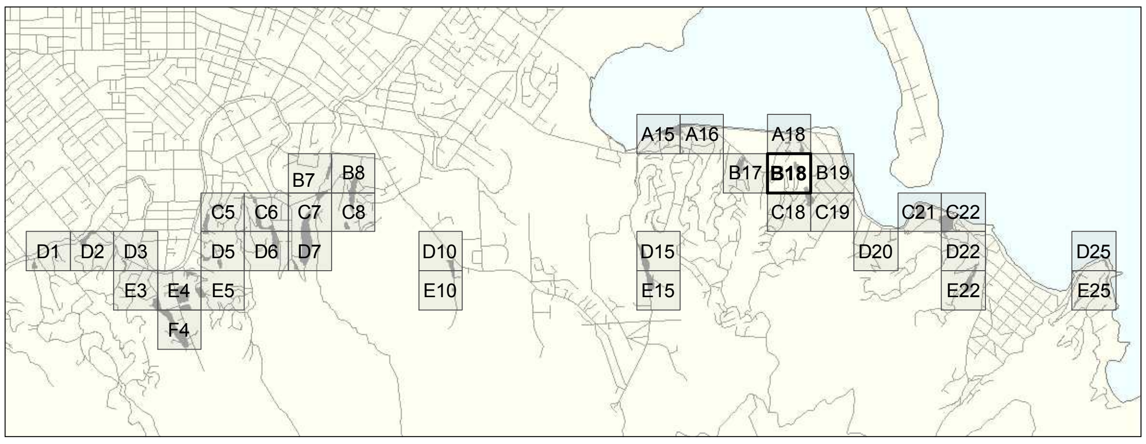
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map B18**

REPORT: CR2012/317

DATE: July 2013


N

**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

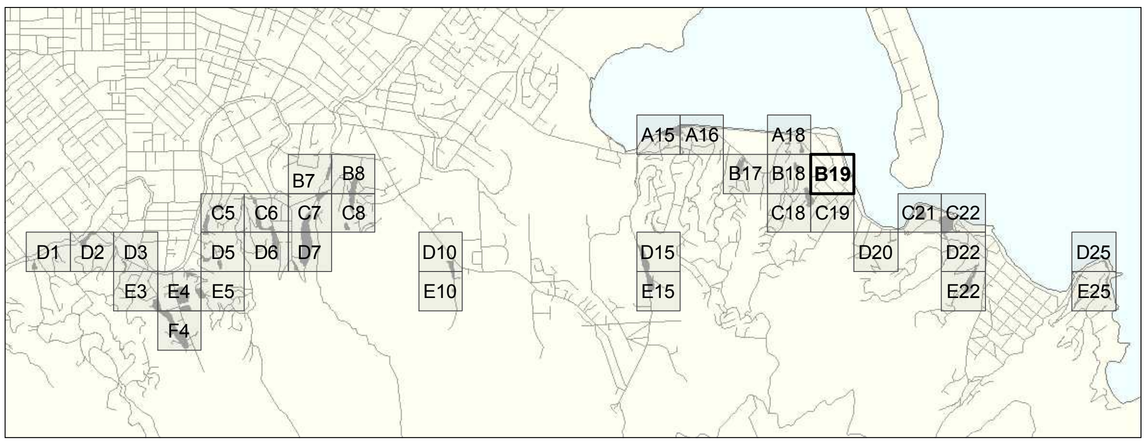
**Curent mass movements**

- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

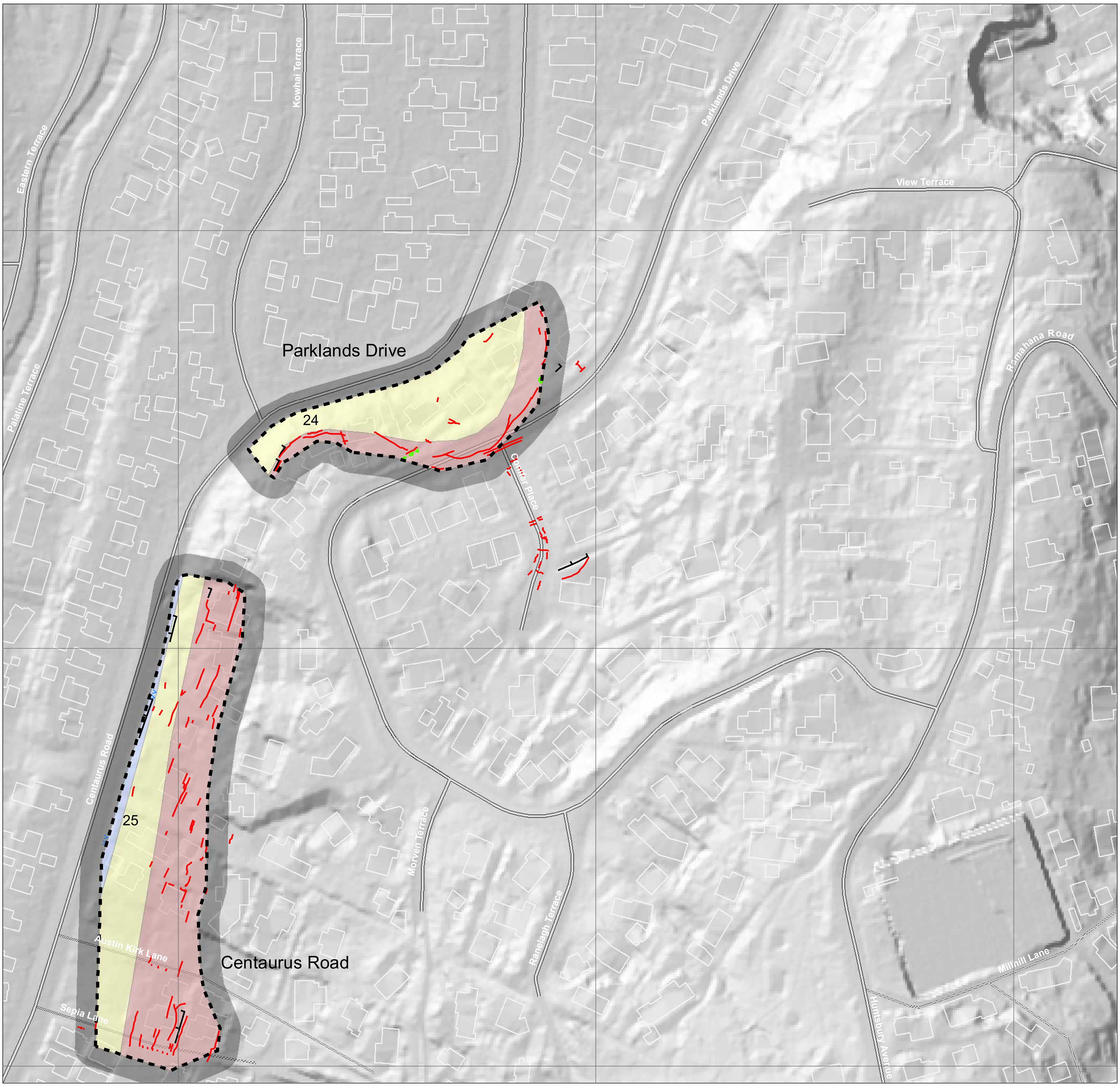
- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 / **FINAL** |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL / CHK: CM, JC, MY | | Port Hills Christchurch | Map B19 / REPORT: CR2012/317 / DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

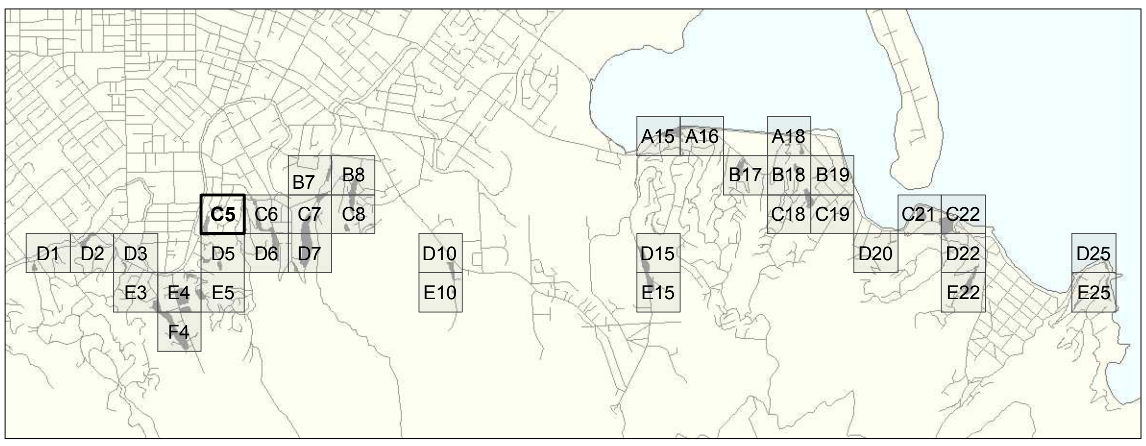
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

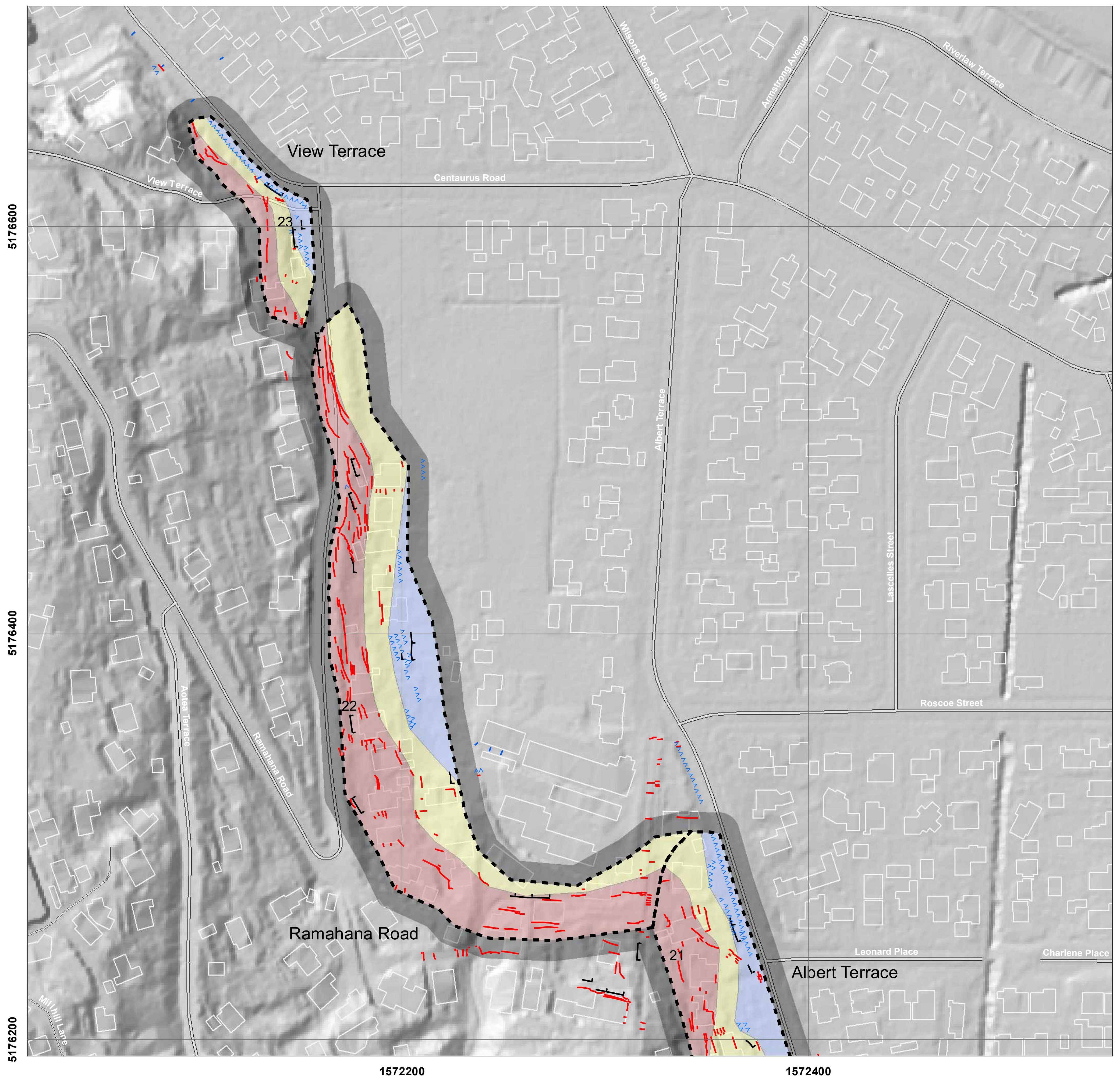
**Appendix 2**

**FINAL**

**Map C5**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

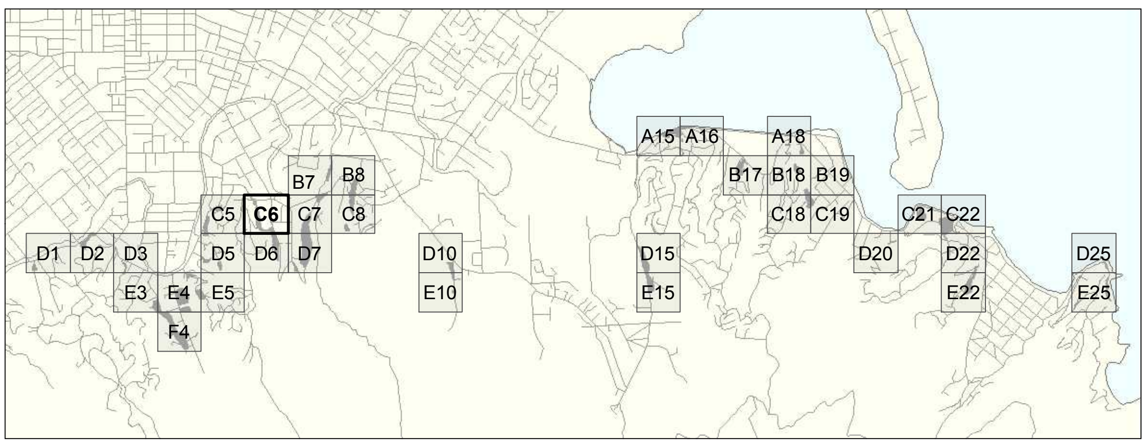
**Curent mass movements**

- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

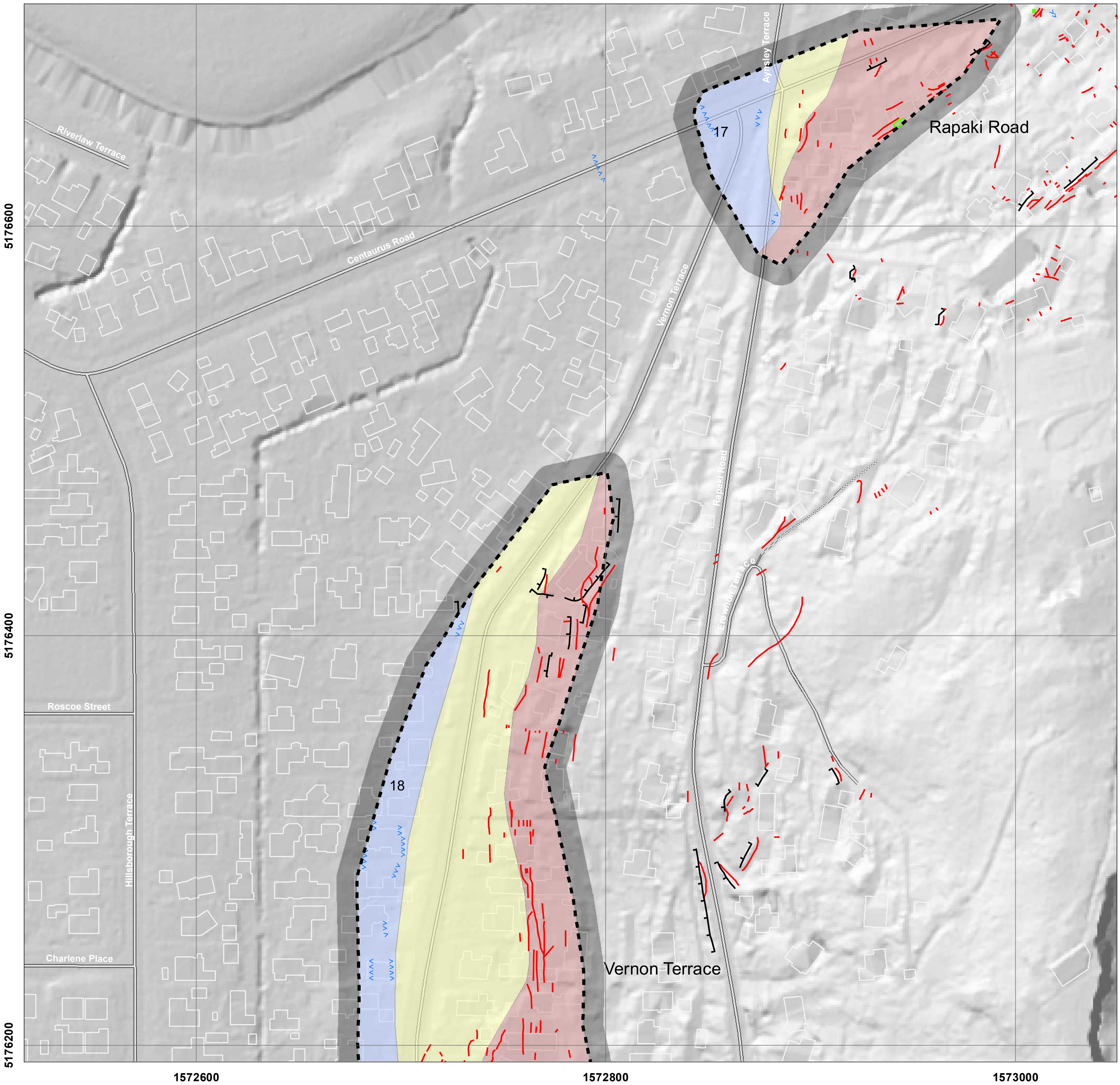
**Appendix 2**

**FINAL**

**Map C6**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

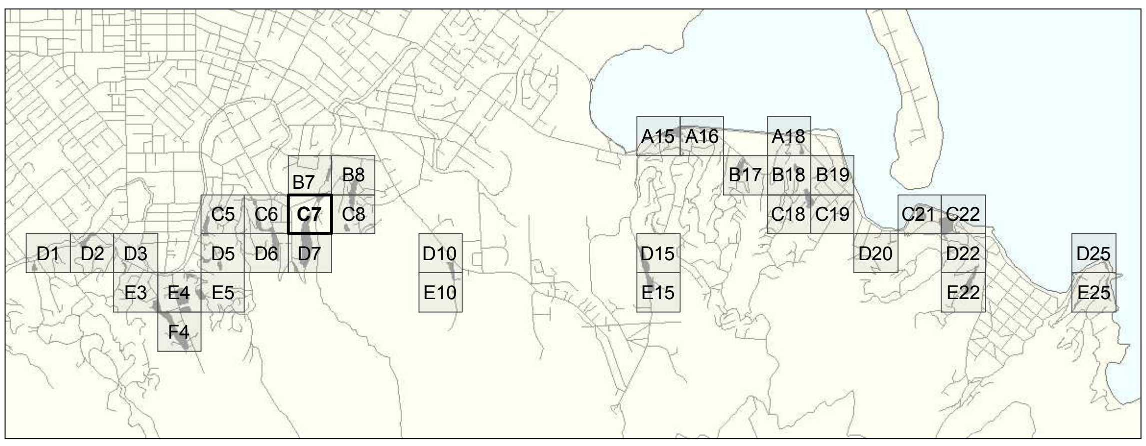
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

