Report Superseded

The landslide mapping in this report has been superseded by the 2017 report:

Revised landslide database for the coastal sector of the Dunedin City district.

Please refer to the 2017 document for the most up to date landslide information.

Landslide maps and associated information are available online through the ORC's Natural Hazard Database:

https://www.orc.govt.nz/managing-our-environment/natural-hazards/otago-natural-hazards-database

The hazard significance of landslides in and around Dunedin City

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EXECUTIVE SUMMARY

The Otago Regional Council (ORC) is developing a natural hazards database. Landslides are a significant hazard in the Otago Region and an inventory of landslide information is a key data set in the natural hazard database. The database documents existing landslides, and does not provide forecasts of future landslides.

An update of the ORC landslide database for the Dunedin City district was completed in 2012, utilising data from a variety of sources. It was realised that the landslide database contains little, if any, information on the significance of the hazard posed by landslides. ORC subsequently contracted GNS Science to provide more information on the hazard significance of the landslides within six areas in and around Dunedin City, and that is the subject of this report.

Four additional categories of information have been added to the database to highlight the 'hazard significance' of the existing landslides. The first, and perhaps most important, is the *certainty* of the interpretation that the mapped feature is actually a landslide. Second is a classification, in general terms, of the age and degree of *activity* of each landslide. Third is classification of what *remediation* (stabilising measures), if any, have been undertaken, and fourth is an estimate of the *sensitivity* of the landslide, i.e. an estimate of how easily landslide movement could be reactivated.

Whether the landslide movement is deep-seated or shallow-seated provides further insight into the nature of the hazard. Landslides in the Dunedin district, and elsewhere, can be segregated into bedrock landslides, which are developed in the underlying bedrock, and surficial landslides, which are developed in shallow soils that mantle the bedrock. Bedrock landslides are typically large, in most cases originated in prehistoric times, and are most common in areas where the bedrock is weak mudstone. Some continue to move and evolve, but generally at slow rates. Surficial landslides occur where the soils are thicker than a metre or so, and the ground slope is moderate to steep. Surficial landslide movements are commonly triggered by rainstorms of a scale that usually occur once every few years, thus their occurrence is commonplace.

Landslides comprise between one-fifth and one-quarter of the overall land area assessed in this report. However, for as many as one-third of those landslides, there is notable uncertainty as to whether they actually are landslides. In regard to the utilisation of the landslide database information, the *certainty* attribute in concert with the *sensitivity* attribute provide an indication of the degree of hazard. In regard to risk reduction of landslide hazards, there remains no substitute for good geotechnical practice, such as avoiding hazardous areas where possible, minimising slope modifications, and not discharging water into the ground.

1.0 INTRODUCTION

The Otago Regional Council (ORC) is developing a natural hazards database that is accessible via the internet. Landslides are a significant hazard in the Otago region and landslide information is one of the key data sets in the ORC natural hazard database.

In 2012, ORC commissioned GNS Science to review, rationalise and update the landslide information ORC had collected into a dataset for the Dunedin City district (Glassey & Smith Lyttle 2012). As a result of that work, about 1200 additional landslide areas ('polygons') were added, duplicated landslide information was removed, and source(s) of information on each landslide were identified, including any specific report(s) documenting the landslides. Several new categories of information ('attribute fields') were added to the database to allow capture of descriptors ('attributes') that characterise a particular landslide. Point locations of landslide information held by GNS Science were also incorporated into the database.

A limitation of the updated landslide dataset is that it contains little, if any, information on the significance of the hazard posed by each identified landslide. ORC subsequently contracted GNS Science to provide more information on this aspect of the mapped landslides within six areas within the Dunedin City district, and that is the subject of this report (Figure 1).

The information provided in this report is intended to be used primarily to assist in planning, policy and consenting activities. The information is, for the most part, based on generalised assessments and broad-scale inferences, rather than detailed investigations, and should not be used in isolation for any purposes that require site-specific information. Readers of this report are referred to the previous report (Glassey & Smith Lyttle 2012) for more detailed information on database structure and attributes.

1.1 SCOPE OF WORK UNDERTAKEN

The focus of the work described in this report is to devise better ways of highlighting the hazard significance of landslides identified in six assessment areas within the Dunedin City district. The work has involved:

1. Revising the database structure to allow incorporation of attributes that contribute to describing the hazard significance of existing landslides in the assessment areas.
2. Providing a generalised description of the overall character and hazard significance of landslides in each assessment area.

As a result of this work we have modified the landslide database to allow reasonable assignation of the attributes, and corrected any errors we have encountered.

Conventions for database nomenclature used in this report are as follows:

- **Bold** (e.g. **Landslides**) refers to a database entity or table.
- *Italicised* (e.g. *Landslide_id*) refers to a field (column name) within a database table.
- <u>Underline</u> (e.g. <u>Active</u>) refers to an attribute value that can populate a field.