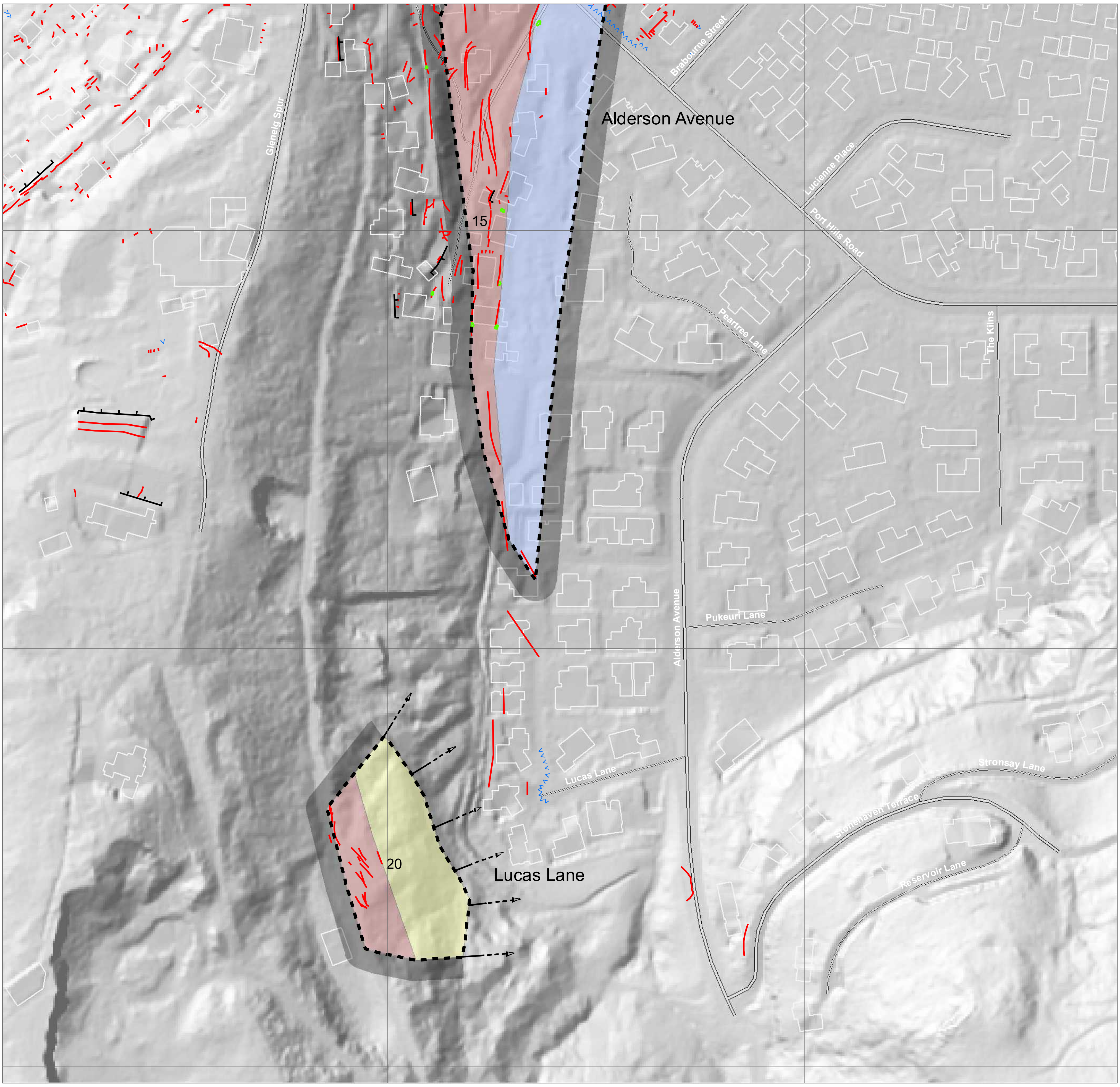
**Appendix 2**

**FINAL**

**Map C7**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

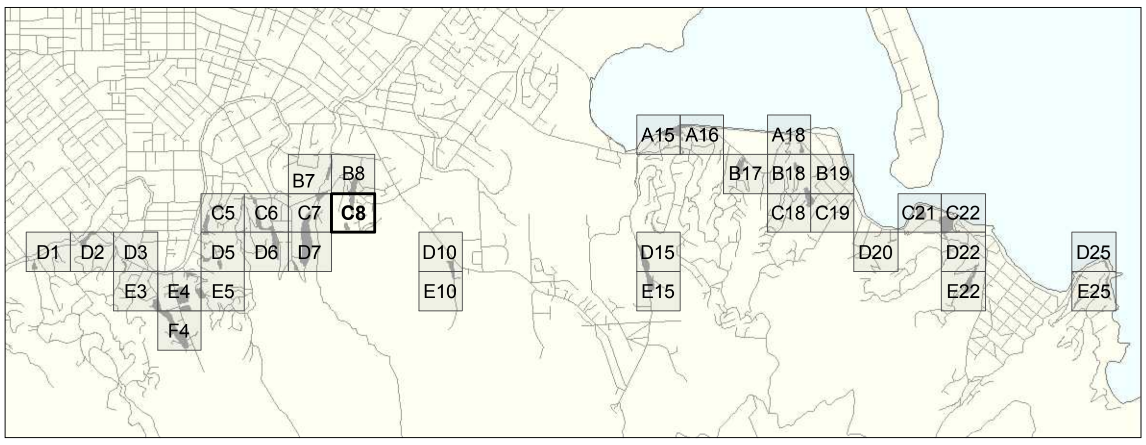
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

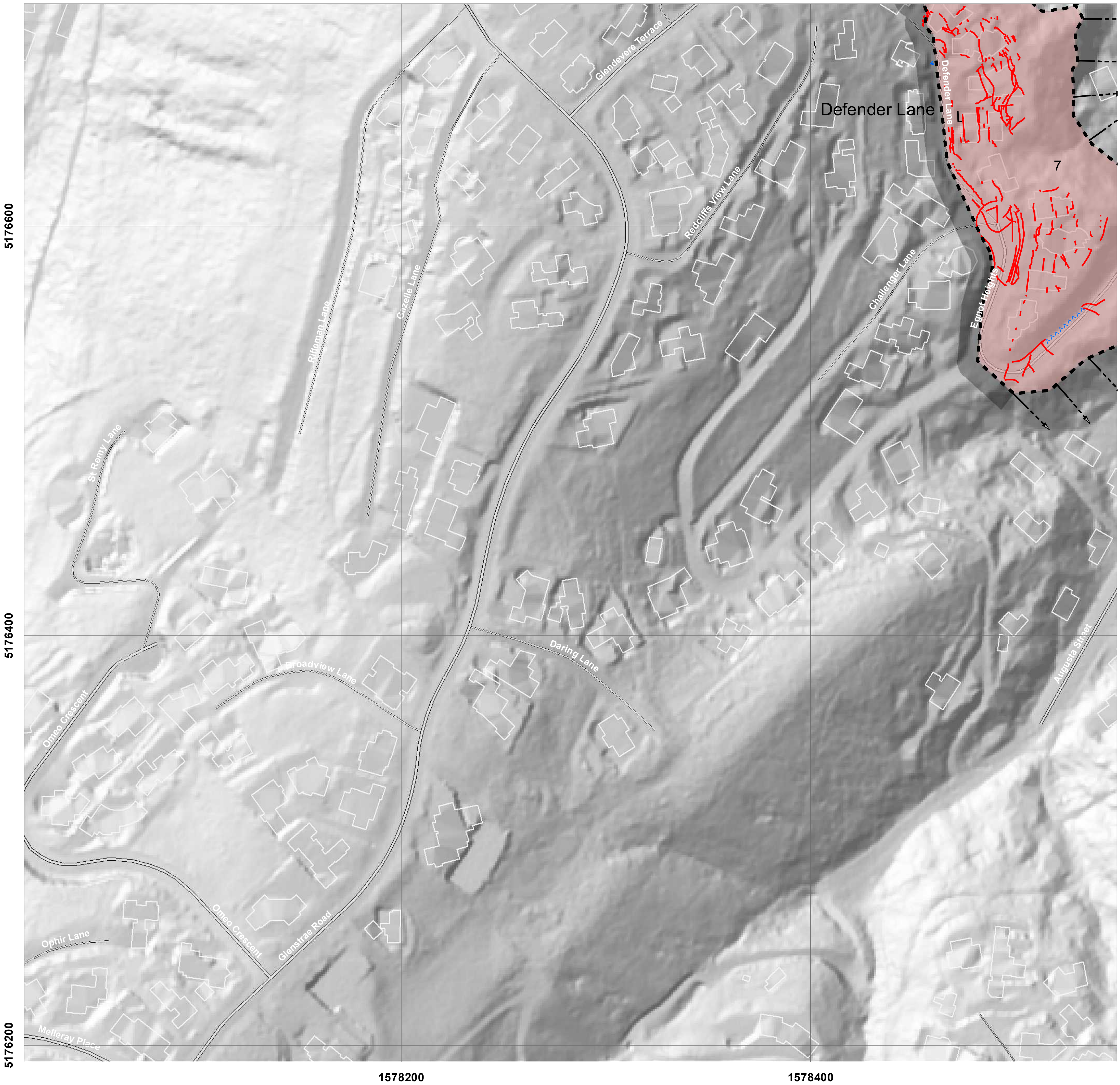
**Appendix 2**

**FINAL**

**Map C8**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

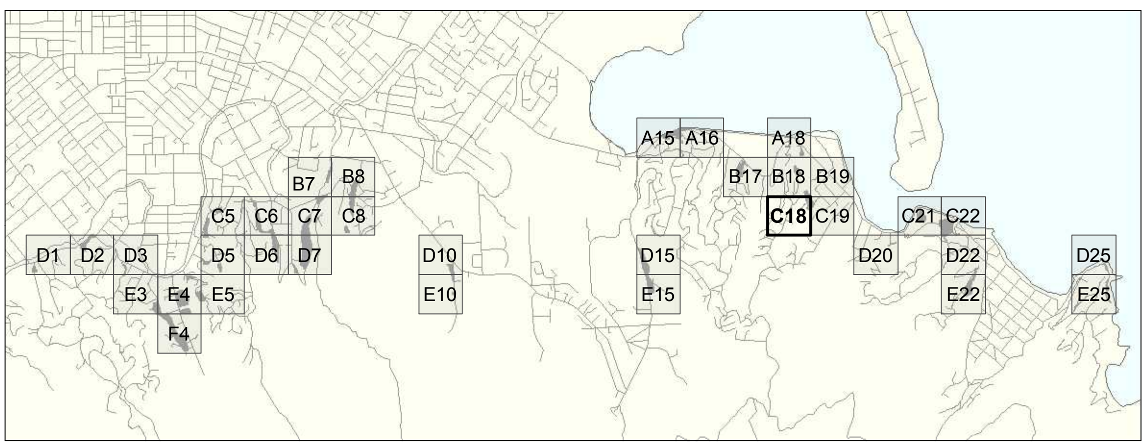
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

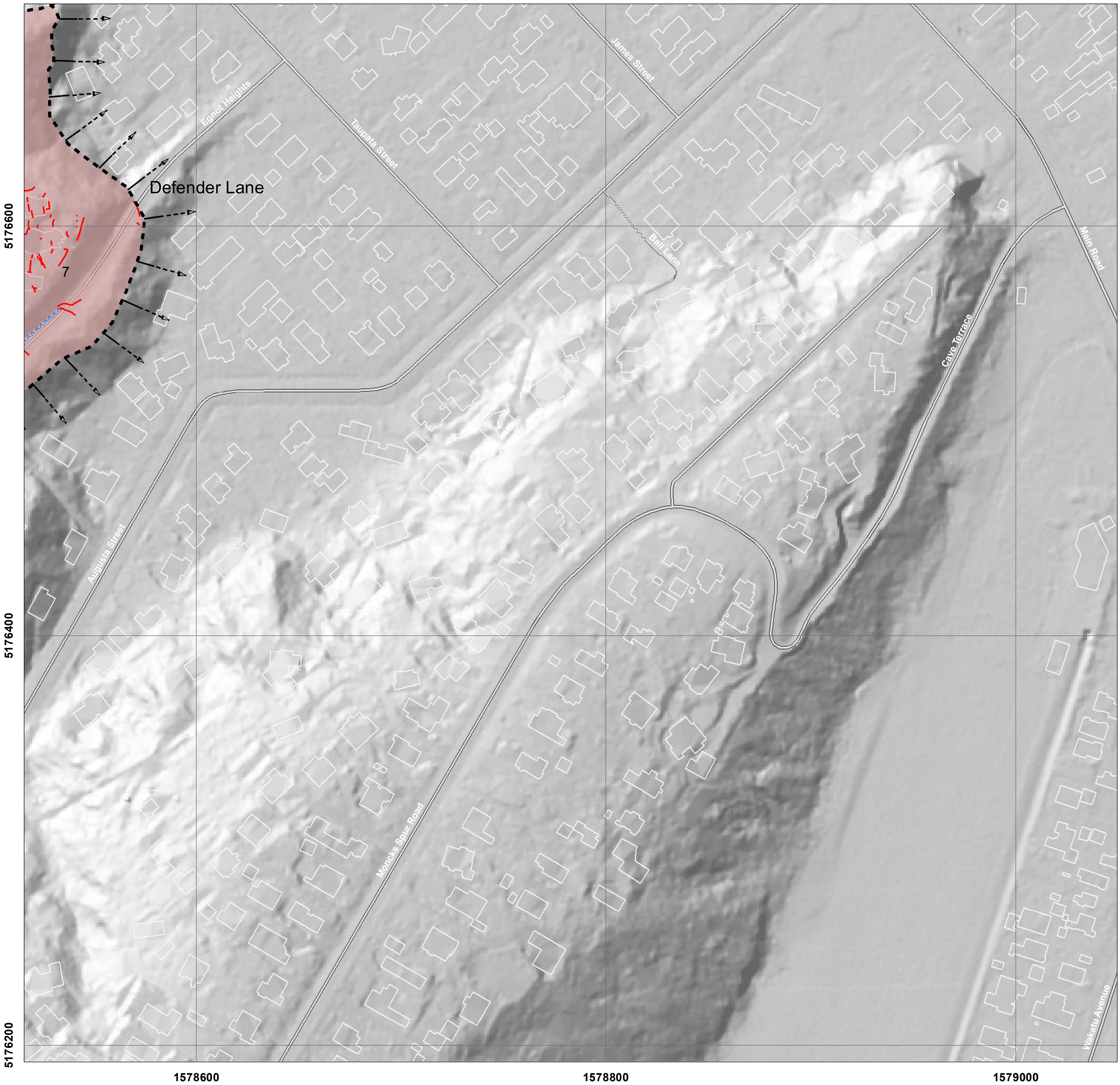
**Appendix 2**

**FINAL**

**Map C18**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

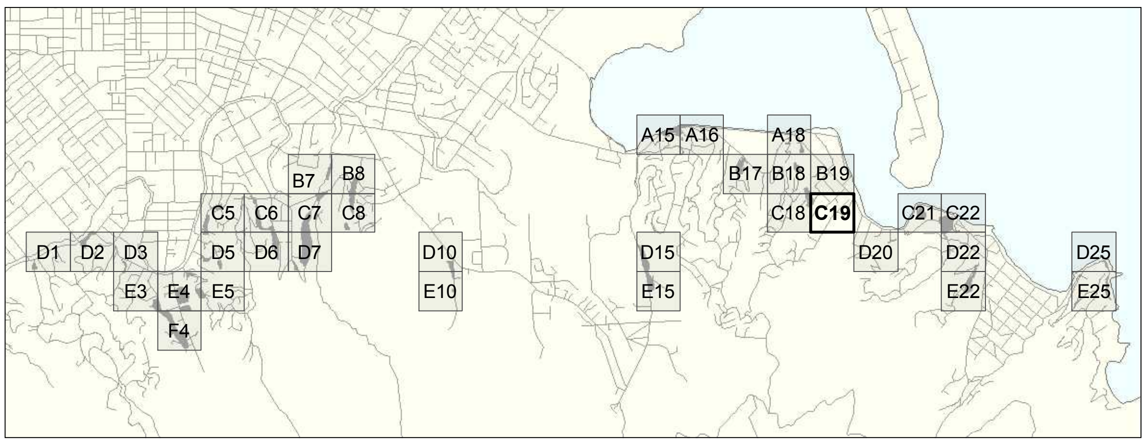
**Curent mass movements**

- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:
Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL
CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map C19**

REPORT: CR2012/317
DATE: July 2013


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

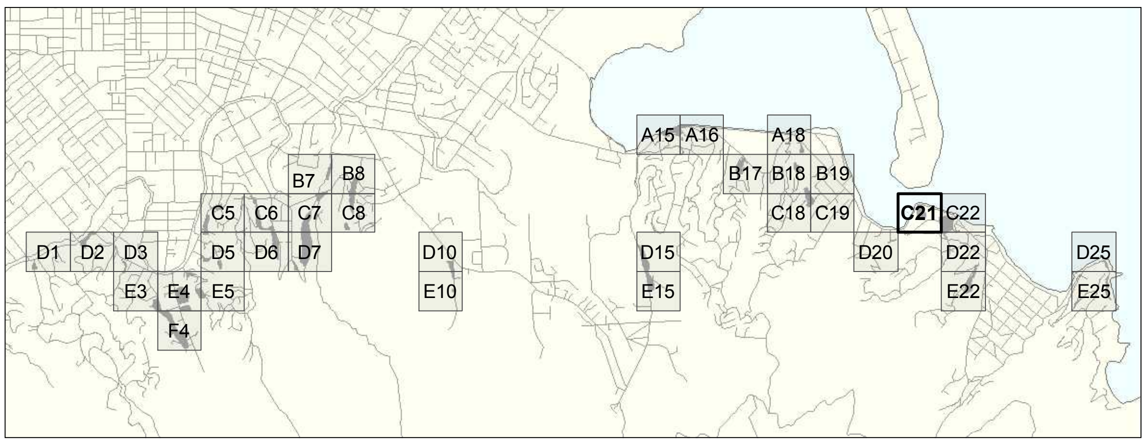
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

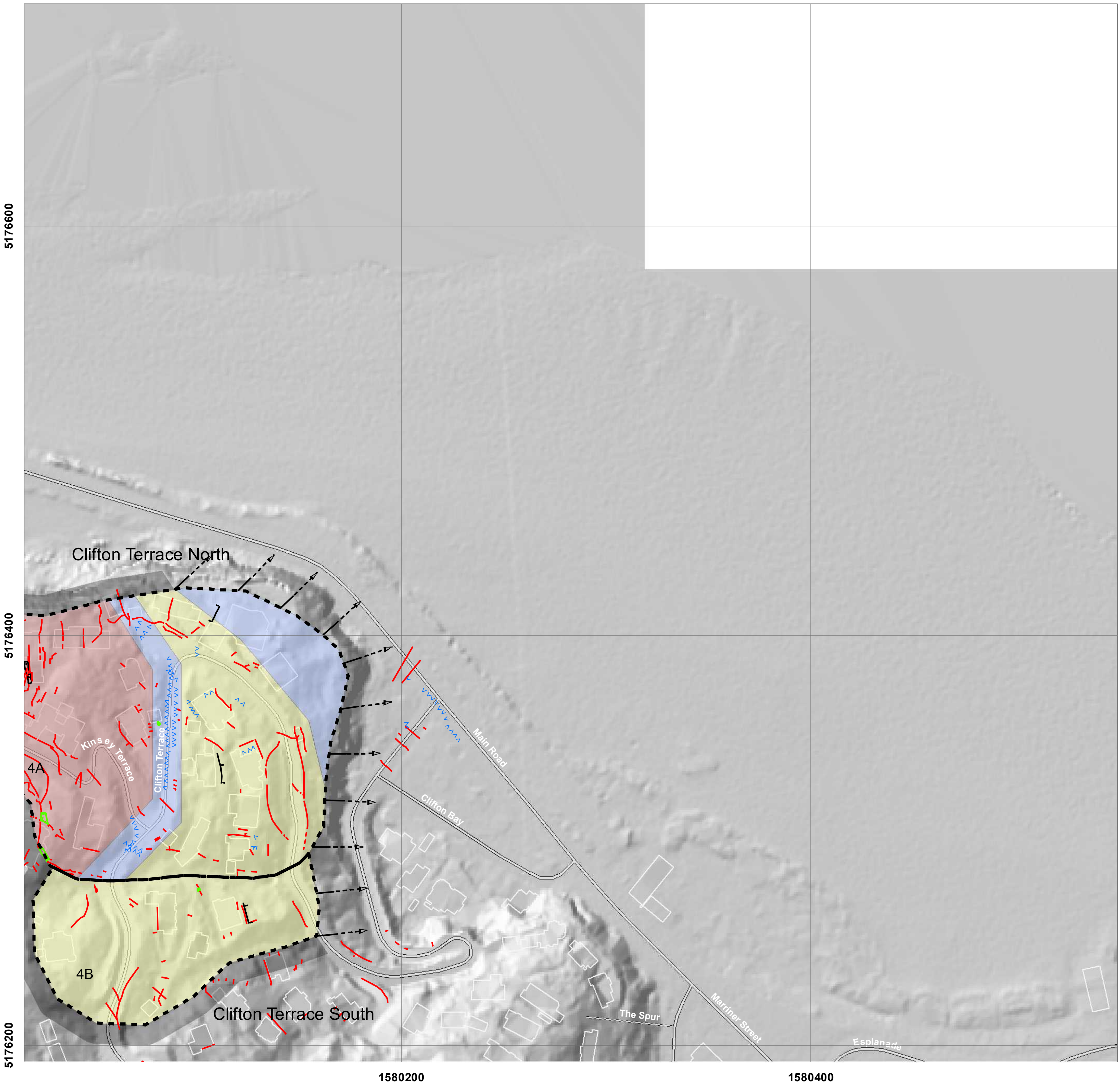
N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | |
|---|---|---|---|
| SCALE BAR: 0 50 100 m | | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| EXPLANATION:<br>Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).<br>PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | **Port Hills Christchurch** | **FINAL**<br>**Map C21**<br>REPORT: CR2012/317 DATE: July 2013 |

GNS SCIENCE TE PŪ AO




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

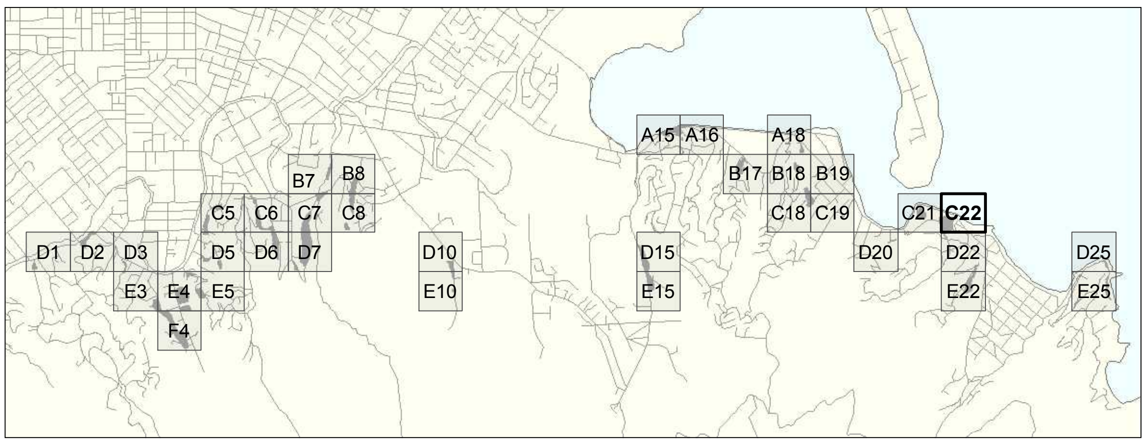
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

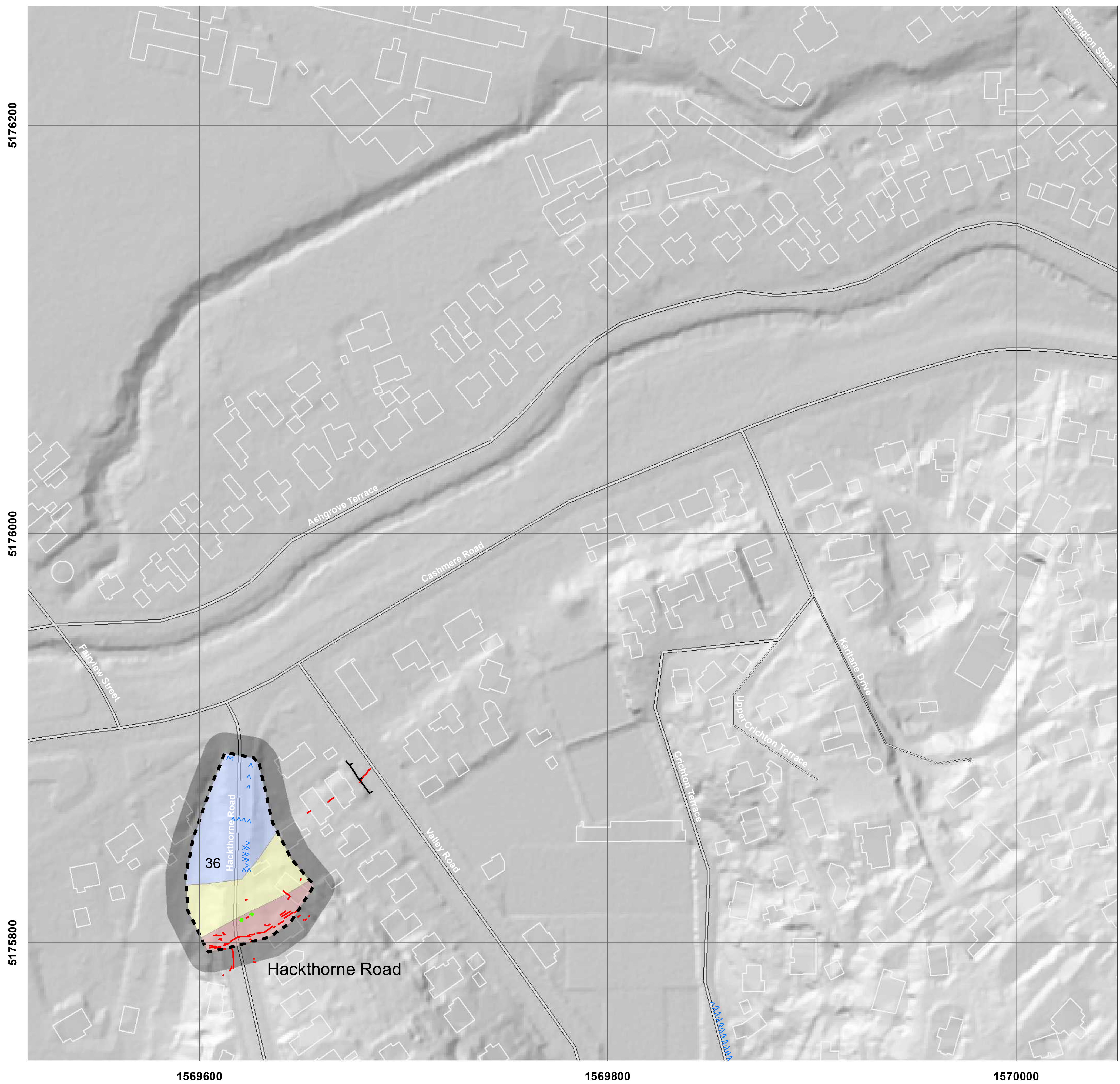
**Appendix 2**

**FINAL**

**Map C22**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

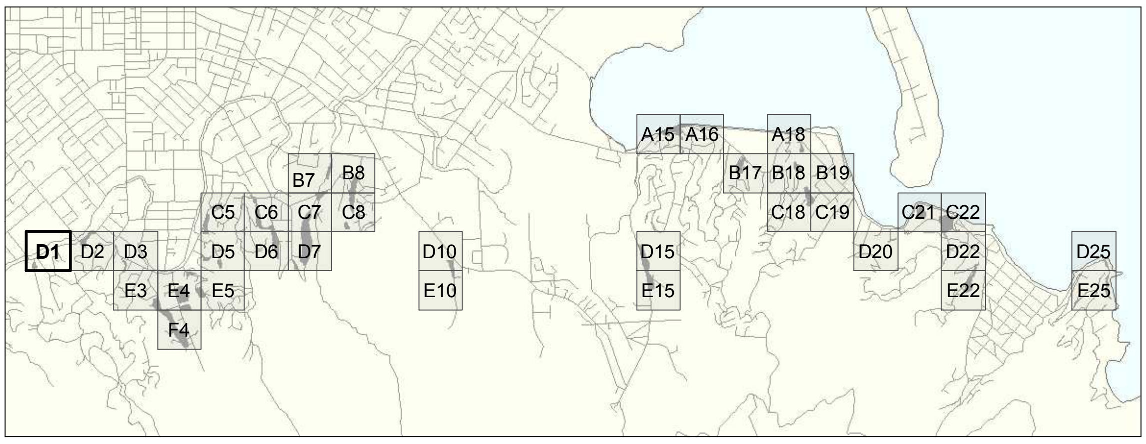
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

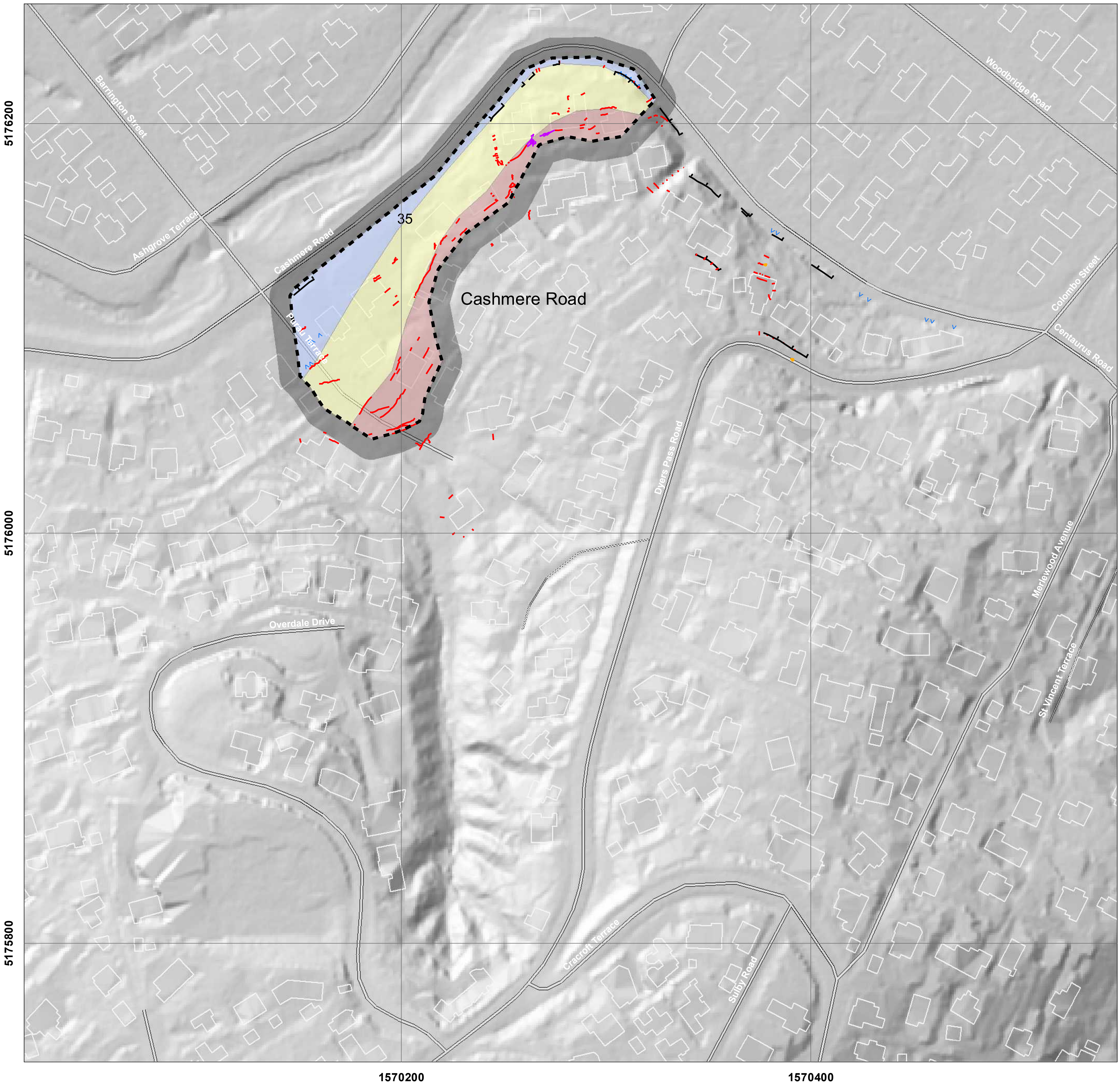
**Appendix 2**

**FINAL**

**Map D1**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

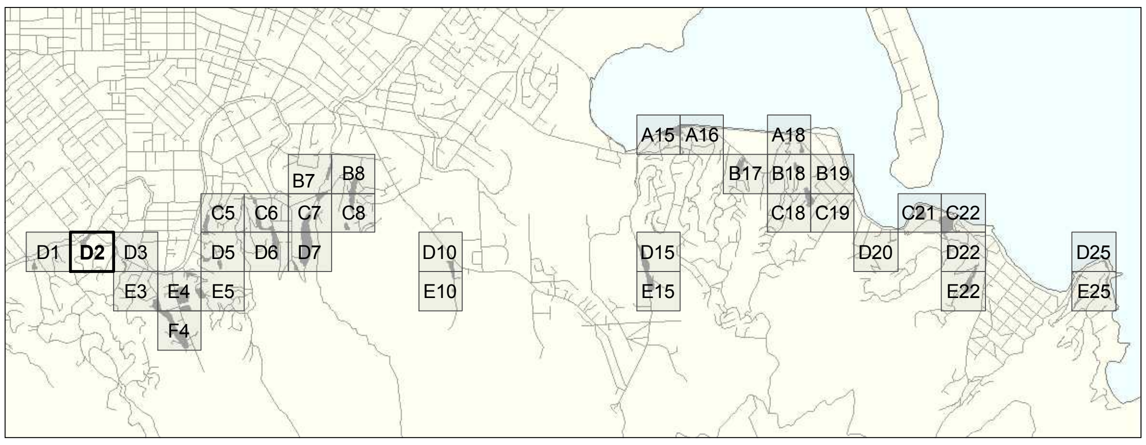
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
|---|---|---|---|---|
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | | Port Hills Christchurch | FINAL<br>Map D2<br>REPORT: CR2012/317 DATE: July 2013 |


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

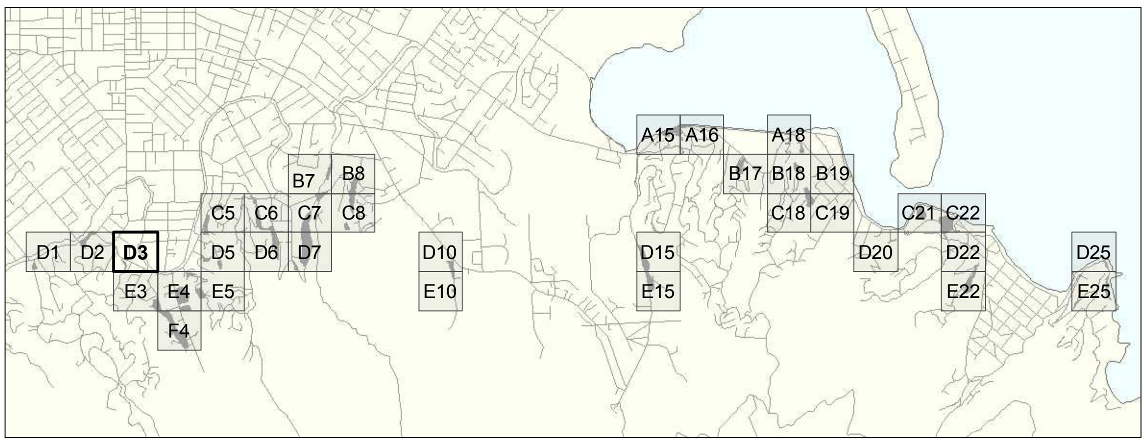
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