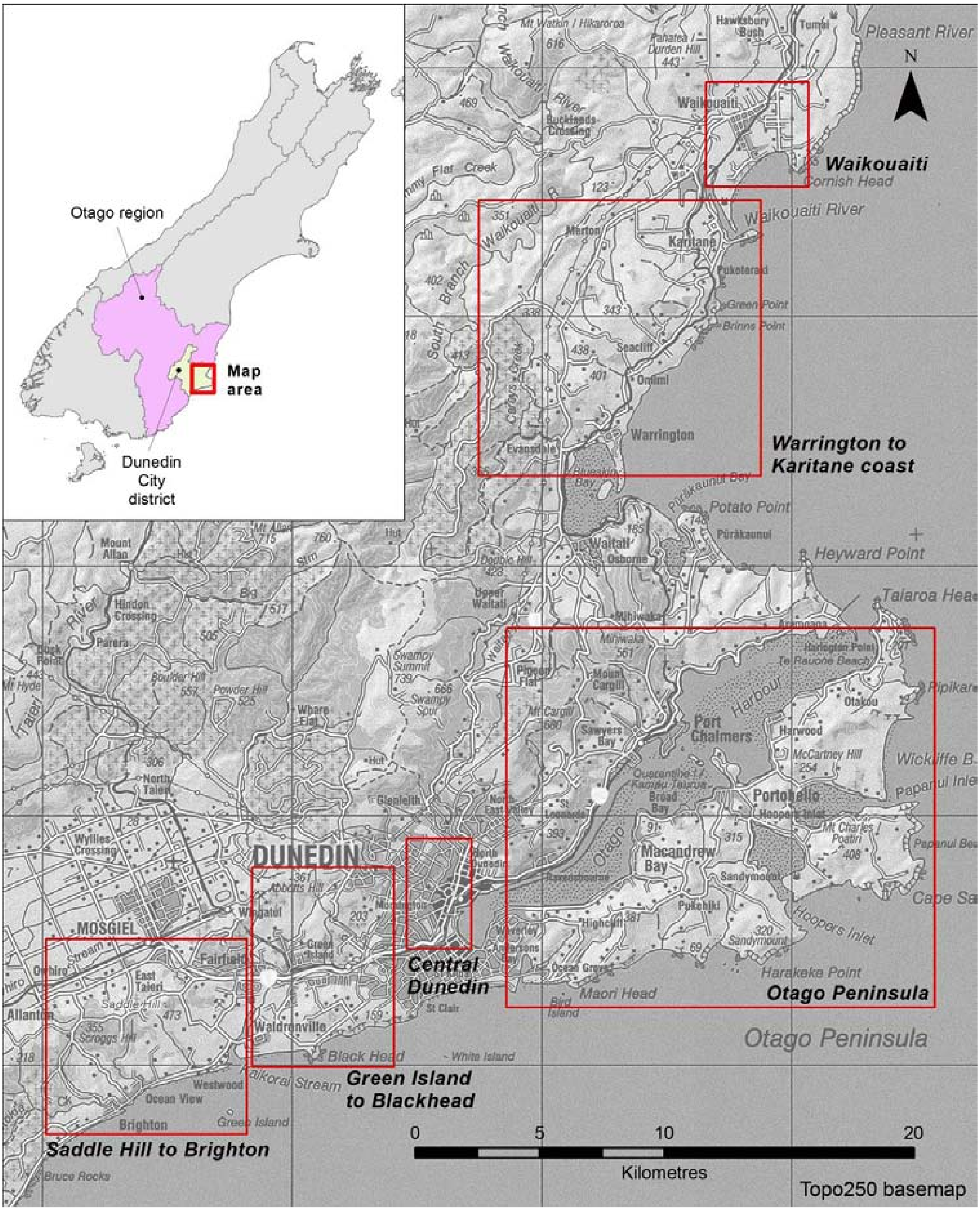

Figure 1 Location of the six landslide hazard assessment areas that are addressed in this report.

2.0 LANDSLIDE INFORMATION

The landslide component of the ORC natural hazards database contains an inventory of information on existing landslides; in other words locations where landslide movement is known or thought to have occurred at some time in the past. It does not provide any information on the likelihood of the formation of new landslides, commonly called ‘first time’ landslides.

In order to qualify the ’hazard significance’ of the existing landslides, four additional attributes have been added to the dataset. The first, and perhaps most important, is the *certainty* of the interpretation that the mapped feature is actually a landslide. Second is a classification, in general terms, of the estimated age and degree of *activity* of each landslide. Third is classification of what *remediation* (stabilising measures), if any, have been undertaken, and fourth is an estimate of the *sensitivity* of the landslide, i.e. an estimate of how easily landslide movement could be reactivated. Section 3 of the report provides a general description and evaluation of the landslide hazard in the six areas addressed in this report.

2.1 LANDSLIDE CERTAINTY

An often-overlooked aspect of the identification of landslides is that the mapping usually involves the interpretation of landforms, either in the field or using aerial photos, focusing on landform features that are considered to be diagnostic of landslide movement. However, some of the landform features associated with land movement are subtle and there may be other explanations for the origin of these features. Many of the landslides delineated in the database have not been verified by detailed investigation, or the identification of actual movement having occurred. An important characteristic to define is therefore whether a landslide is known for sure to be a landslide, or is simply suspected of being a landslide.

Accordingly, the attribute “*certainty*” has been added to the **landslide** table in the database (Table 1). Where there is historical evidence of landslide movement, or where landslide movement is the only plausible explanation for the features observed, a landslide has been classed as definite. Where there is no historical evidence of landslide movement, but other lines of evidence indicate to a good level of confidence that a feature is likely to have resulted from landslide movement, it is classed as likely. Where a landslide has been identified from general or indirect evidence, such as by interpretation of high-altitude aerial photographs, or topographic maps, and where there could be other plausible explanations for the nature of the landform, the landslide has been classified as possible.

Table 1 Definition of values for the Landslide_*certainty* attribute.

Code	Certainty	Landslide certainty Description
1	Definite	Landform features that can only be the result of landslide activity [and/or] has been observed to have moved.
2	Likely	Landform features that are most likely the result of landslide activity, and other explanations are less likely.
3	Possible	Landform features that may possibly be indicative of landslide movement having occurred, but other explanations are plausible.

2.2 LANDSLIDE ACTIVITY

A new attribute, *activity* has been added to the **landslide** table to provide a clearer and more useful classification of the age and level of activity of the mapped landslides. *Activity* is intended to supersede and replace the existing attributes for landslide *age* and *activity_status* fields defined by Glassey & Smith Lyttle (2012). The new *activity* attribute defines activity classes that align better with planning timeframes.

The displacement of walls, road kerbs, breakages in services and deformation of houses, can be used to identify recent or ongoing activity, as can historic accounts of slope movement. In the absence of historic movement, the presence and nature of loess deposits mantling landslide features, for example, can be used to discriminate between younger and older prehistoric movements (Table 2).

Table 2 Definition of the values for the Landslide_*activity* attribute.

Activity_id	Activity name	Activity Description
-1	Not collected	No information on the activity of the landslide has been sought.
0	Unknown	No activity information for a landslide has been determined.
1	Ongoing Activity	The landslide occurred in the last year, or movement has been recorded or observed in a pre-existing landslide in the last year.
2	Recent Historical Activity	Movement was initiated, or has recurred at least once, since the early 1960s (i.e. in the past 50 years or so).
3	Older Historical Activity	Movement was initiated, or has recurred at least once, between the late 1800s and the early 1960s (i.e. between about 150 and 50 years ago).
4	Prehistoric Activity (young)	No landform indications of historical or ongoing activity, but landslide features moderately- to well-expressed suggest movement was initiated/has recurred within the past 12,000 years (Holocene). Where present, Pleistocene loess deposits in the landslide area have been displaced.
5	Prehistoric Activity (old)	No landform indications of historical or ongoing activity, and landslide features have a subdued expression, suggesting that there has been no movement since the Pleistocene (older than 12,000 years ago). Where present, the youngest loess sheet drapes the landslide terrain and has not been displaced.

2.3 LANDSLIDE REMEDIATION

In order to better ascertain the hazard significance of a landslide, it is useful to know what measures, if any, may have been taken to try and improve its stability. A *remediation* attribute has been added to the landslide database with values as defined in Table 3.

Table 3 Definition of the values for the Landslide_*remediation* attribute.

Code	Remediation_name	Remediation_Description
-1	Not collected	No information on landslide remediation has been sought.
0	No remediation	No remediation appears to have been undertaken.
1	Minor remediation	Minor remediation measures undertaken, such as drainage ditching, small retaining walls, deliberate planting of deep-rooted trees to aid dewatering.
2	Moderate remediation	Engineered measures, such as drainage relief holes, rock or soil anchors, water cut-off trenches, toe buttressing or head unloading. Generally accompanied by movement monitoring installations such as survey pillars, piezometers or inclinometers.
3	Major remediation	Major engineered works, such as large-scale removal of the landslide materials, construction of engineered shear keys, or large-scale anchoring or buttressing.

2.4 LANDSLIDE SENSITIVITY

Landslides form, or may experience renewed movement, as a result of factors that drive slope movement overcoming the factors that resist movement. Driving factors include gravity, high water content or water pressures, and whether material is being removed from the lower part of the slope by natural erosion or human activities. Resisting factors include friction and the strength or cohesion of the geological materials. Once commenced, landslide movement continues until the moving material attains equilibrium between forces driving and opposing mass movement.

A distinction is commonly made between a landslide that is active and one that is inactive. However, this is a difficult and often subjective distinction. It rarely provides useful information on whether a landslide that has not moved historically is simply dormant, but remains in a quasi-unstable condition, or whether the forces that caused the landslide to move originally are no longer operative (e.g. erosion at the toe of the landslide has stopped, drainage has improved, or material has accumulated, or been placed, at the toe of the slope). In general, it is best to assume that an existing landslide is in a close-to-unstable condition unless there is good reason to think otherwise.

A new attribute has been added to the landslide table in the database, comprising an interpretation of how sensitive a landslide is to environmental and/or human-induced modifications, which may result in reactivation. The attribute definition includes an assessment of the extent to which the surrounding area has been affected by landsliding. The definitions of the *sensitivity* attribute values are given in Table 4.

Table 4 Definition of values for the Landslide_*sensitivity* attribute.

Code	Value	Description	General indicators	Significance
0	Not assessed	No sensitivity assessment has been made.		Assume Sensitivity Code 2 (Moderate) unless work done to show otherwise.
1	Low Sensitivity	Interpreted that a large reduction in stability factors would be needed for reactivation / enlargement.	Little of the adjacent area is affected by landslides [and/or] relatively gentle slope in relatively stable materials [and] no indications of historical activity.	Low risk to buildings / infrastructure, providing destabilising changes are kept to a minimum.
2	Moderate Sensitivity	Interpreted that a moderate reduction in stability factors would result in reactivation / enlargement.	Some of the surrounding area is affected by landslides with a range of ages [and/or] relatively moderate slope in relatively moderately stable materials [and/or] may or may not have indications of historical activity.	Low risk to buildings / infrastructure, providing no destabilising changes are imposed. Risk increases relative to extent / intensity of destabilising changes.
3	High Sensitivity	Interpreted that small reduction in stability factors would result in reactivation / enlargement.	Much of the surrounding area is affected by landslides with range of ages [and/or] relatively steep slope in relatively weak materials [and/or] historical evidence for previous reactivation events.	Moderate to high risk to buildings / infrastructure.

2.5 OTHER CONSIDERATIONS

Factors such as topography and land-use, geology, size and depth of landslides, and rates of movement have a bearing on the hazard significance of landslides. In addition, there are various analytical approaches that can be applied to assessing landslide hazards and risks.

2.5.1 Topography and land-use

The primary driver of landslide movement is gravity, and the presence of sufficient slope is necessary for the effects of gravity to overcome the strength of the geological materials. Strong rock can stand in very steep slopes, whereas weak rocks or soils may fail on moderate slopes. Generally speaking, the more topographic relief there is, the greater the likelihood of landslide movements. In addition, erosion by rivers, streams, or the sea can undercut the lower parts of slopes, and induce landslide movement. From a hazard perspective, it is important to appreciate that landslide debris can under some circumstances run out and encroach onto gentle or flat ground at the foot of a slope. Landslides can also undermine flat or gentle ground at the crests of slopes. Land-use may influence the occurrence of landslides, for example where deforestation increases water infiltration to a slope, and soil exposed to seasonal wetting and drying may develop deep cracks that enhance water infiltration. Activities such as modifying slopes by cutting or filling, and modifying natural run-off and drainage, are potentially important influences on slope stability.

2.5.2 Geology

At the scale of an individual landslide, published geological maps provide a broad indication of the underlying rock type, but there are limitations arising from scale (Saunders & Glassey, 2007). New Zealand's national geological maps are compiled at a regional scale (e.g. 1:250,000, where 1 cm on the map represents 2.5 km on the ground), and much geological detail and some degree of accuracy has been sacrificed in the interests of clarity of map presentation. Nonetheless, generally speaking there are notable correlations between the distributions, types and sizes of landslide and the underlying geology (Figure 2), which we illustrate by comparing the percentage areas affected by landslides within different components of the geological sequence (Table 5). This highlights that the Cretaceous - Cenozoic sedimentary rocks are particularly susceptible to landsliding. However, inspection of Figure 2 reveals that this is more the case in the northeastern part of the Dunedin district, where very large landslides are present, compared with southwestern Dunedin, for example. Figure 2 also illustrates that schist is little-affected by landslides in some places, but greatly affected in others. Most likely this reflects the roles of local topographic factors, along with variable distributions of unfavourably orientated fractures and weak layers in the rock mass.

Table 5 Percentage of geological unit (by area) affected by landsliding.

SIMPLIFIED LITHOLOGY	% of geological unit affected by landslide
Quaternary deposits	6.0
Volcanics	12.9
Cretaceous-Cenozoic sedimentary rocks	46.7
Schist	17.5

An important geological factor, and one not shown on regional-scale geological maps, is a widespread mantle of various types of soils that overlies the bedrock. Commonly known as ‘surficial materials’ (also called ‘regolith’), these soils are distinct from the underlying bedrock whose nature is shown on geological maps. In the Dunedin district, surficial materials include accumulations of loess, aprons of gravelly silt or clay (colluvium) on hillslopes, and or zones of clay-rich, rotten bedrock close to the ground surface.

A distinction is commonly made between deep-seated landslides that have resulted from failure of the underlying rock, and are usually called ‘bedrock’ landslides, and shallow landslides which have occurred within the surficial materials and generally referred to as ‘surficial’ landslides. The influence of geology on landsliding is discussed further in Section 3.

2.5.3 Characteristics of bedrock and surficial landslides

Generally speaking, most medium to large landslides, such as are shown in Figure 2 as areas (polygons), are deep-seated and probably are bedrock landslides. In contrast, most small landslides, such as are represented in Figure 2 by points, are probably surficial landslides. However, small landslides can occur within surficial materials that have formed on larger bedrock landslides.