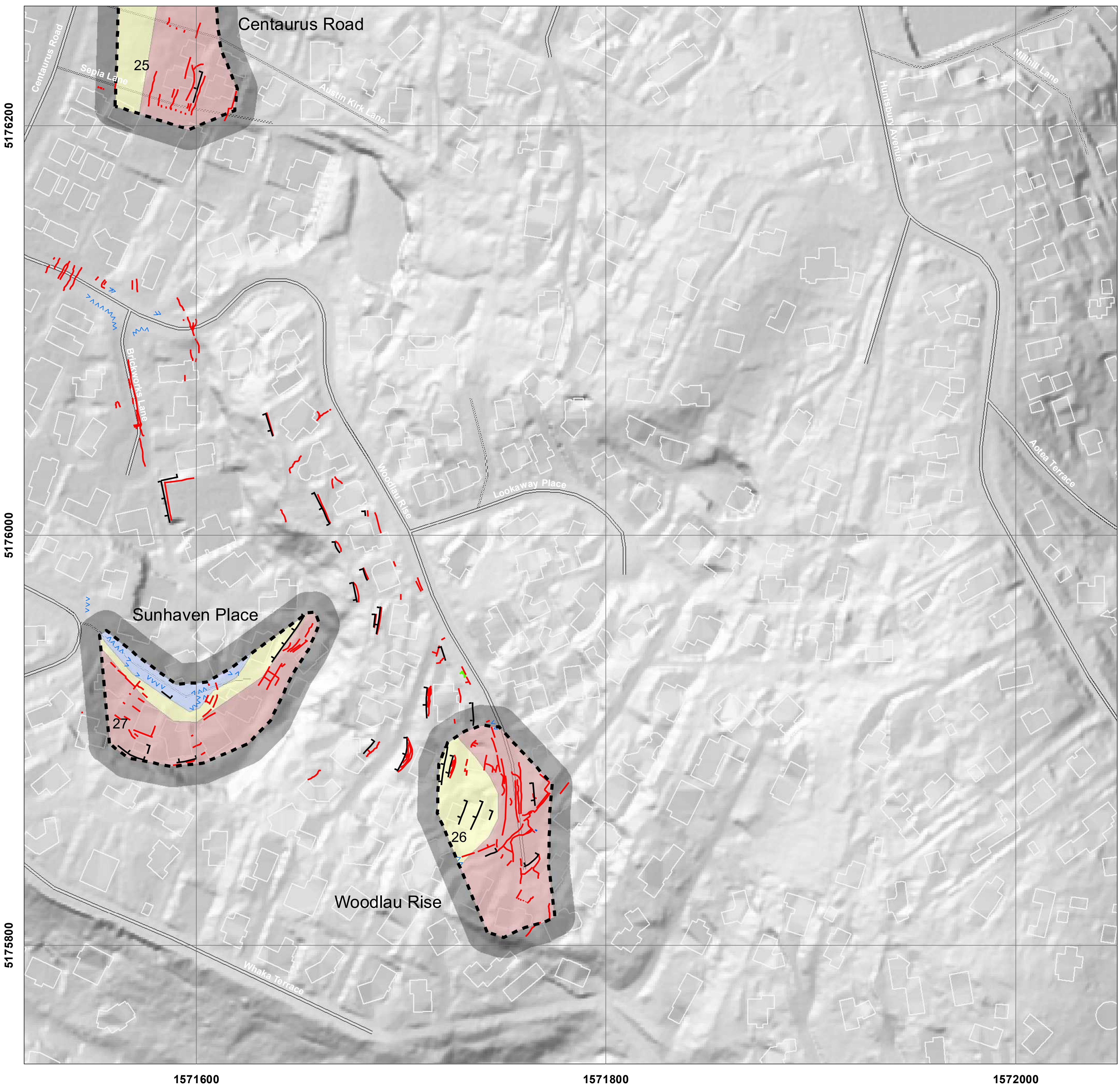
N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| SCALE BAR: 0 50 100 m | | STAGE 1: MASS MOVEMENTS | Appendix 2 |
|---|---|---|---|
| | | | FINAL |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | Port Hills Christchurch | Map D3 |
| | | | REPORT: CR2012/317 — DATE: July 2013 |

GNS SCIENCE TE PŪ AO




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

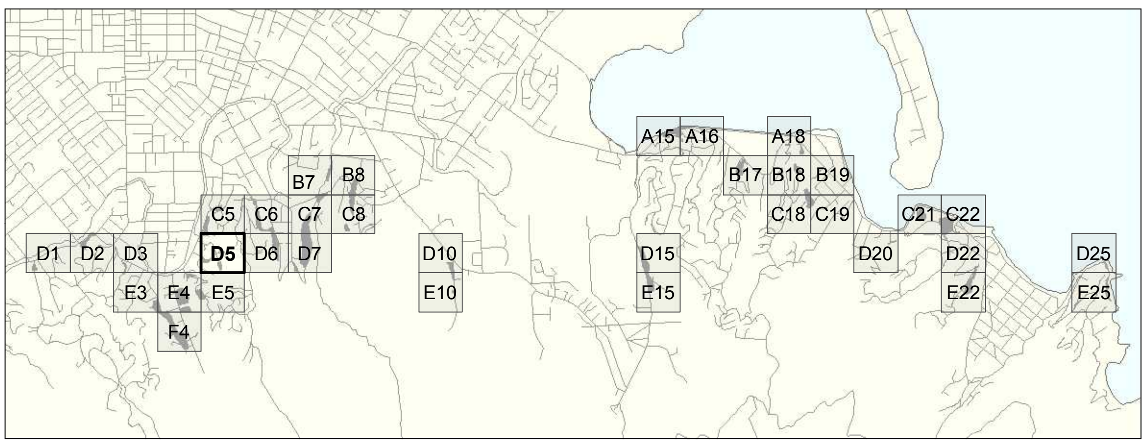
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

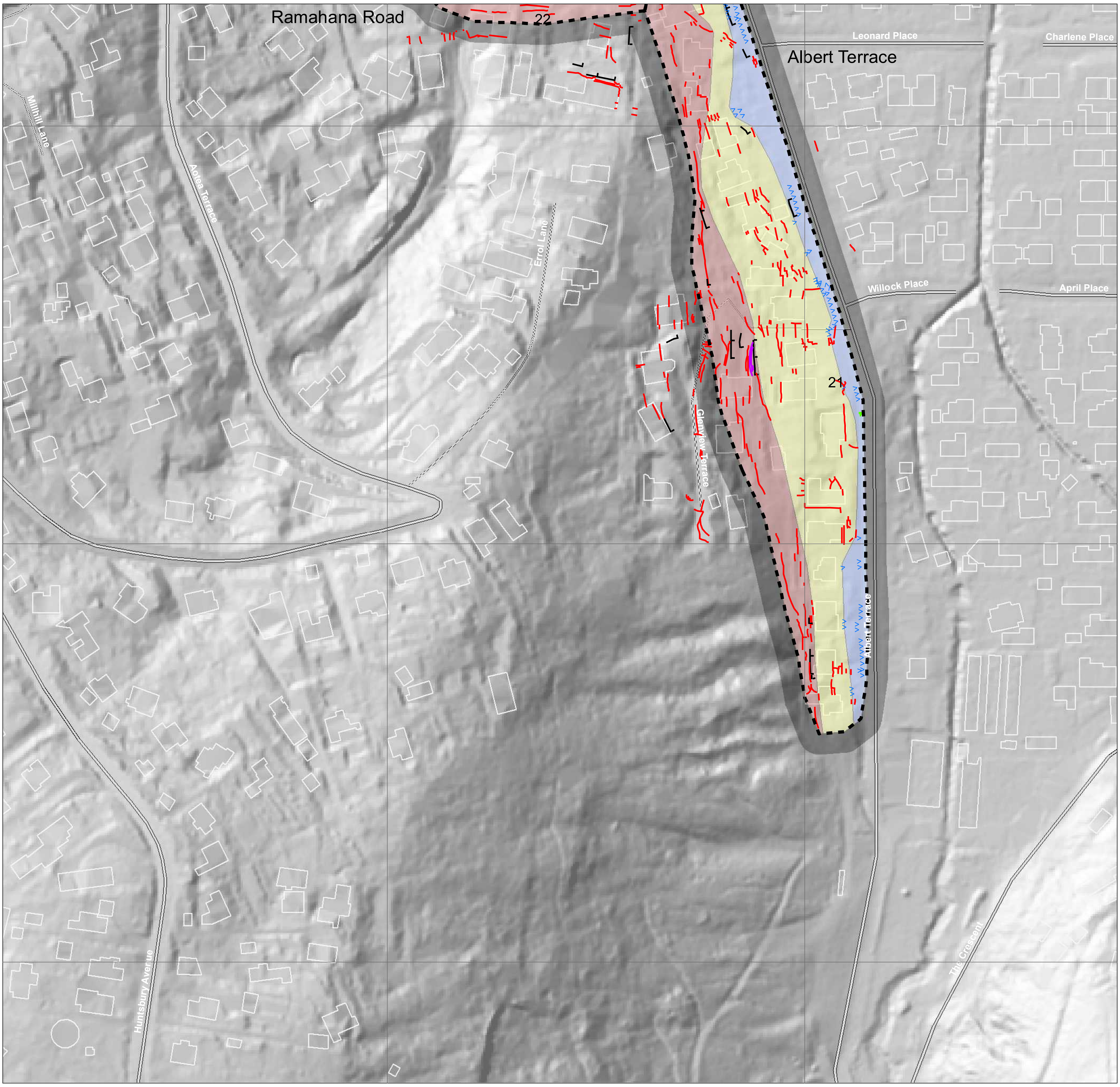
**Appendix 2**

**FINAL**

**Map D5**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

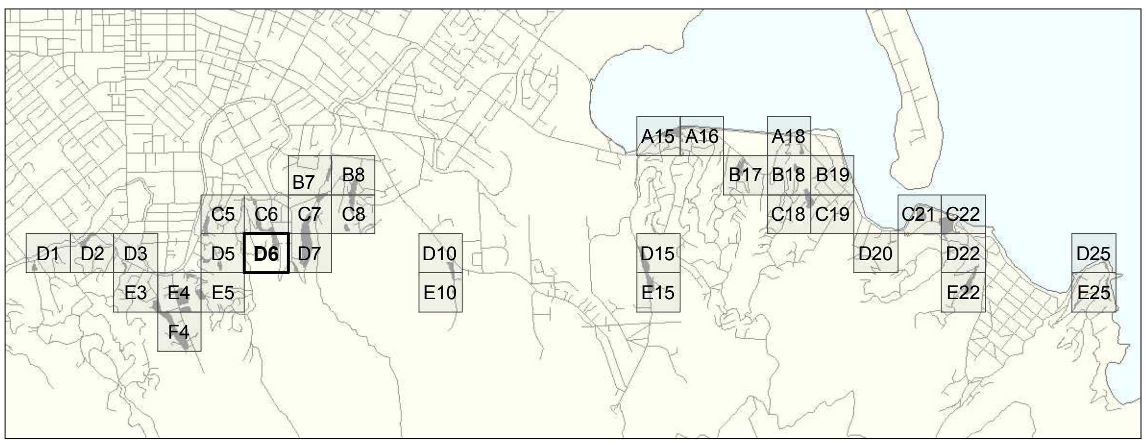
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

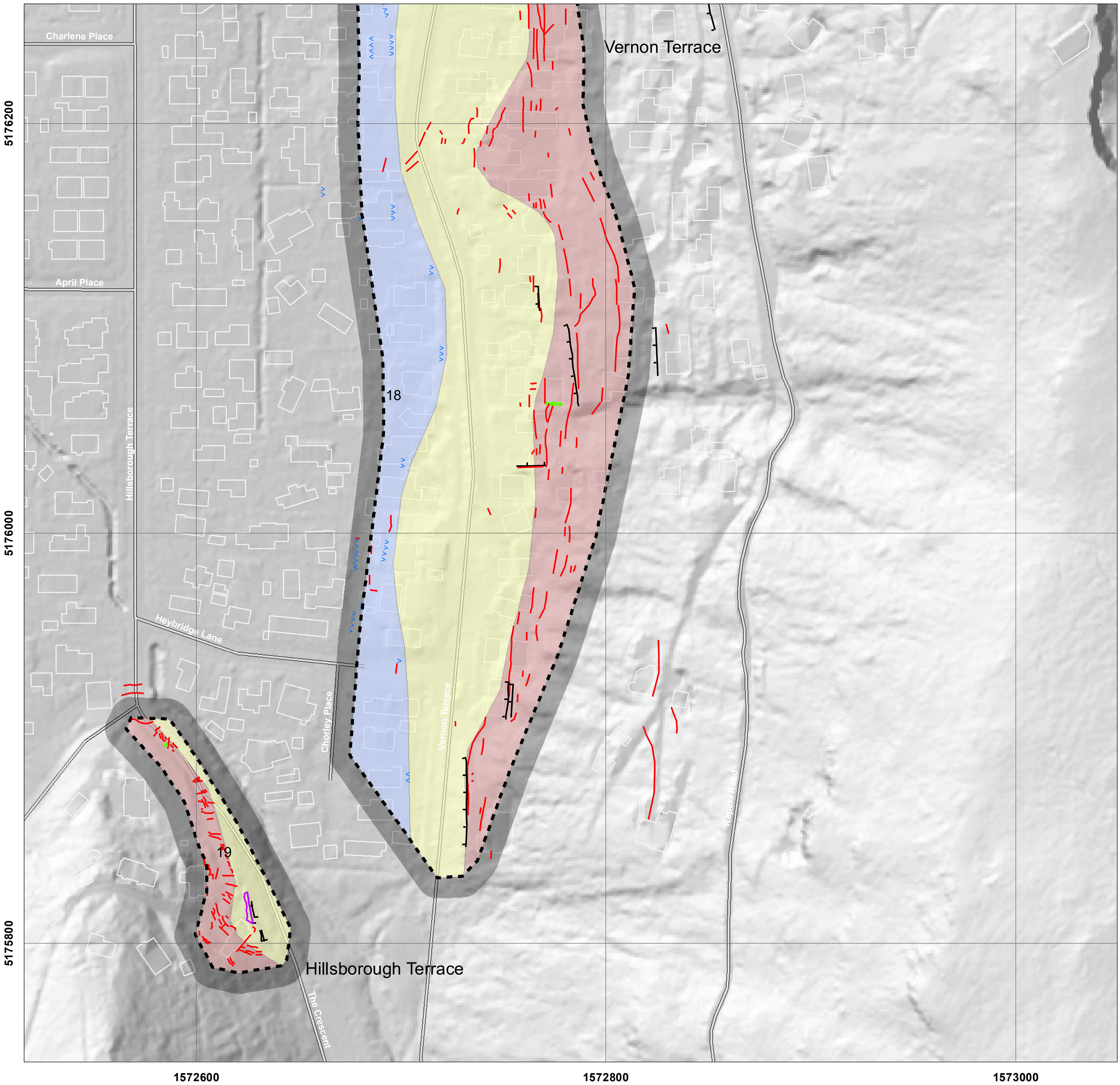
**Appendix 2**

**FINAL**

**Map D6**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

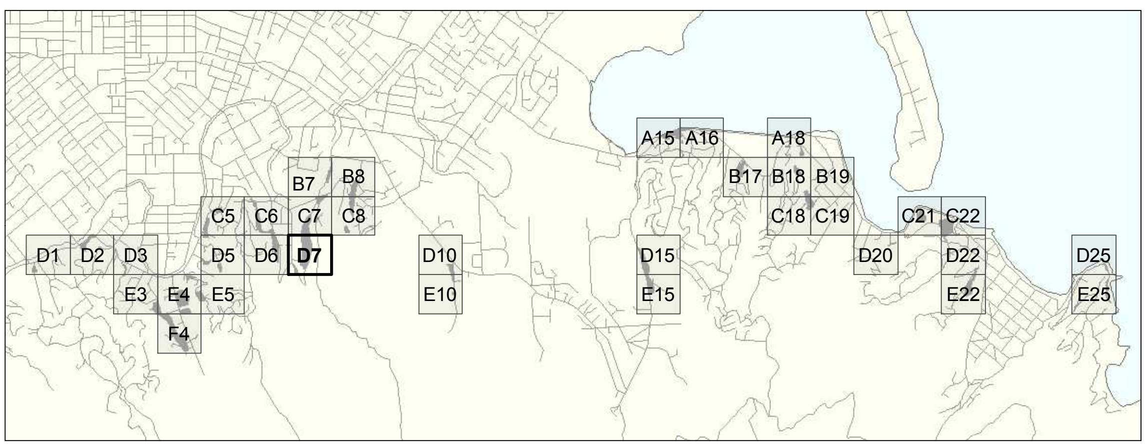
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

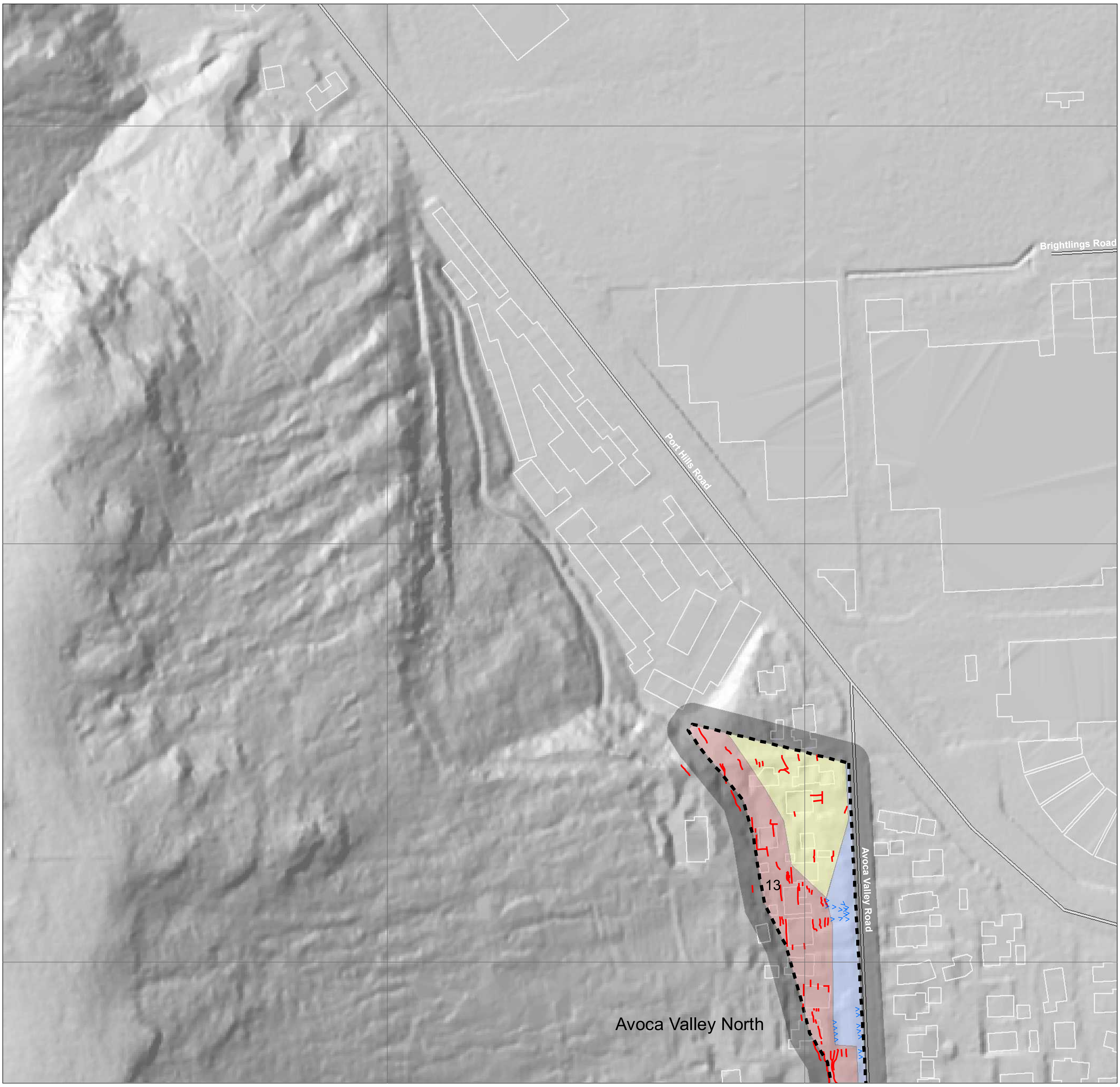
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| | | | | FINAL |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL | | Port Hills Christchurch | Map D7 |
| | CHK: CM, JC, MY | | | REPORT: CR2012/317 · DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

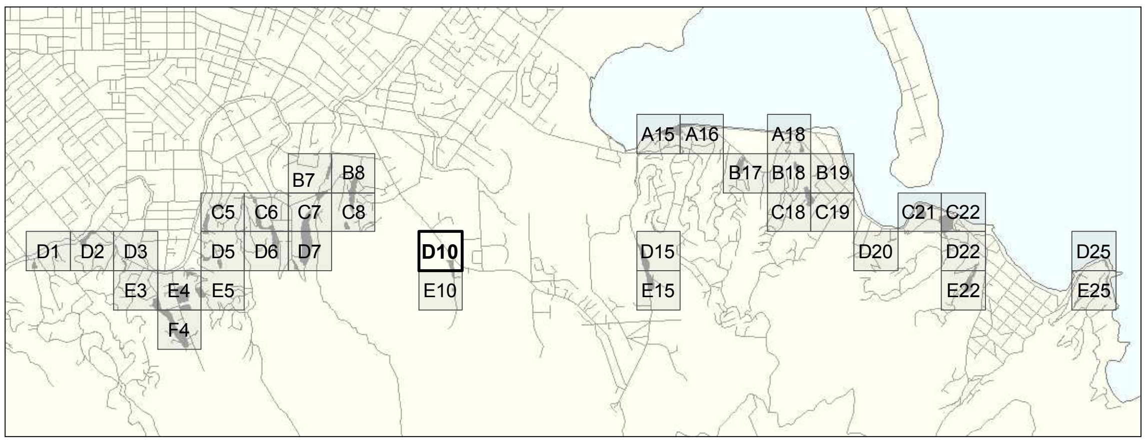
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