Bedrock landslides occur in a variety of settings. Fundamentally, they are related to the underlying rock type, but their occurrence is usually influenced by unfavourably-aligned fractures or weak layers in the rock, which commonly are hidden from view. This often makes it difficult to explain the distributions and causes of existing bedrock landslides. It also makes the occurrence of future first-time bedrock landslides difficult to forecast. In Otago, most large bedrock landslides are natural landscape features that were initiated far back in prehistoric times, well before human arrival. The initiation and evolution of these landslides reflects long-term geological processes such as uplift of the land, and its dissection by the progressive deepening and widening of river and stream valleys. Once formed, large landslides may persist as recognisable landscape features for many tens of thousands of years. In some cases, movements may have ceased long ago, and the landslide terrain is a relict feature. In other cases, movement may be continuing, either steadily or in movement episodes interspersed with dormant periods. Existing landslides may reactivate due to natural changes, or as a result of human activities. Large existing landslides may require larger destabilising forces (e.g. earthquake shaking, major slope modification, or major groundwater changes (e.g. burst pipe) to become re-activated than do smaller landslides.

Surficial landslides occur in places where surficial materials are thicker than a metre or so, and where the ground slope is steeper than about 12°. This makes it relatively easy, with limited investigation, to identify areas that may be susceptible to surficial landsliding. Some types of regolith may be less prone to instability (e.g. gravelly colluvium) than other types (e.g. clay-rich weathered volcanic rock). A typical surficial landslide can be up to several tens of metres across and tens to hundreds or so metres long (down slope). Surficial landsliding is a natural land-shaping process, and is typically triggered by prolonged or intense rainfall. Erosion or human modifications of the slope, such as devegetation, are also common factors that may aid the initiation of surficial landslides. Surficial landslides may be initiated by relatively minor changes to the slope, such as making cuts or placing fills, or by adding water to the ground.

Both bedrock landslides and surficial landslides are potentially damaging, and despite their relatively smaller size, surficial landslides can nonetheless contain sufficient material, and move sufficiently fast, to seriously damage or destroy buildings, and pose a threat to the safety of any occupants.

2.5.4 Rates of landslide movement

An aspect of the hazard significance of landslides is whether landslide movement occurs slowly or rapidly. The ORC landslide database classifies the main type of landslide movement that has occurred, but not the rate at which landslide movement occurred. The reason for its exclusion is that for most of the mapped landslides, the actual movements were not observed, and indeed many of the mapped landslides pre-date human settlement (i.e. are prehistoric). Nonetheless, some generalisations can be made. Most of the mapped landslides can reasonably be assumed to have moved at rates ranging between slow (about 1 m per year), moderate (about 1 m per day) and rapid (about 1 m per minute), based on the classification of Cruden & Varnes (1996). Only in proximity to very steep slopes or cliffs is there a possibility of very rapid rock or soil falls, although noting that in small valleys and gullies, small landslides have been known to temporarily block or impede drainage. Build-up of water behind the blockage can result in remobilisation of the landslide material into a very rapid debris flow that sweeps down the valley (see Figure 10).

First-time landslides tend to move more rapidly, and potentially pose more catastrophic consequences, than reactivated pre-existing landslides, which tend to creep at slow rates.

2.5.5 Analytical approaches

Analytical approaches range from simple comparative evaluations, through to increasingly sophisticated analyses utilising multiple variables or probabilities.

The presence of many landslides in a particular area indicating a general propensity of the rocks or soils to instability, is an example of a simple evaluation. However, the presence of relatively few landslides does not necessarily mean that there is no landslide hazard.

A more comprehensive way to evaluate the significance of hazards posed by landslides, both existing ones and any new ones that may form, is to consider the general geology, the nature of local topography, whether steep or gentle for example, and the general nature of the existing landslides, such as whether they are generally large and widespread (and thus likely deep-seated), or generally small and localised (thus likely surficial). This is an example of multiple-variable evaluation, and can be done descriptively, or mathematically using computer methods, to determine how susceptible an area is to landsliding, and forecast the circumstances under which future movements may occur. Other approaches include probabilistic landslide evaluations that use statistical analyses of historical landslide data, in order to estimate the probability of landslides occurring at particular locations.

For individual landslides, site-specific geotechnical investigations can be used to gather detailed information for analysing the stability of the landslide. Investigations typically include mapping and surveying of the landslide, drilling to determine the subsurface geology and hydrology, and strength testing of landslide materials. The resulting data can be used in multiple-variable calculations to estimate the main factors controlling the stability of the landslide, and identify the best remedial measures (e.g. drainage or buttressing) for improving the landslide’s stability. However, such investigation work is costly and is generally only applied where important infrastructure or assets are at risk from landslide movement.

No analyses of these types have been undertaken as part of the present report, other than the simple comparison of bedrock geology to landslide distribution (Figure 2) and consideration of the percentage of land area affected by landslides in each of the assessment areas.

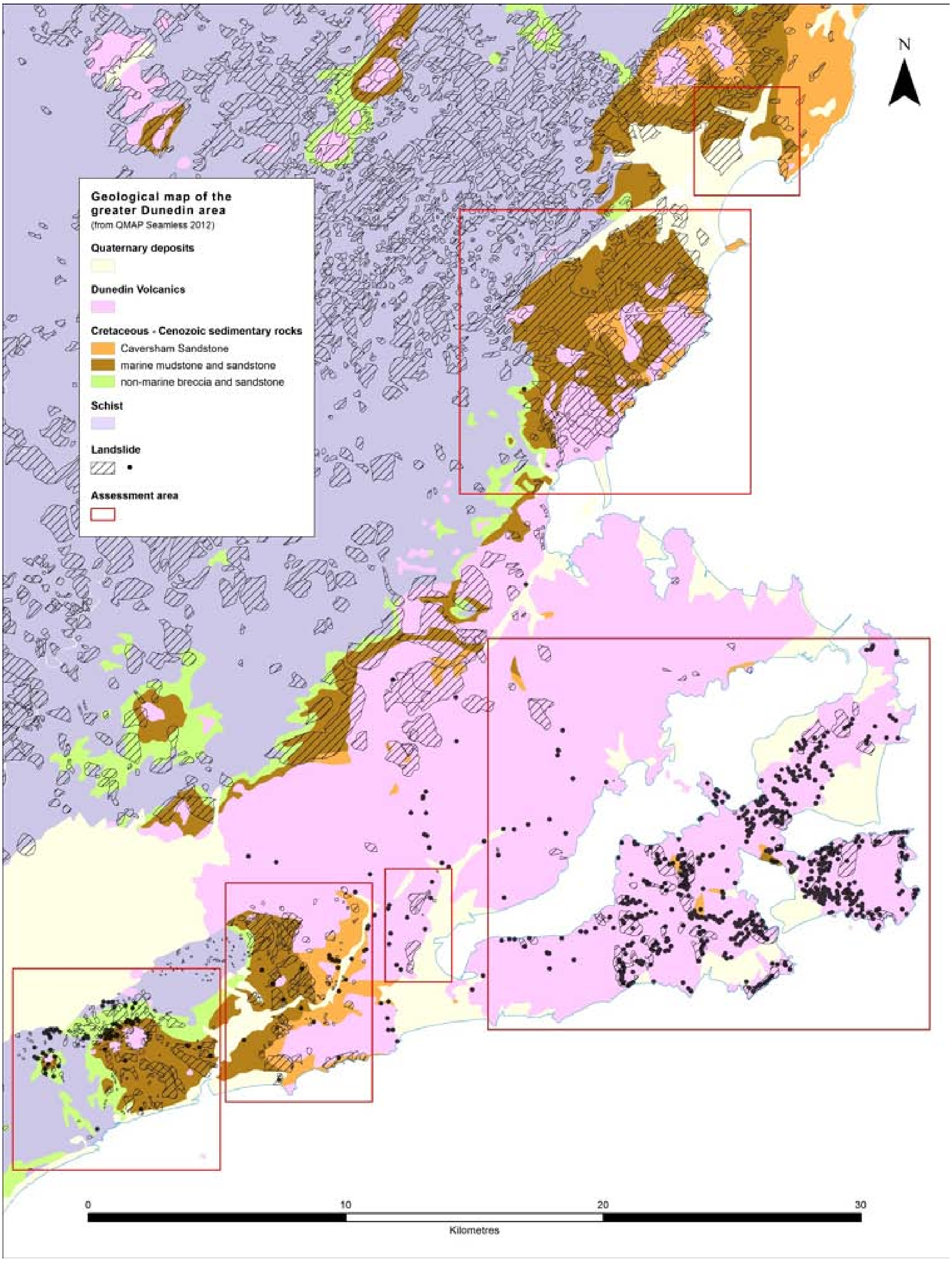

Figure 2 Simplified geology of the Dunedin area and landslides from the ORC landslide database. The landslides are represented by both black cross-hatched areas (polygons) and black dots (points).

3.0 LANDSLIDE HAZARD CHARACTERISATION

The nature and distribution of landslides is described for six selected areas (Figure 1), with emphasis on aspects that highlight the significance of landslide hazards, as illustrated on maps accompanying each sub-section. The selected areas include existing urban sectors of Dunedin, places where further development may occur, and areas known to have a propensity for landsliding. Table 6 presents a statistical evaluation of the extent to which each area has been affected by landsliding (noting that only the on-land area, not estuaries or the sea, is considered). The landslide areas (polygons) are evaluated separately from the landslides that are denoted only as points in the database. The statistics are discussed below in relation to each assessment area.

Table 6 Statistical evaluation of landslide (lsd) distributions. Areas are expressed in square kilometres. Landslide points are total number within each area, and this value is divided by the total land area to derive an average number of points per square kilometre. The overall value for % of all landslides is total landslide area divided by total land area. Similarly, the overall % for definite and likely landslides is total landslide area (definite & likely) divided by total land area.

Area	Total land area (km^2)	Lsd area (km^2)	Lsd % by area (all Lsds)	Lsd area (km^2) (*certainty* = definite & likely)	Lsd % by area (definite & likely)	Lsd Points total	Lsd Points per km^2
Central Dunedin	10.6	0.8	7.5	0.02	0.2	11	1.0
Green Island to Blackhead	42.7	6.6	15.4	5.3	12.4	25	0.6
Saddle Hill to Brighton	51.3	6.5	12.7	6.5	12.6	62	1.2
Otago Peninsula	157.2	11.7	7.5	1.4	0.9	599	3.8
Warrington to Karitane coast	87.9	44.3	50.4	35.9	40.8	1	0.0
Waikouaiti	14.4	5.3	36.6	1.7	12.2	0	0.0
total	*364.1*	*75.2*		*49.3*			
overall			*20.7*		*13.5*		

3.1 CENTRAL DUNEDIN

The landslides within central Dunedin are shown on Figure 3. About 7% of this area comprises mapped landslides, but most of these have a *certainty* attribute of possible. Definite and likely landslides comprise only 0.2% of the assessment area, while the mean density of landslide points is 1.0 per square kilometre (Table 6). Overall, existing identified landslides in the central Dunedin are relatively sparse.

Examination of aerial photographs and topographic maps has identified three areas that have features that are similar to those associated with large block landslides (City South, Southern Cemetery and Town Belt block slides – see Figure 3). They are attributed as possible slides and have no record of historical movement. Intensive urban development has taken place across much of these suspected landslide areas, and they also include parts of the Town Belt reserve. The urbanisation in conjunction with the vegetation of the Town Belt has masked many of the diagnostic features of these suspected landslides and their full extents are uncertain. Alternative interpretations of the features are possible, and the landslide-like features could be formed by differential erosion of various volcanic lavas flows, for example. If they are in fact landslides, then they are interpreted as having formed in pre-Holocene times and are assessed as having low sensitivity to natural or anthropogenic changes in stability factors.

Relatively small slides exist at Cargill Street, Albany Street and on Duke Street. These landslides have been investigated and are well documented (Johnson 1987, Glassey 1991a, 1991b, Macfarlane 1989) and the Albany Street and Cargill Street slides have been subject to moderate remediation and minor remediation respectively. Despite having had some remedial works, recent historic activity has been recorded at Albany Street (Lee Paterson, MWH, pers. comm.) and the others have moved in recent historical times (i.e. within the past 50 years). These slides are assessed as having high sensitivity to natural or anthropogenic changes in stability factors. While not considered likely to undergo future rapid movement, continued periodic movement may affect infrastructure and buildings located on, or adjacent to, these slides. These small localised failures indicate that conditions (slope, groundwater, geology) exist in places that are conducive to localised instability on slopes in the central Dunedin area.

Most of the landslide point data relate to minor surficial landslides that occurred during the March 1994 rainstorm (Stewart 1996).