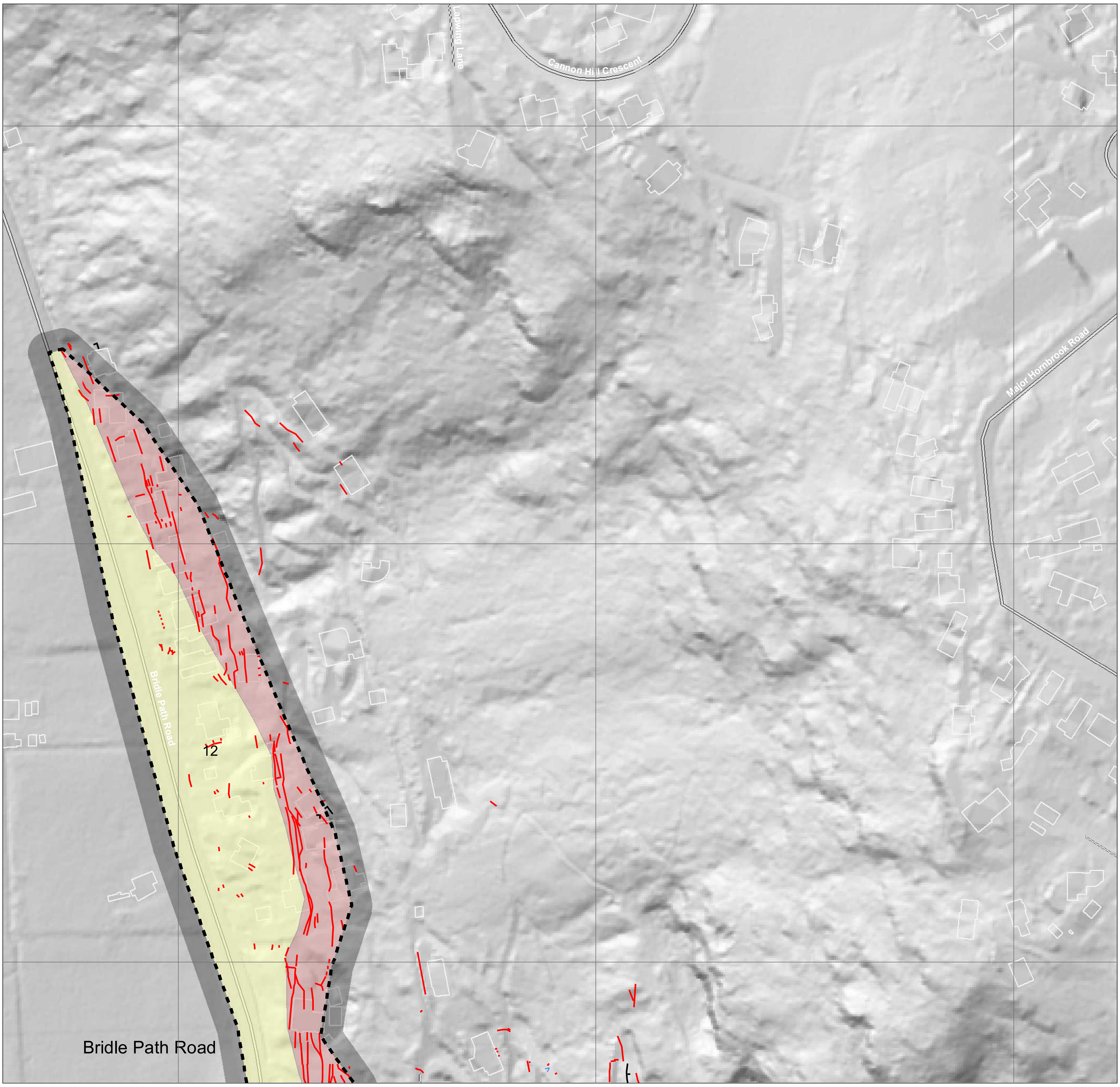
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
|---|---|---|---|---|
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | | Port Hills Christchurch | **FINAL**<br>**Map D10**<br>REPORT: CR2012/317 DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

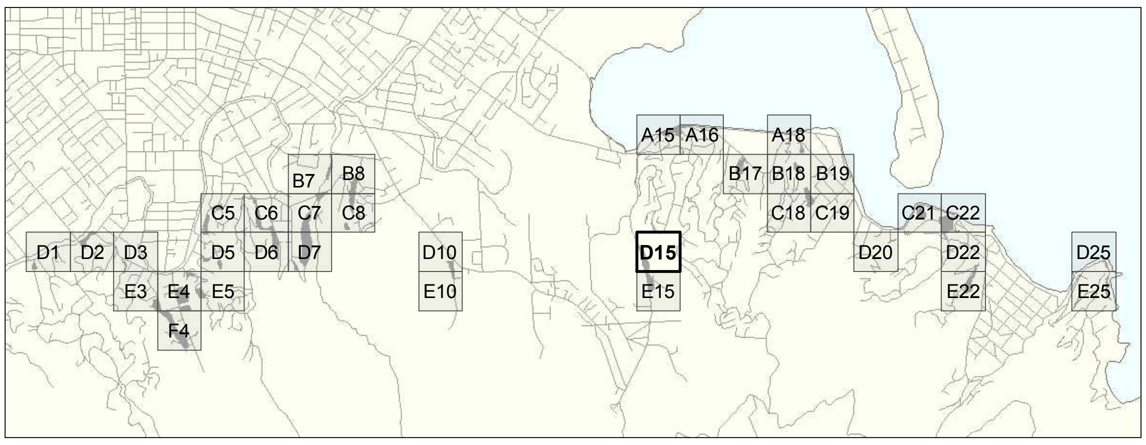
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

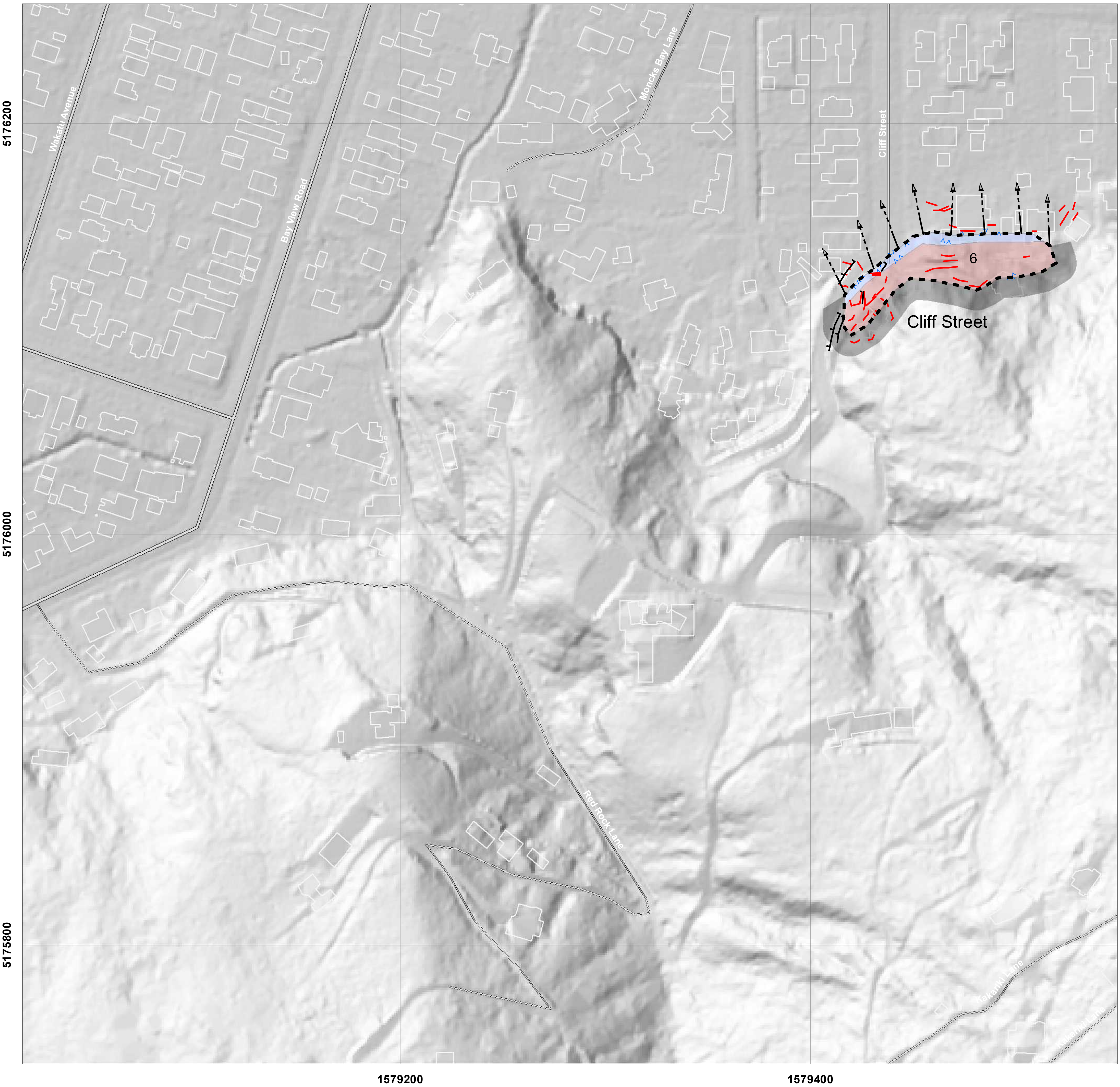
**Appendix 2**

**FINAL**

**Map D15**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

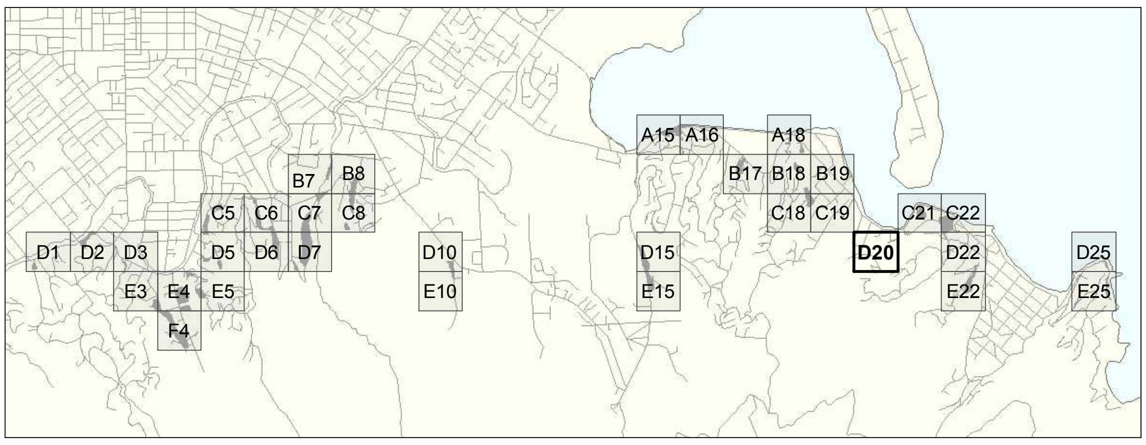
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

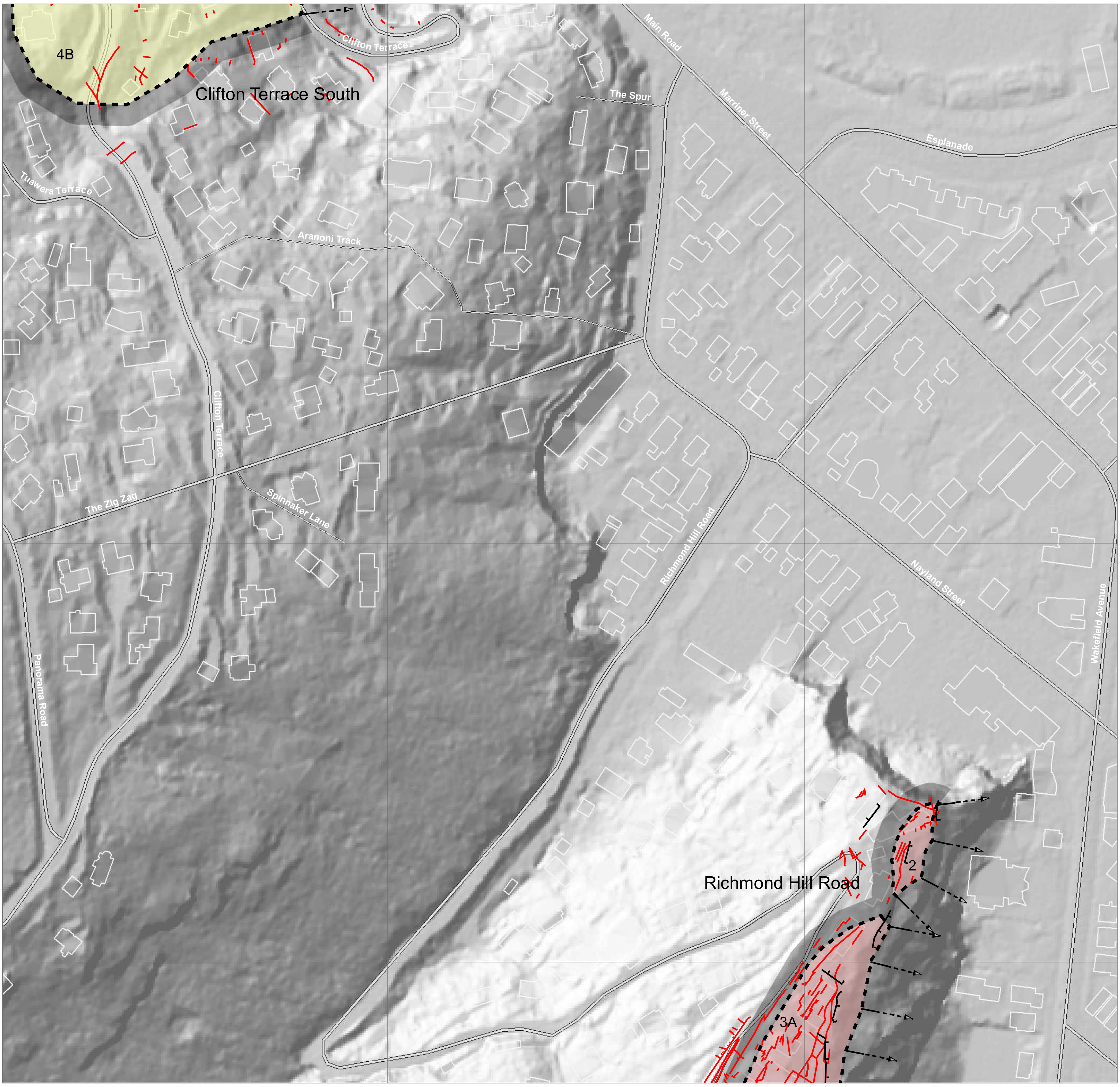
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| | | | | FINAL |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | | Port Hills Christchurch | Map D20 |
| | | | | REPORT: CR2012/317 | DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

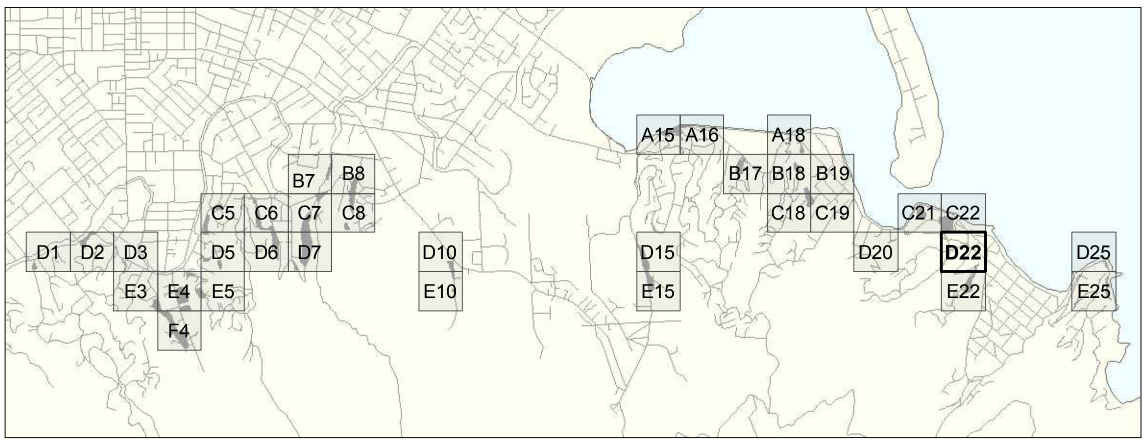
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

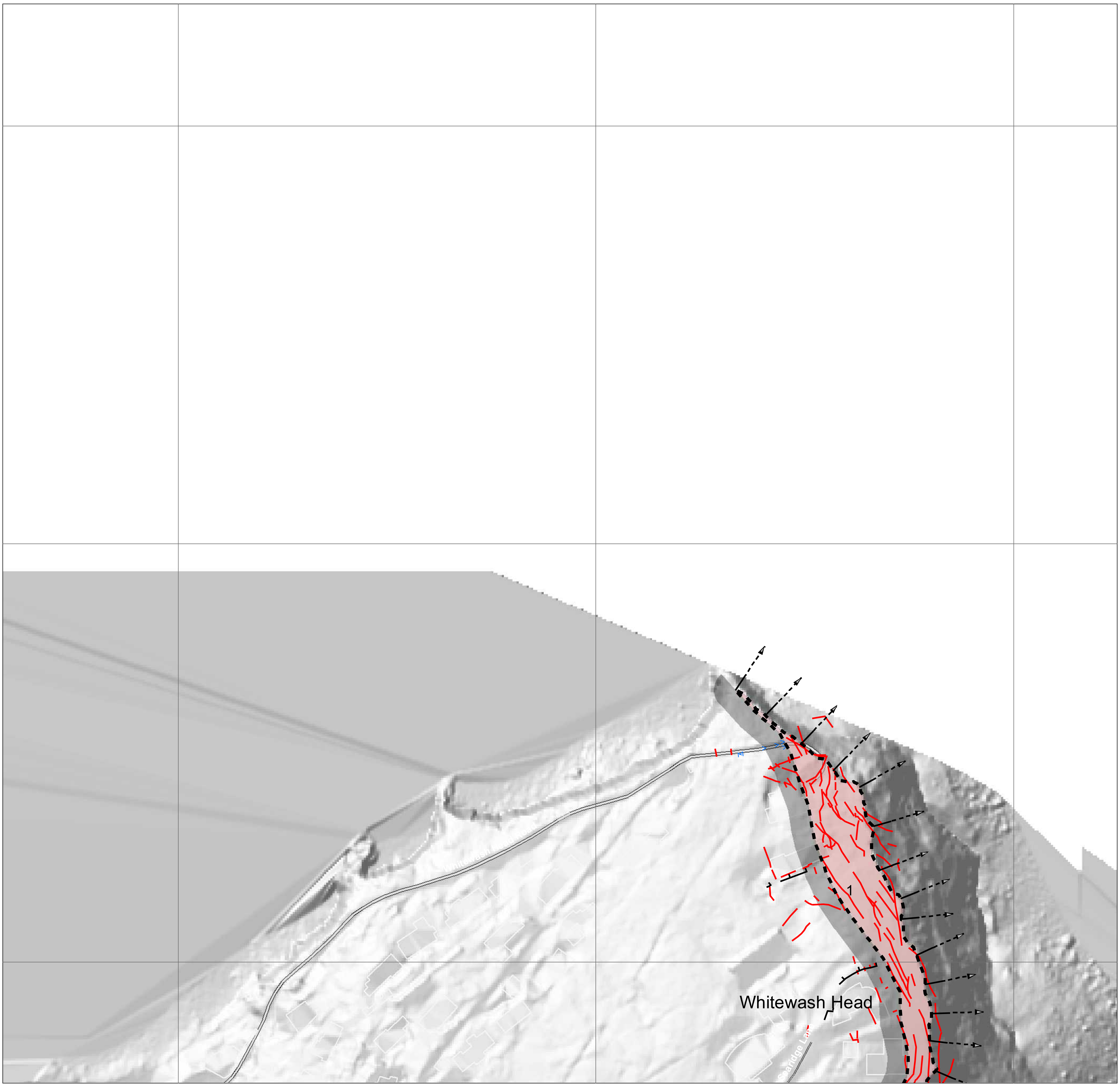
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL | | | FINAL |
| | CHK: CM, JC, MY | | Port Hills Christchurch | Map D22 |
| | | | | REPORT: CR2012/317 — DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

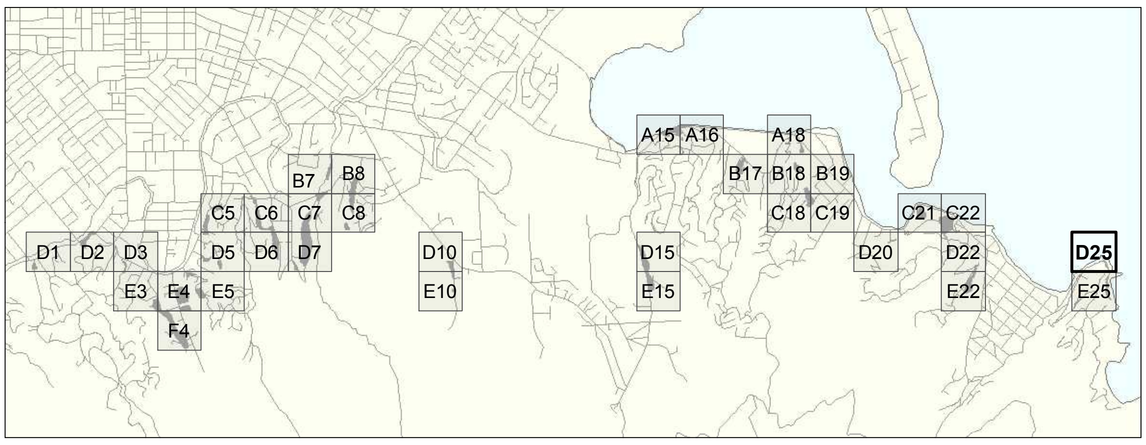
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).
PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

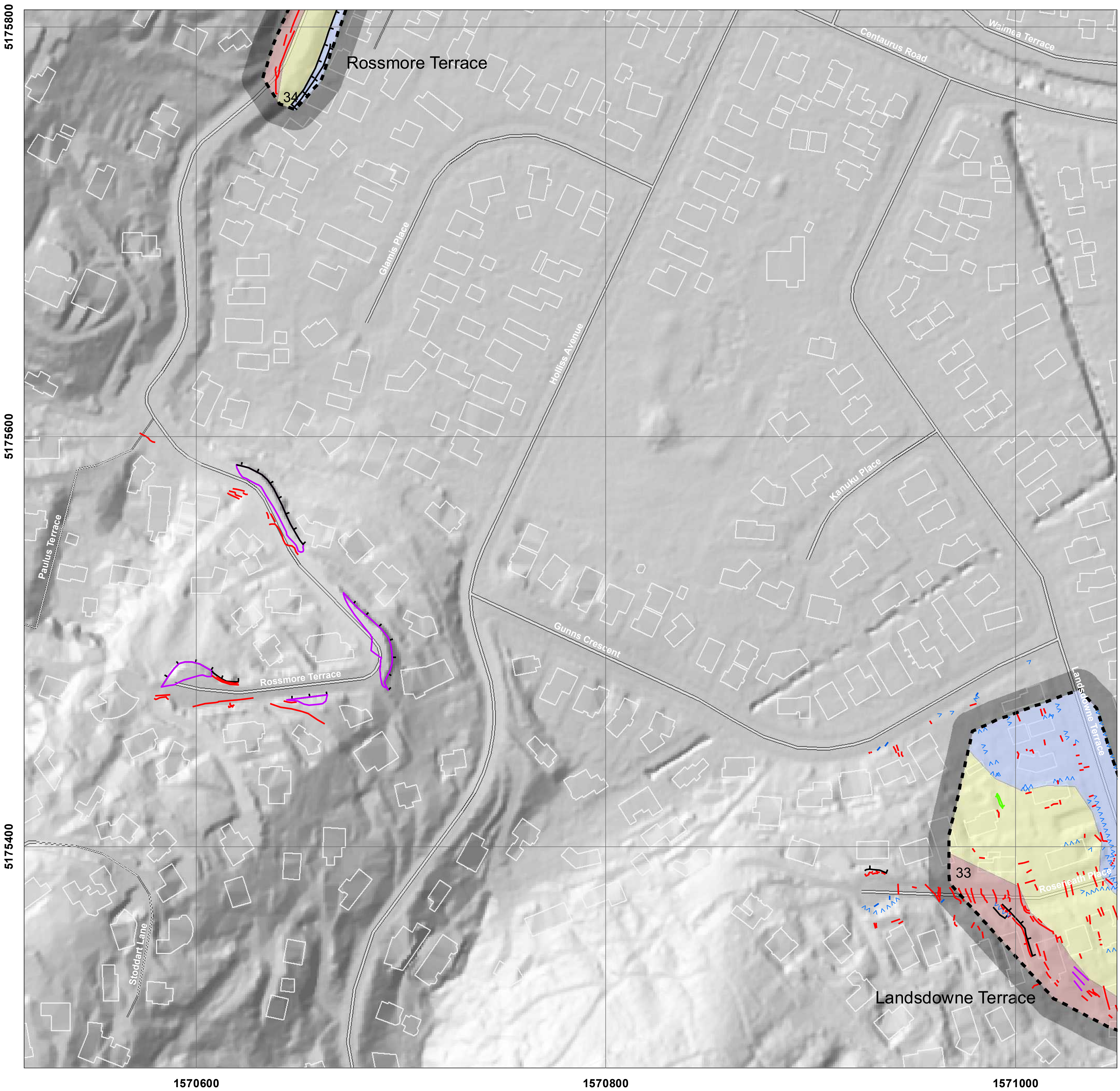
**Appendix 2**

**FINAL**

**Map D25**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

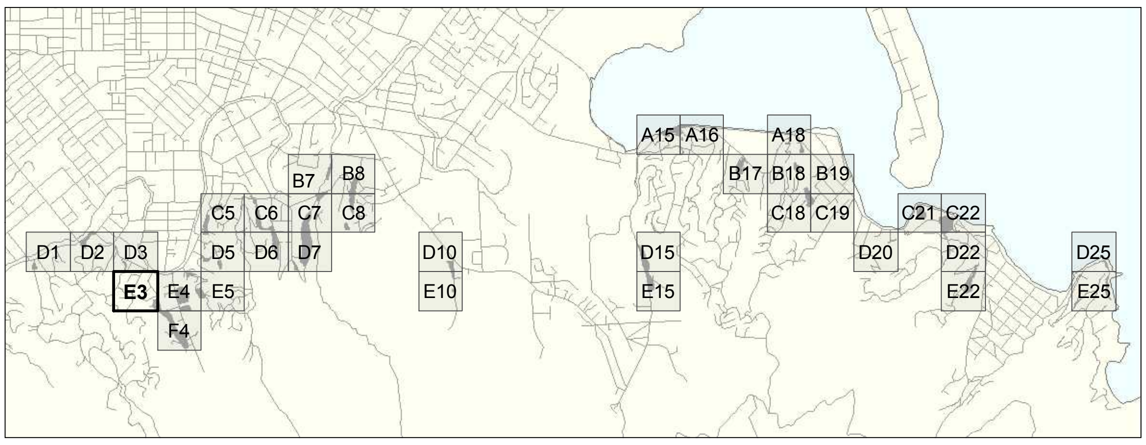
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

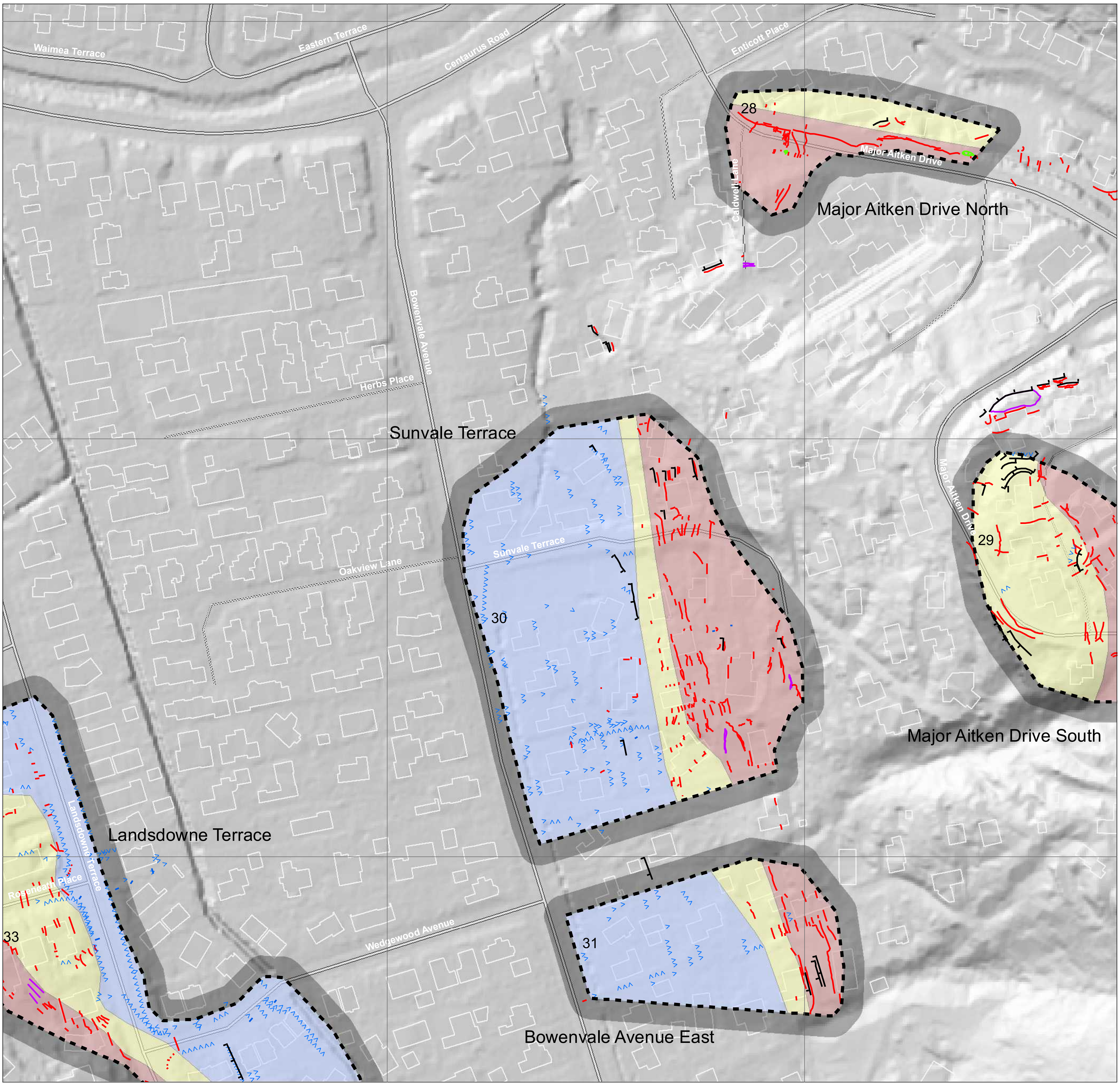
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| SCALE BAR: 0 50 100 m | | STAGE 1: MASS MOVEMENTS | Appendix 2 |
|---|---|---|---|
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | Port Hills Christchurch | FINAL<br>Map E3<br>REPORT: CR2012/317 DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

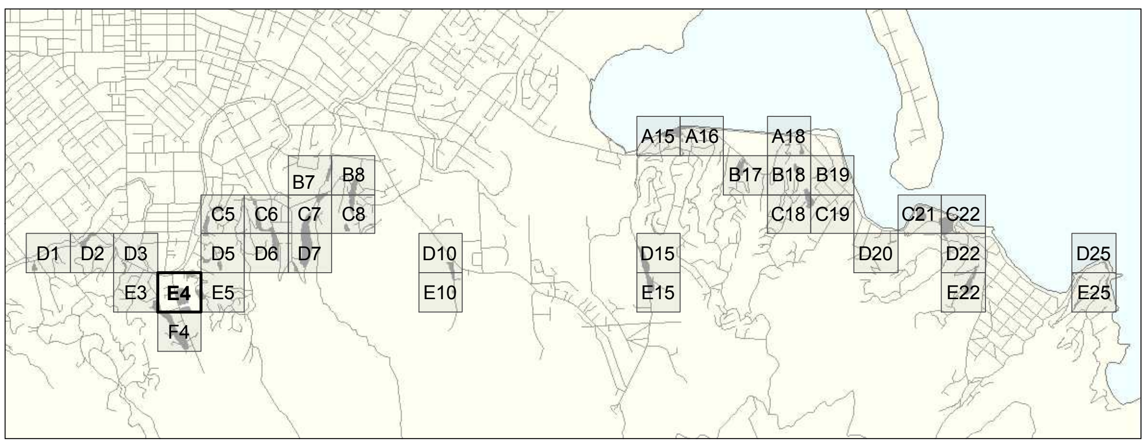
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

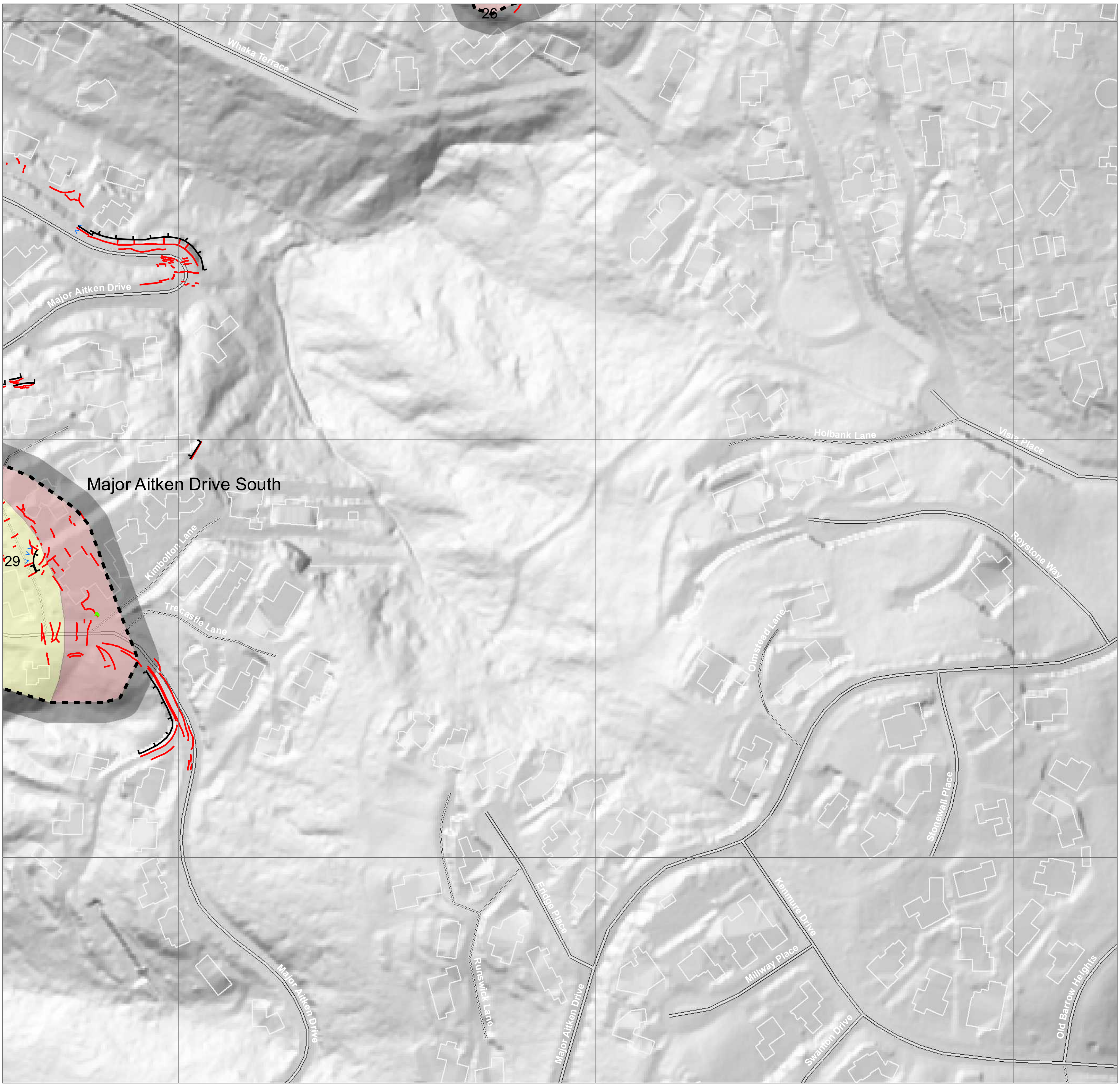
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | **Appendix 2** / **FINAL** |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL / CHK: CM, JC, MY | | **Port Hills Christchurch** | **Map E4** / REPORT: CR2012/317 / DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

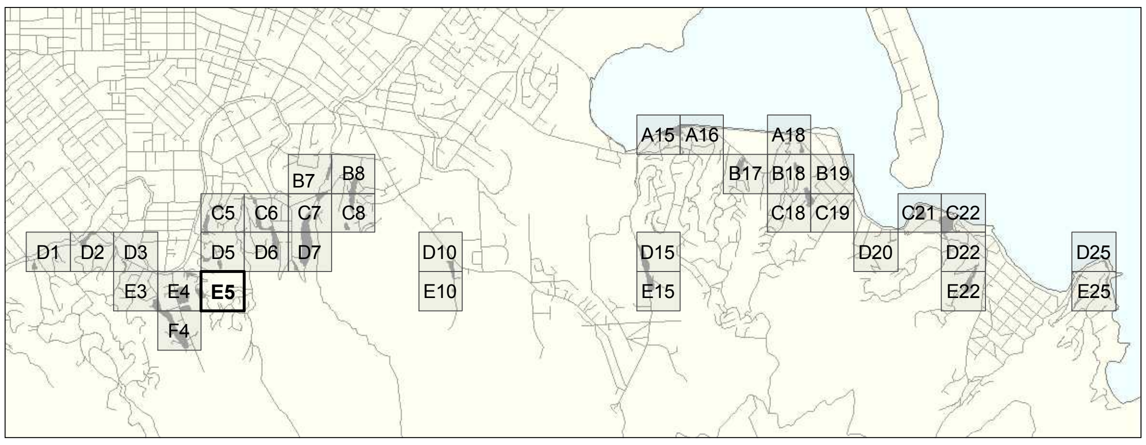
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