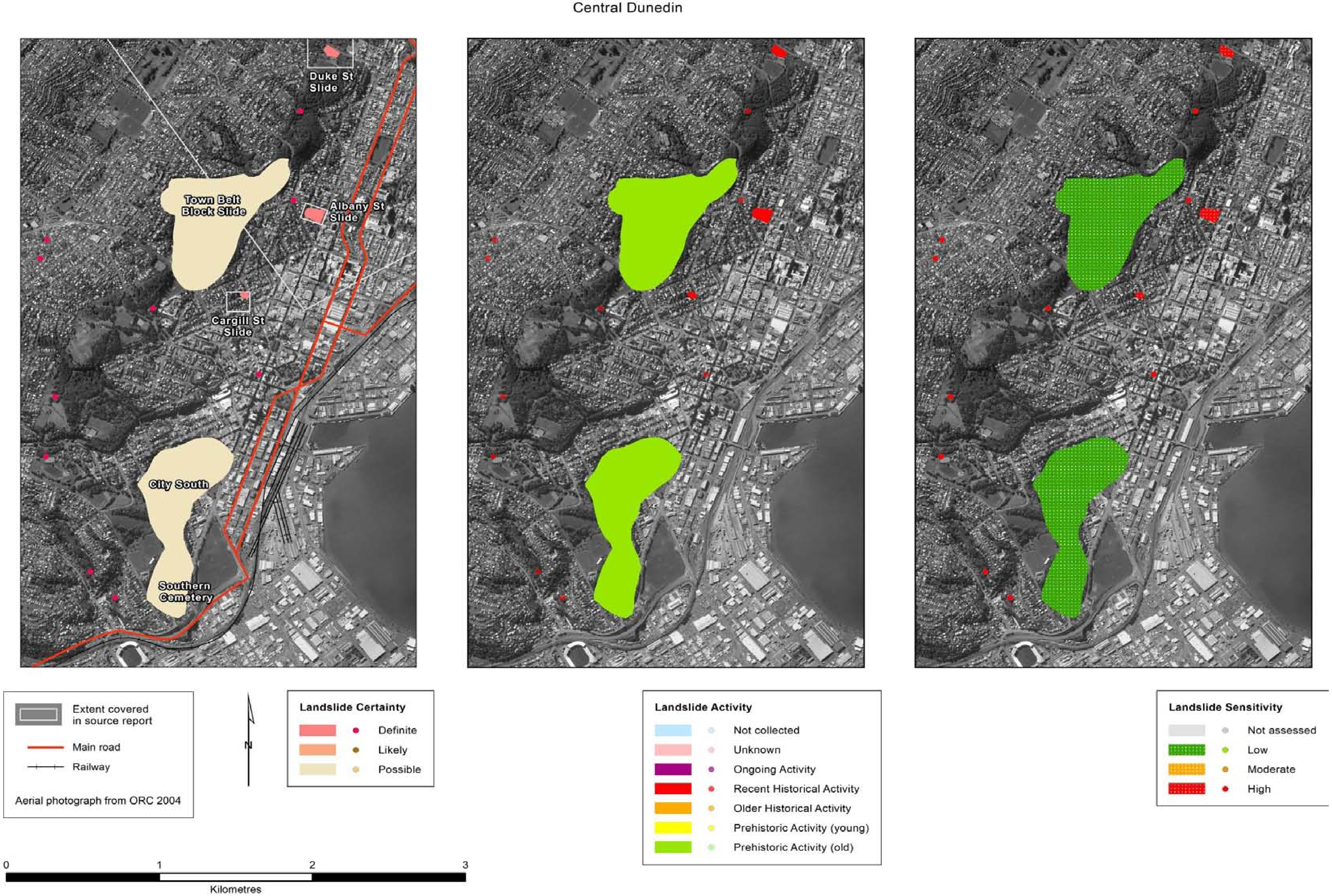

Figure 3 Central Dunedin Landslide Certainty, Activity, and Sensitivity.

Figure 4 A surficial landslide occurred midway up the eastern side of Kaikorai valley during the March 1994 rainstorm. Near the upper limit of the plantation, the steep crests at the top of the scars are the landslide head scarps. The waterlogged landslide debris mobilised into a porridge-like slurry and ran down the slope as a debris flow, which had sufficient power to uproot or break off several pine trees. The debris flow extended onto to Kaikorai Valley Road (obscured in the middle ground) where it completely blocked the southbound lane. Photo: GNS Science, D.L. Stewart, March 1994.

Rainfall induced landslide events in the Dunedin area

More than 100 mm of rain fell on 16 and 17 June 2013 and activated numerous landslides. On Otago Peninsula, Portobello Road and Harington Point Road were closed by landslide debris. On the northern side of Otago Harbour, a landslide was initiated at Upper Junction Road, removed the road carriageway and shed debris as far downslope as Blanket Bay Road alongside the harbour. As of January 2014, Upper Junction Road still remained closed.

Landslide-generating rainfall events tend to occur at least once a decade or so, although there is no regular pattern. In April 2006, 170 mm rainfall in 30 hours caused much flooding and many minor/shallow landslides. But perhaps the most impressive event in recent decades was between 17–19 March 1994, when as much was 225 mm of rain drenched coastal Otago and triggered at least 186 shallow landslides in the Dunedin area. Of those landslides, 45 % were thought to be reactivations of existing landslides, while 55% were consider as new (first time) landslides (Stewart 1996).

3.2 GREEN ISLAND TO BLACKHEAD

The landslides within the Green Island to Blackhead area are shown on Figure 5. About 15% of the area comprises mapped landslides, most of which are classified as definite or likely. The mean density of landslide points is 0.6 per square kilometre (Table 6).

The landslides have been delineated mostly using aerial photo interpretation, and some have been documented and confirmed from field inspections and deformation surveys. Several large landslides are postulated in the Abbotts Creek catchment (Barrell 1997), and are classified as definite or likely. Localised large landslides are mapped on the western side of Kaikorai valley, and around the margin of the broad tableland extending from Waldronville and Green Island township east to Corstorphine and St Clair. Several of these are classified as possible landslides.

The West Abbotsford Landslide reactivation that occurred during motorway construction in 1968, and the East Abbotsford Landslide which occurred in 1979 were significant events. The East Abbotsford Landslide resulted in 69 houses being destroyed or rendered inaccessible. Fortunately, the landslide developed over a period of many weeks prior to its main movement, and for several days beforehand was creeping at between 15 and 60 cm per day, which allowed sufficient warning for an orderly evacuation of residents. The final movement, totalling about 50 m, occurred over a period of about 30 minutes (Hancox 2008, 2009; see Figure 6). The reactivation of the prehistoric West Abbotsford slide in 1968 resulted from removal of toe support during excavations for the State Highway 1 motorway. Both of these slides have been subject to moderate *remediation*. Ironically, material was excavated from the base of the future East Abbotsford slide to form the toe support remediation of the West Abbotsford slide, and this slope modification contributed to the formation of the East Abbotsford Landslide. Despite remediation, minor movement of the West Abbotsford slide has been observed by visual survey but no movement observed from visual inspection of 2012 (Lee Paterson, MWH, pers. comm.).

A surficial landslide occurred at Waldron Crescent, in Green Island, in 1993 when a 1.5 m high cut was excavated across a moderate slope of about 15° (Barrell & Glassey 1993). Minor instability continues to affect houses and infrastructure at the Church Hill Road and District Road slides in Green Island despite minor *remediation* (Lee Paterson, MWH, pers. comm.). These movements all indicate that the slopes are highly sensitive to small changes in stability factors, such as groundwater fluctuations due to rainfall variation and slope modification. The sensitivity is primarily due to the nature of the underlying geology which is dominated by Cretaceous-Cenozoic sedimentary rocks that appear to be particularly susceptible to landsliding (Table 5).