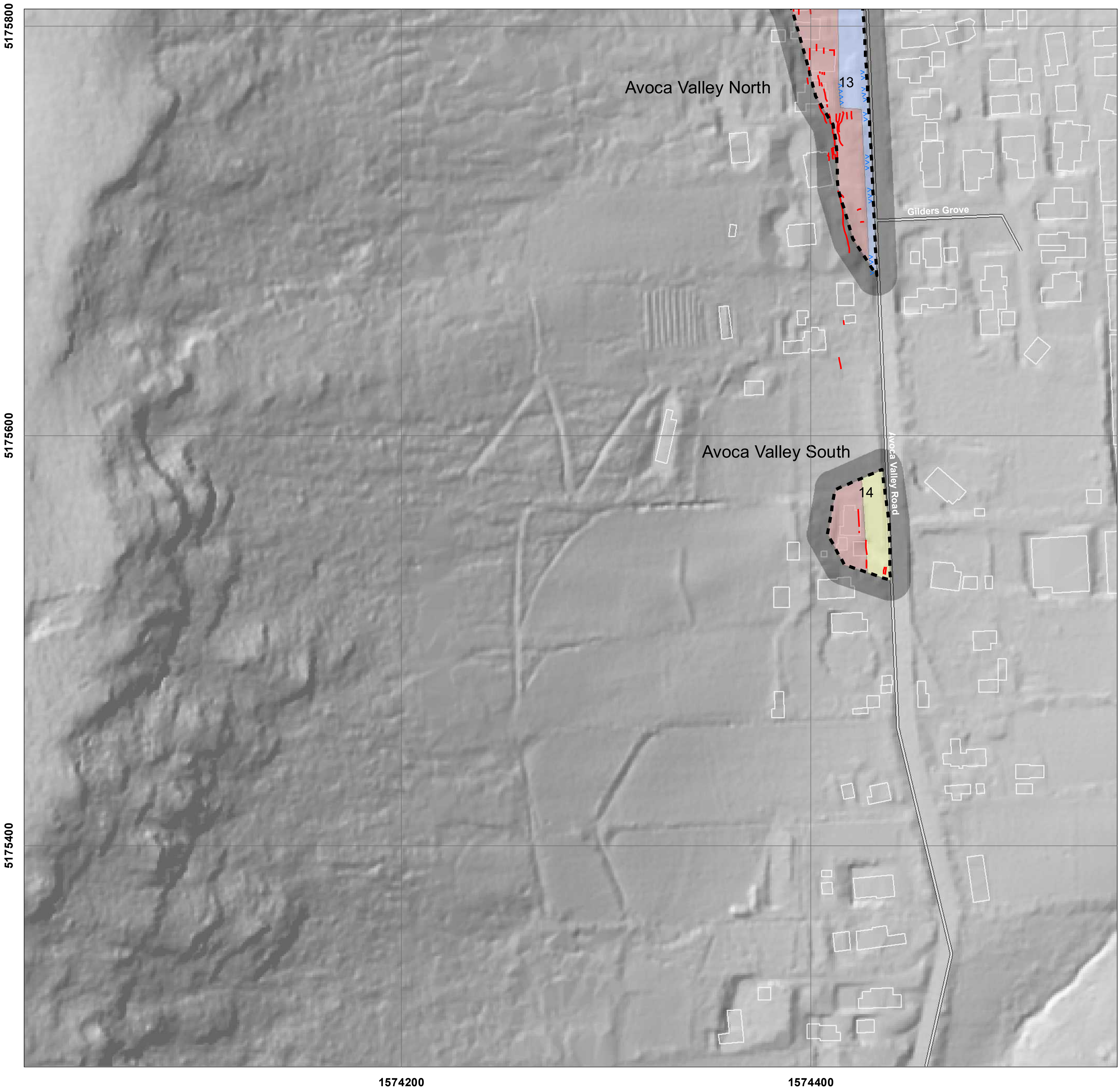
**Appendix 2**

**FINAL**

**Map E5**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

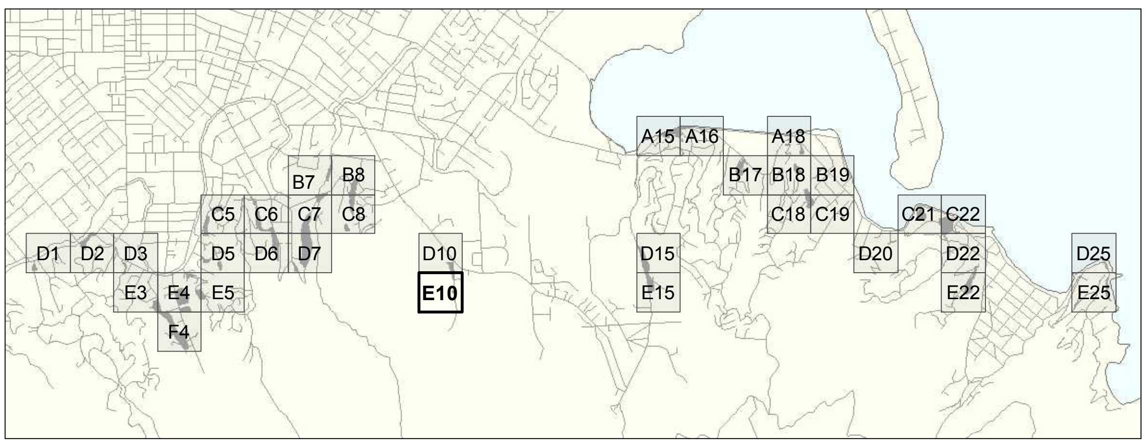
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

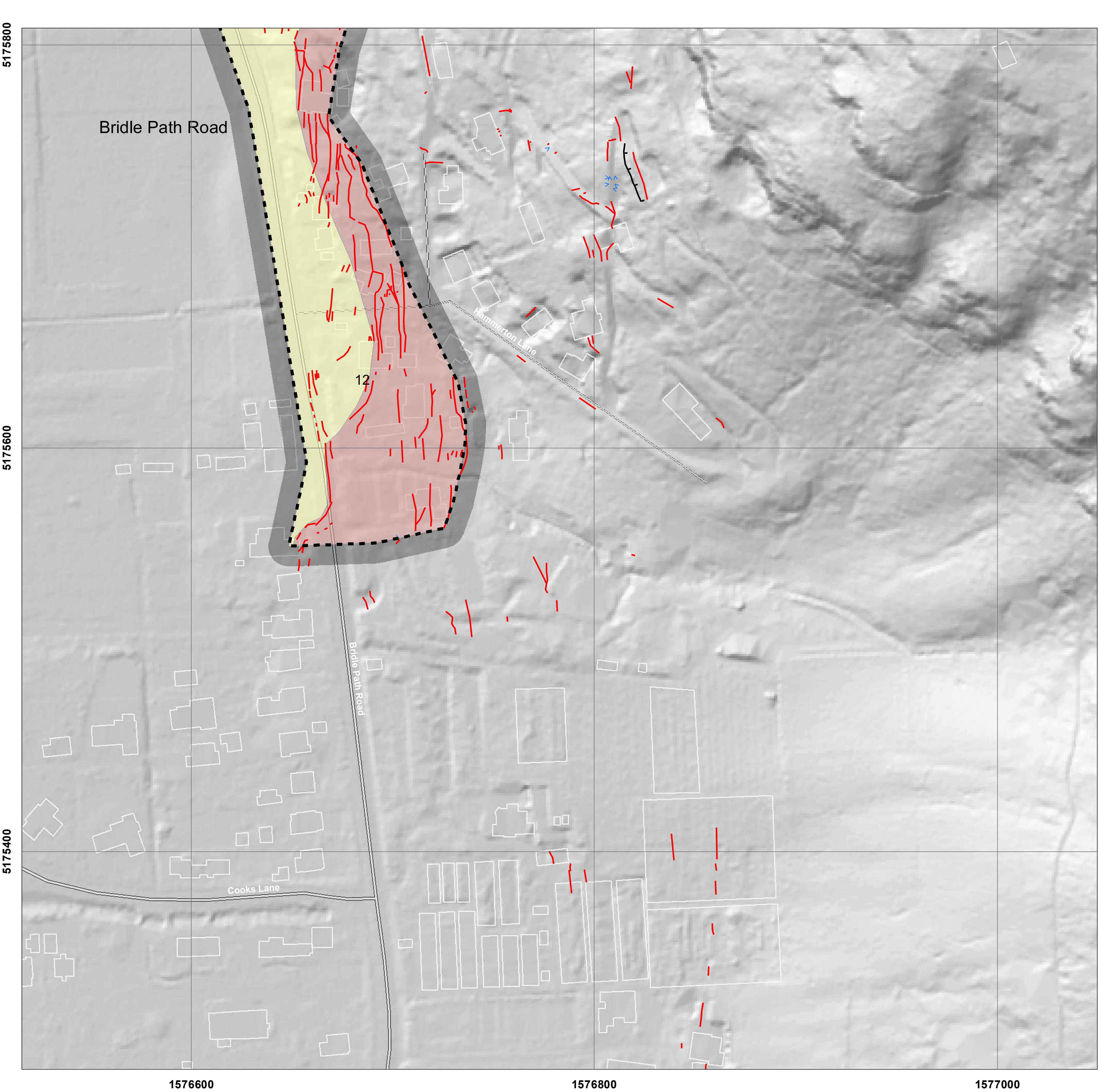
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| SCALE BAR: 0 50 100 m | | | STAGE 1: MASS MOVEMENTS | Appendix 2 |
|---|---|---|---|---|
| EXPLANATION:<br>Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).<br>PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | GNS SCIENCE TE PŪ AO | **Port Hills Christchurch** | **FINAL**<br>**Map E10**<br>REPORT: CR2012/317<br>DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

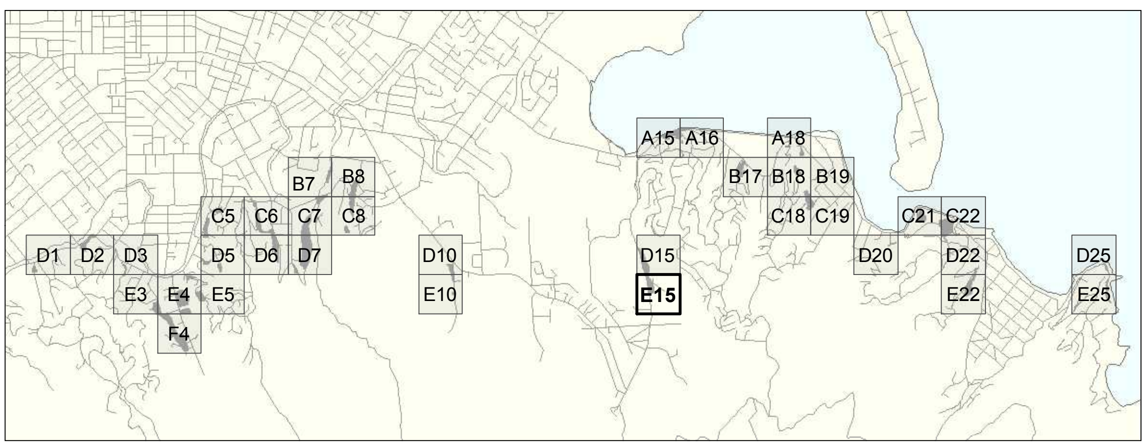
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map E15**

REPORT: CR2012/317

DATE: July 2013


**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

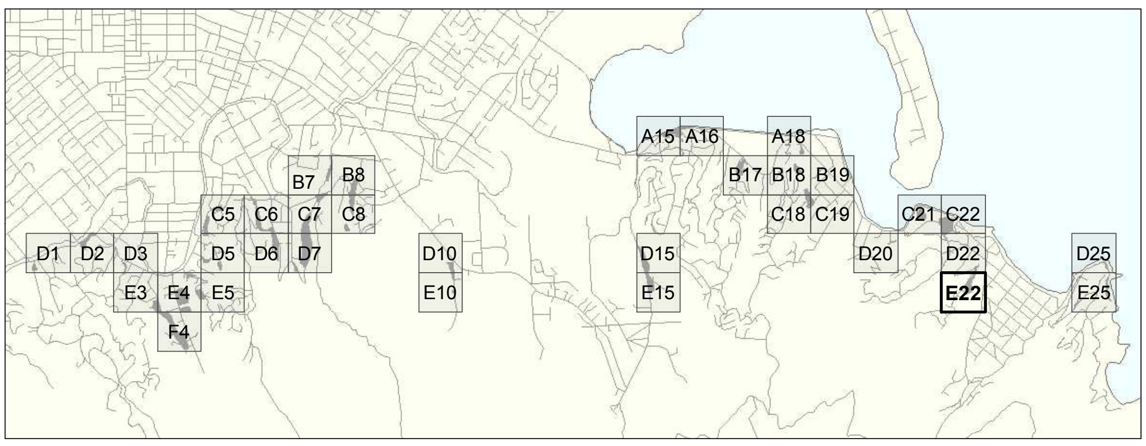
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

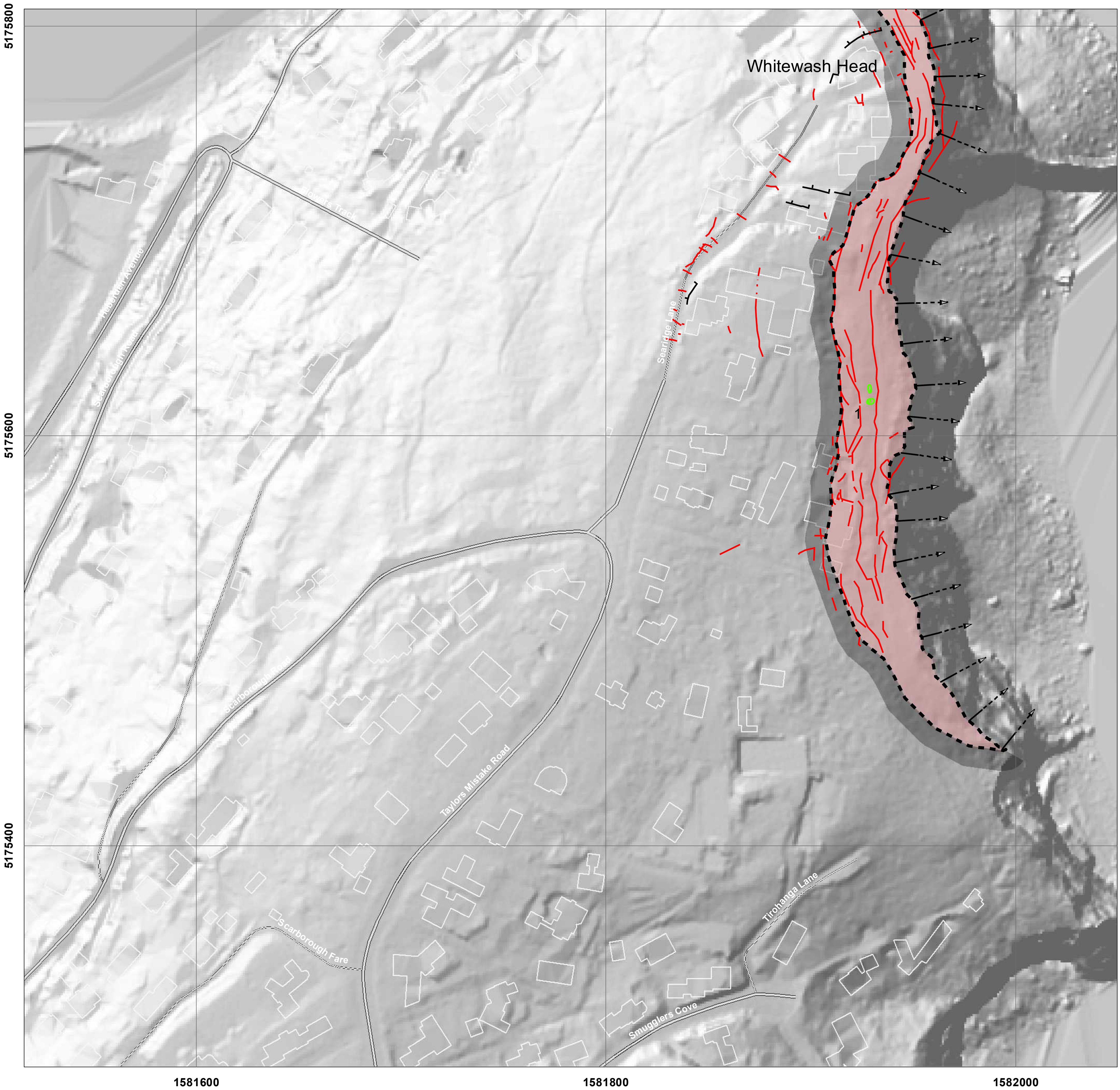
**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

| | | | | |
|---|---|---|---|---|
| SCALE BAR: 0 50 100 m | | GNS SCIENCE TE PŪ AO | STAGE 1: MASS MOVEMENTS | Appendix 2 |
| EXPLANATION: Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012). PROJECTION: New Zealand Transverse Mercator 2000 | DRW: BL<br>CHK: CM, JC, MY | | Port Hills Christchurch | **FINAL**<br>**Map E22**<br>REPORT: CR2012/317 DATE: July 2013 |