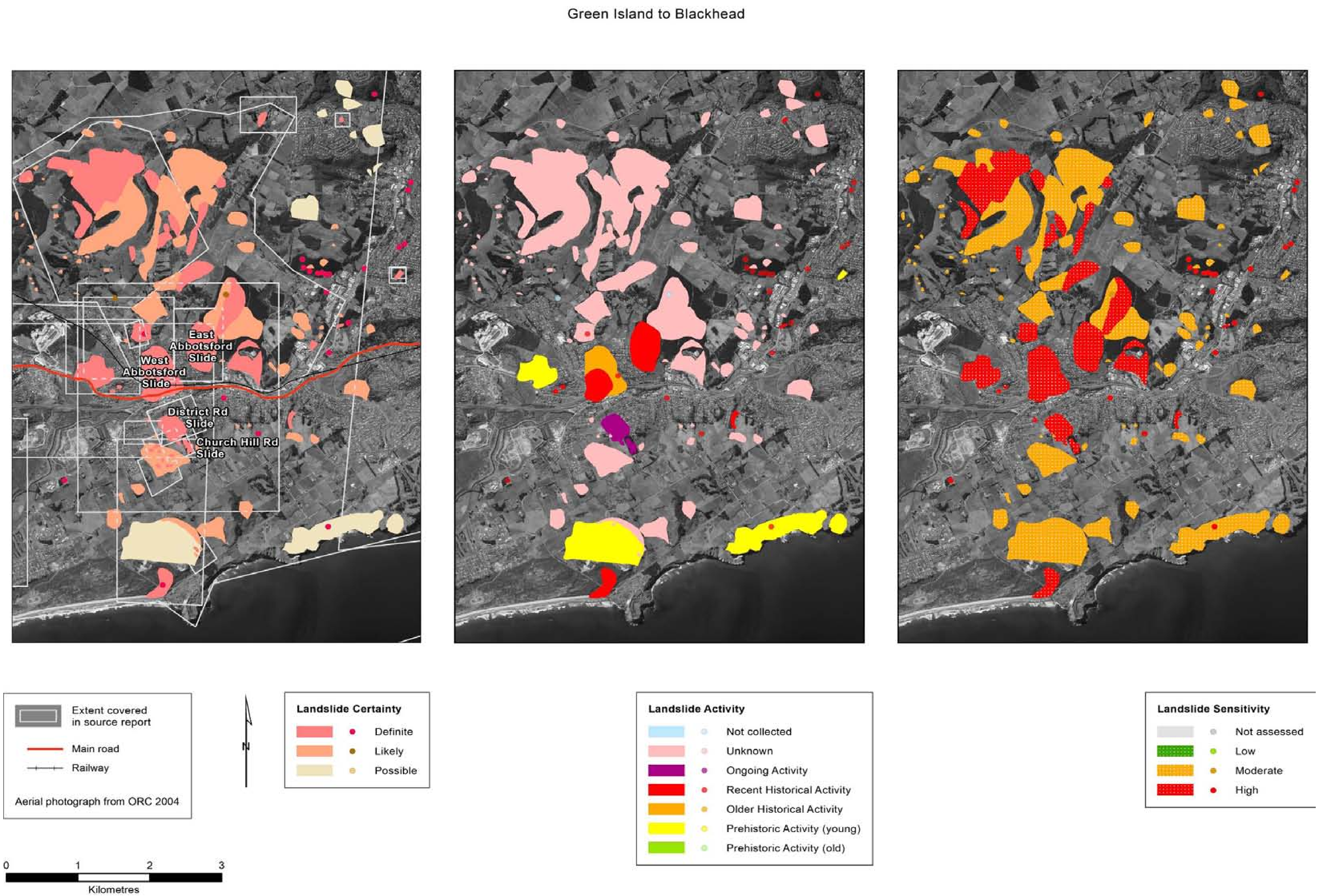

Figure 5 Green Island to Black Head: Landslide Certainty, Activity, and Sensitivity.

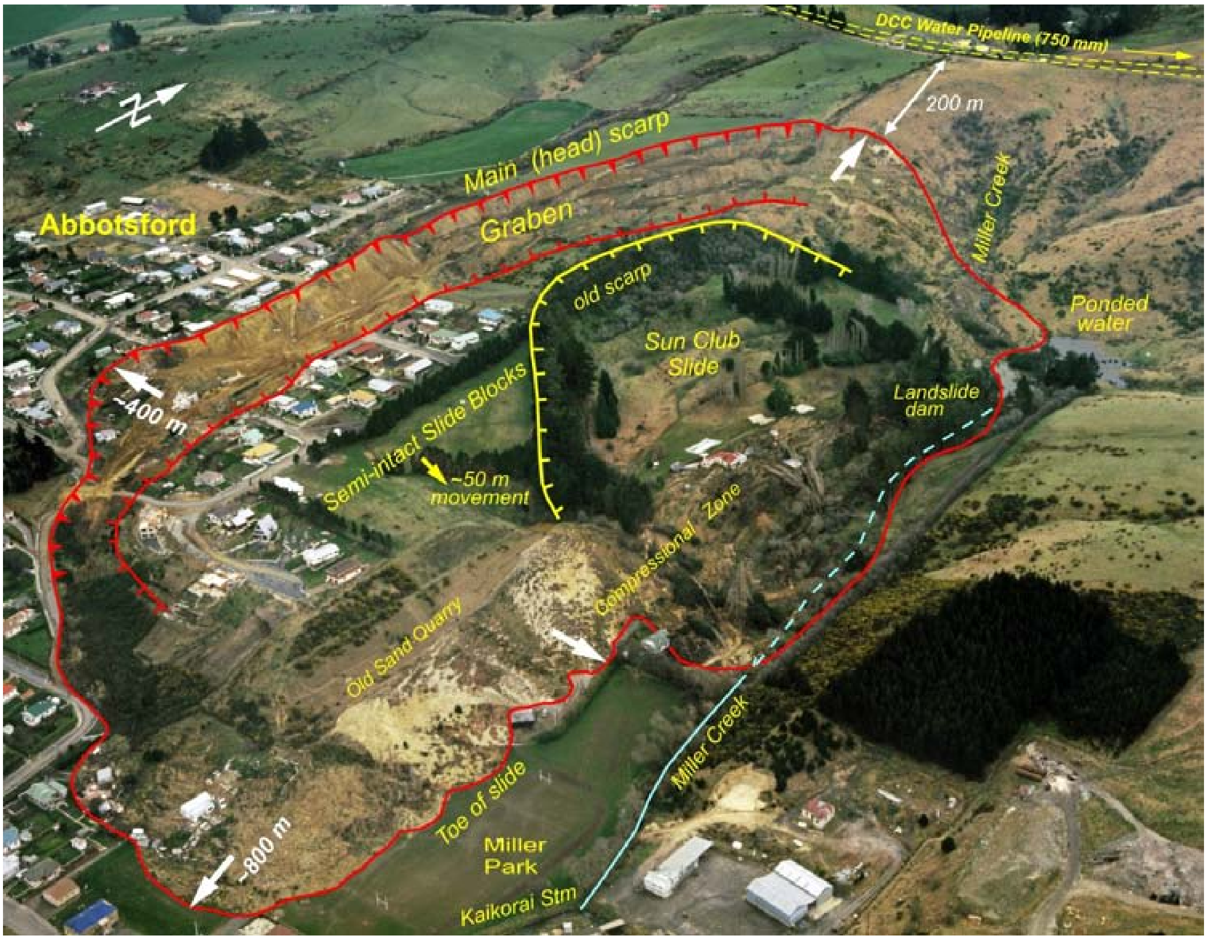

Figure 6 An annotated photograph looking northwest across the 1979 East Abbotsford Landslide on 9 August 1979, the day following the main movement. This was a 'first time' bedrock landslide, of the 'block slide' variety. The slide block is about 400 m long, from the head of the graben to the toe of the slide, and about 800 m wide. The Sun Club Slide was an existing prehistoric landslide on the flank of the Miller Creek valley. The Sun Club Slide area was 'piggy-backed' downhill during the 1979 block slide. Illustration from Hancox (2009).