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

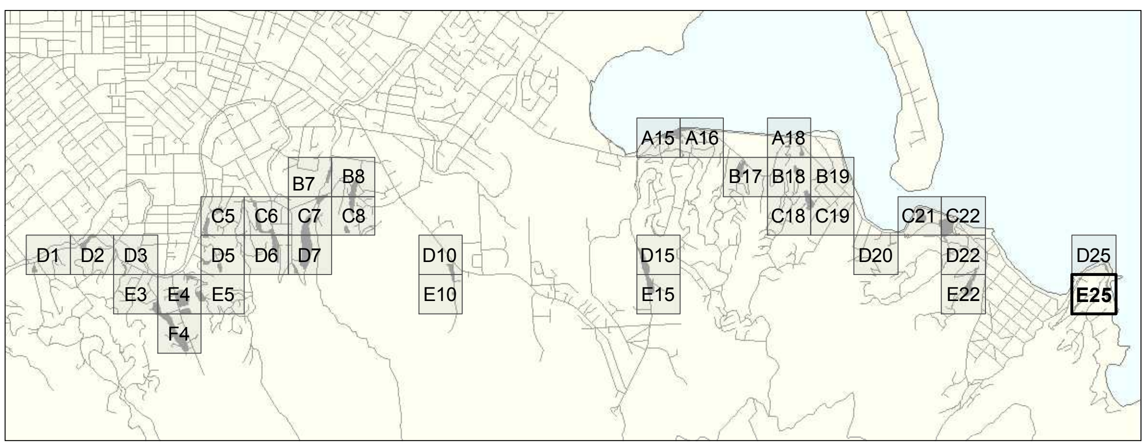
**Curent mass movements**

- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

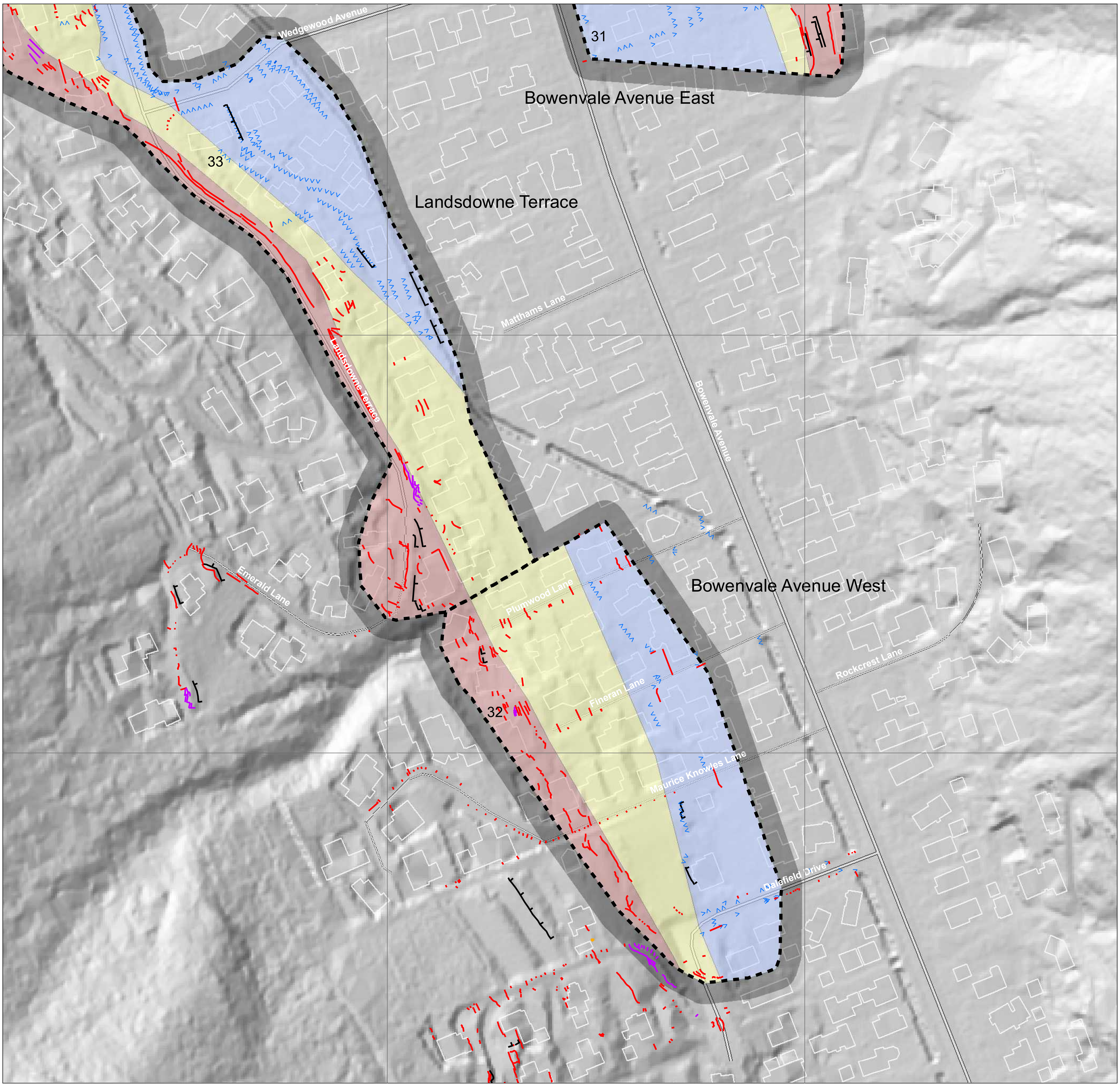
**Appendix 2**

**FINAL**

**Map E25**

REPORT: CR2012/317

DATE: July 2013




**Surface deformation***

- Tension crack
- Complex zone of cracking
- Subsidence
- Compression zone
- Tunnel gully
- Tilted/deformed retaining wall/fence
- Spring

**Curent mass movements**

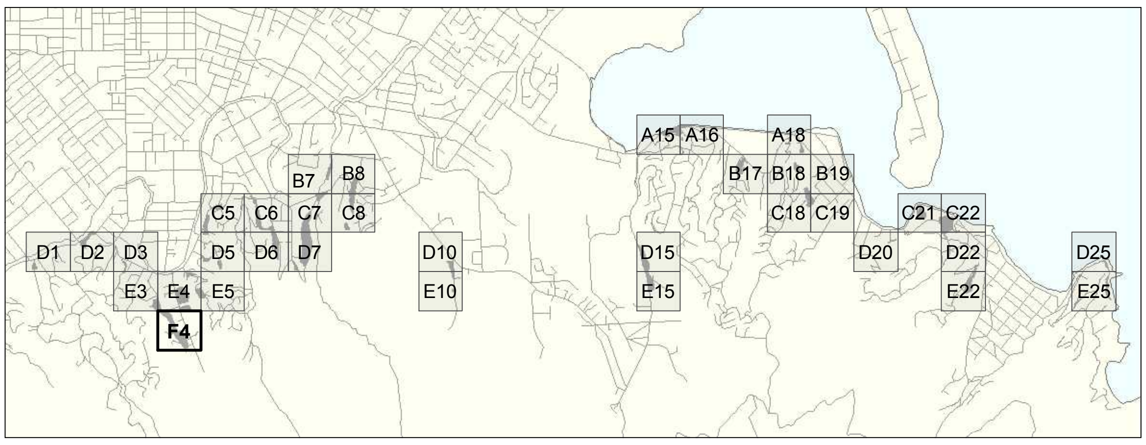
- Inferred mass movement boundary (June 2013)
- Mainly extensional area
- Mainly translational area
- Mainly compressional area

**Potential future enlargement of mass movements**

- 10 m enlargement area
- Estimated runout directions. Length of arrow does not indicate runout distance.

**Refer to Appendix 1 for mass movement hazard exposure categories. Details (ID/location) are contained in Table A 3.1.**

N




* The information shown on this map is based on field mapping that is accurate to approximately +/- 5m. The mapping was of features apparent between October 2012 and January 2013. It should be noted that these features may change over time. For example new cracks and areas of subsidence may appear and some cracks may disappear.

SCALE BAR: 0 50 100 m

EXPLANATION:

Background shade model derived from NZAM post earthquake 2011c (July 2011) LiDAR survey resampled to a 1 m ground resolution. Roads and building footprints and types provided by Christchurch City Council (20/02/2012).

PROJECTION: New Zealand Transverse Mercator 2000

DRW: BL

CHK: CM, JC, MY

GNS SCIENCE TE PŪ AO

**STAGE 1: MASS MOVEMENTS**

**Port Hills Christchurch**

**Appendix 2**

**FINAL**

**Map F4**

REPORT: CR2012/317

DATE: July 2013

## APPENDIX 3: CHARACTERISATION OF MASS MOVEMENTS IN THE PORT HILLS PROJECT AREA

**Table A 3.1** Characterisation of mass movements in the Port Hills. Areas highlighted in yellow are those already covered by existing risk maps[iii], but where potential exists for larger failures to occur that could run-out beyond the current risk map extents. AA is Area Affected, CD is cumulative displacement, CR is Cliff edge Recession, FV is Failure Volume. Cumulative displacements are inferred from cumulative crack openings along section lines through the features.

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 1 | | Whitewash Head | 4) Rock | AA: 11,400 $m^2$<br>FV: 150,000 $m^3$<br>CR: 20 m<br>CD: 1.5 m | 1 | 1 | CLASS I | Area already covered by risk maps[iii] |
| 2 | | Richmond Hill Road | 3) Loess and rock | AA: 500 $m^2$<br>FV: 200 $m^3$<br>CR: About 1 m<br>CD: 0.5 m | 1 | 1 | CLASS I | Area already covered by risk maps[iii] |
| 3 | A | Richmond Hill Road | 3) Loess and rock | AA: 9,300 $m^2$<br>FV: 5,000 $m^3$<br>CR: About 5 m<br>CD: About 2 m<br>On-going movement (of loess and/or rock) following heavy rain | 1 | 1 | CLASS I | Area already covered by risk maps[iii], but where potential exists for larger failures to occur that could runout further than the current risk map extent. |
| 3 | B | Richmond Hill Road | 5b) Loess slump | AA: 8,200 $m^2$<br>FV (off cliff face): 5,000 $m^3$<br>CR: About 1–5 m<br>CD: 0.5 m | 2 | 3 | CLASS II | Local services only. |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 4 | A | Clifton Terrace North | 3) Loess and rock | AA: 21,200 $m^2$<br>• About 1 m of cumulative horizontal displacement and about 0.3 m of vertical displacement.<br>• Has moved three times during earthquakes.<br>• Possible past evidence of movement expressed in slope morphology. | 1 | 1 | CLASS I | Area already covered by risk maps[iii,] but where potential exists for larger failures to occur that could runout further than the current risk map extent. |
| 4 | B | Clifton Terrace South | 5b) Loess slump | AA: 7,500 $m^2$<br>• About 0.4 m of cumulative horizontal displacement and less vertical displacement.<br>• Possible past evidence of debris flows/landslide scars expressed in slope morphology. | 2 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |
| 5 | | Deans Head | 2) Loess on rock | AA: 11,800 $m^2$<br>• About 1.5 m of cumulative horizontal displacement and about 0.5 m of vertical displacement.<br>• Debris flow from toe triggered by August 2012 rain (approximate volume: 50 $m^3$ with debris runout of 40 m).<br>• Adjacent slope has evidence of large (>1,000 $m^3$) evacuated debris flow scars. | 1 | 1 | CLASS I | Area already covered by risk maps[iii,] but where potential exists for larger failures to occur that could runout further than the current risk map extent. |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 6 | | Cliff Street | 3) Rock and loess | AA: 2,200 $m^2$<br>• About 0.3 m of cumulative horizontal displacement of the rock slope and loess.<br>• Debris flow sourcing from loess (approximate volume: 30 $m^3$ with debris runout of 20 m).<br>• Possible relict large landslide | 1 | 1 | CLASS I | Area already covered by risk maps[iii,] but where potential exists for larger failures to occur that could runout further than the current risk map extent. |
| 7 | | Defender Lane | 2) Loess on rock | AA: 15,300 $m^2$<br>• About 1 m cumulative horizontal displacement and 0.5 m vertical displacements.<br>• Past evidence of debris flows from toe of loess slope above rock cliff. | 1 | 1 | CLASS I | Area already covered by risk maps[iii,] but where potential exists for larger failures to occur that could runout further than the current risk map extent. |
| 8 | | Glendevere Terrace | 3) Rock and loess | AA: 7,400 $m^2$<br>FV: 5,000 $m^3$ (off rock face behind school)<br>CR: About 8 m (along Main Road).<br>CD: About 1.5 m horizontal displacement.<br>• On-going movement apparent. | 1 | 1 | CLASS I | Area already covered by risk maps[iii,] but where potential exists for larger failures to occur that could runout further than the current risk map extent. |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 9 | | Balmoral Lane (Redcliffs Main Road) | 3) Rock and loess | AA: 4,400 $m^2$<br>FV: 1,600 $m^3$ (off rock face along Main Road)<br>CR: About 5 to 10 m along Main Road.<br>CD: 0.5 m horizontal displacement.<br>• On-going movement recorded during rain. | 1 | 2 | CLASS I | Area already covered by risk maps[iii], but where potential exists for larger failures to occur that could runout further than the current risk map extent. |
| 10 | A | Maffey's Road | 2) Loess on rock | AA: 13,100 $m^2$<br>CD: 0.5 m<br>• Relict landslide area. Evidence of reactivation in winter 2012. | 1 | 1 | CLASS I | Area not covered by existing risk maps[iii] |
| 10 | B | Maffey's Road | 5a) Toe slump | AA: 1,200 $m^2$<br>CD: 0.2 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 11 | A | Quarry Road | 1) Loess<br>2) Loess on rock<br>3) Rock and loess | Complex area of multiple mass movement types. Significant slope modifications due to old quarrying and filling.<br>Total AA: 20,500 $m^2$<br>FV (recent earthquakes): <50 $m^3$<br>CD: Up to 0.5 m horizontal displacement. | 1 | 1 | CLASS I | Area not covered by existing risk maps[iii] |
| 11 | B | Quarry Road | | | 1 | 1 | CLASS I | Area is already covered by risk maps[iii] |
| 11 | C | Quarry Road | | | 1 | 1 | CLASS I | Area not covered by existing risk maps[iii] |
| 11 | D | Quarry Road | | | 1 | 1 | CLASS I | Area not covered by existing risk maps[iii] |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 11 | E | Quarry Road | | | 1 | 1 | CLASS I | Area not covered by existing risk maps[iii] |
| 11 | F | Quarry Road | 5a) Toe slump | Complex area of multiple mass movement types. Significant slope modifications due to old quarrying.<br>Total AA: 20,500 $m^2$<br>FV (recent earthquakes): <50 $m^3$<br>CD: Up to 0.5 m horizontal displacement. | 2 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |
| 11 | G | Quarry Road | 5a) Toe slump | | 2 | 2 | CLASS II | |
| 11 | H | Quarry Road | 5a) Toe slump | | 2 | 2 | CLASS II | |
| 12 | | Bridle Path | 5a) Toe slump | AA: 33,300 $m^2$<br>CD: 1.3 m horizontal and 0.4 vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |
| 13 | | Avoca Valley North | 5a) Toe slump | AA: 7,300 $m^2$<br>CD: 0.2 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 14 | | Avoca Valley South | 5a) Toe slump | AA: 1,200 $m^2$<br>CD: 0.2 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 15 | | Alderson Avenue | 5a) Toe slump | AA: 20,300 $m^2$<br>CD: 0.7 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 3 | CLASS II | Local services only |
| 16 | | Aynsley Terrace | 5a) Toe slump | AA: 8,500 $m^2$<br>CD: 0.3 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 17 | | Rapaki Road | 5a) Toe slump | AA: 8,400 $m^2$<br>CD: 0.2 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 2 | CLASS II | Significance of critical infrastructure needs to be confirmed |
| 18 | | Vernon Terrace | 5a) Toe slump | AA: 59,700 $m^2$<br>CD: 0.7 m horizontal and 0.5 m vertical displacement.<br>• Displacement mainly during earthquakes some evidence of on-going movement not earthquake triggered. | 2 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 19 | | Hillsborough Terrace | 5a) Toe slump | AA: 3,500 $m^2$<br>CD: 0.3 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 20 | | Lucas Lane | 1) Loess and 2) Loess on rock | AA: 4,500 $m^2$<br>FV (EQ and rainfall): about 50 $m^3$<br>CD: 0.7 m<br>• Significant slope modification due to quarrying. | 3 | 3 | CLASS III | Would have been CLASS I but now modified due to removal of hazard. Design carried out by Aurecon NZ Ltd. Under contract to CERA. Construction works have been completed and accepted by the Council. |
| 21 | | Albert Terrace | 5a) Toe slump | AA: 19,100 $m^2$<br>CD: 0.8 m horizontal and 0.4 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 3 | CLASS II | Local services only |
| 22 | | Ramahana Road | 5a) Toe slump | AA: 15,300 $m^2$<br>CD: 0.6 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 3 | CLASS II | Local services only |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 23 | | View Terrace | 5a) Toe slump | AA: 2,500 $m^2$<br>CD: 0.2 m horizontal and 0.1 m vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 2 | CLASS II | Significance of critical infrastructure needs to be confirmed |
| 24 | | Parklands Drive | 5a) Toe slump | AA: 5,300 $m^2$<br>CD: 0.2 m horizontal and 0.1 vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 25 | | Centaurus Road | 5a) Toe slump | AA: 10,200 $m^2$<br>CD: 0.4 m horizontal and 0.2 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |
| 26 | | Woodlau Rise | 5b) Loess slump | AA: 4,300 $m^2$<br>CD: 0.3 m horizontal and 0.2 m vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only. Potential for runout of debris, significance unknown. |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 27 | | Sunhaven Place | 5a) Toe slump | AA: 4,200 $m^2$<br>CD: 0.2 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes | 3 | 3 | CLASS III | Local services only |
| 28 | | Major Aitken Drive North | 5a) Toe slump | AA: 4,100 $m^2$<br>CD: 0.5 m horizontal and 0.3 m vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 29 | | Major Aitken Drive South | 5b) Loess slump | AA: 8,200 $m^2$<br>CD: 0.4 m horizontal and 0.3 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 3 | CLASS II | Potential for runout of debris, significance unknown. |
| 30 | | Sunvale Terrace | 5a) Toe slump | AA: 23,200 $m^2$<br>CD: 1 m horizontal and 0.2 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 2 | CLASS II | Significance of critical infrastructure needs to be confirmed |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 31 | | Bowenvale Avenue East | 5a) Toe slump | AA: 7,600 $m^2$<br>CD: 0.2 m horizontal and 0.1 m vertical displacements.<br>• To date displacement only during earthquakes | 3 | 3 | CLASS III | Local services only |
| 32 | | Bowenvale Avenue West | 5a) Toe slump | AA: 19,300 $m^2$<br>CD: 0.4 m horizontal and 0.2 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 3 | CLASS II | Local services only |
| 33 | | Lansdowne Terrace | 5a) Toe slump | AA:31,400 $m^2$<br>CD: 0.6 m horizontal and 0.3 m vertical displacements.<br>• To date displacement only during earthquakes. | 2 | 2 | CLASS II | Significance of critical infrastructure needs to be confirmed |
| 34 | | Rossmore Terrace | 5a) Toe slump | AA: 3,800 $m^2$<br>CD: 0.2 m horizontal and 0.1 m vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |

| Area ID | Sub area | Location | Failure type[i] | Field observed mass movement characteristics[ii] | Hazard Class | Consequence Class | Relative hazard exposure category | Comment |
|---|---|---|---|---|---|---|---|---|
| 35 | | Cashmere Road | 5a) Toe slump | AA: 10,600 $m^2$<br>CD: 0.2 m horizontal and vertical displacement.<br>• To date displacement only during earthquakes. | 3 | 3 | CLASS III | Local services only |
| 36 | | Hackthorne Road | 5a) Toe slump | AA: 3,800 $m^2$<br>CD: 0.1 m horizontal and vertical displacements.<br>• To date displacement only during earthquakes. | 3 | 2 | CLASS II | Critical infrastructure locations need to be confirmed |

---

[Ii] Refer to Table 1 and Figure 2 for descriptions

[II] AA is Area Affected, CD is cumulative displacement, CR is Cliff edge Recession, FV is Failure Volume. Cumulative displacements are inferred from cumulative crack openings along section lines through the features.

[III] Areas covered by cliff collapse and rockfall risk maps contained in reports Massey et al. (2012a,b,c,d).

www.gns.cri.nz

## Principal Location

1 Fairway Drive
Avalon
PO Box 30368
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4600

## Other Locations

Dunedin Research Centre
764 Cumberland Street
Private Bag 1930
Dunedin
New Zealand
T +64-3-477 4050
F +64-3-477 5232

Wairakei Research Centre
114 Karetoto Road
Wairakei
Private Bag 2000, Taupo
New Zealand
T +64-7-374 8211
F +64-7-374 8199

National Isotope Centre
30 Gracefield Road
PO Box 31312
Lower Hutt
New Zealand
T +64-4-570 1444
F +64-4-570 4657