3.3 SADDLE HILL TO BRIGHTON

About 13% of the Saddle Hill to Brighton assessment area is mapped as landslides, almost all of which are classed as definite or likely. The mean density of landslide points is 1.2 per square kilometre (Table 6). Many landslides are located on the slopes surrounding the volcanic necks of Saddle Hill, Jaffray Hill and Scroggs Hill (Figure 7 and Figure 8). The large landslides, in other words those mapped as areas (polygons), are all thought to be bedrock landslides that are seated in relatively unstable Cretaceous-Cenozoic sedimentary rocks. The small landslides, mapped as points are probably all surficial landslides. Many of the bedrock landslides have been produced by 'earthflow' types of movement, and have distinctively rumpled or hummocky surfaces.

Several of the large slides have been investigated geotechnically (e.g., Jeffcoates Road Slide, Glassey 1993b; Old Brighton Road Slide, Coote 1995). Some have shown continued movement historically (e.g. Jeffcoates Road), recorded by deformed road carriageways, warped or offset fences, or bent tree trunks. The Old Brighton Road Slide underwent a major movement in 1939, which severed the original road to Brighton, leading to its abandonment. Surficial landslides are common in many places in this area, and many of the landslides mapped in the Chain Hills area, where the bedrock is schist, have occurred within the regolith (generally loess) that overlies the schist, particular within or close to steep-sided gullies. Many surficial landslide movements occurred as a result of the April 1994 rainstorm (Stewart 1996) (Figure 7; most of the landslide points in Figure 8).

The slides within the Cretaceous-Cenozoic sedimentary rocks are considered to have high *sensitivity* to small modifications in stability factors such as erosion and anthropogenic modification. The slopes developed on those rocks are clearly very susceptible to landsliding and the easiest solution to that is to minimise the placement of high-value infrastructure and assets in those areas.

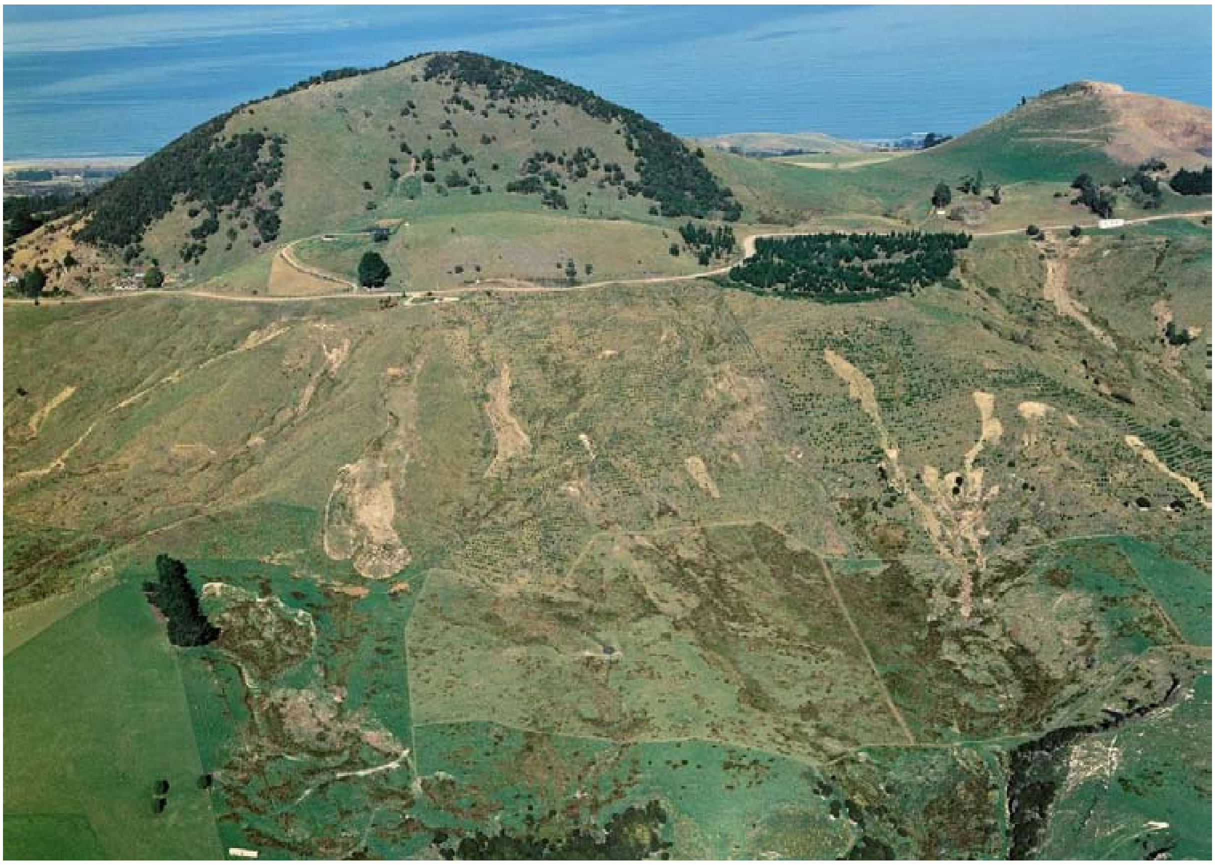

Figure 7 An aerial view south towards Saddle Hill Road, running left-right, above which rise the promontories of Saddle Hill (left) and Jaffray Hill (far right). From Saddle Hill Road to below the bottom of the photo is a moderate slope descending towards the Taieri Plain (out of sight below the photographer). Much of the slope below Saddle Hill Road is interpreted as a large, deep-seated, bedrock landslide. Superimposed on that landslide are numerous surficial landslides, the freshest of which moved during the March 1994 rainstorm, but many older, more subdued, scars relate to previous recent historical activity. This area is clearly very susceptible to landsliding. The young trees evident in this photo are now mature, and today obscure much of the detail of past landsliding on this slope. Photo: GNS Science CN 32285b, D.L. Homer, 1 May 1994,

Saddle Hill to Brighton

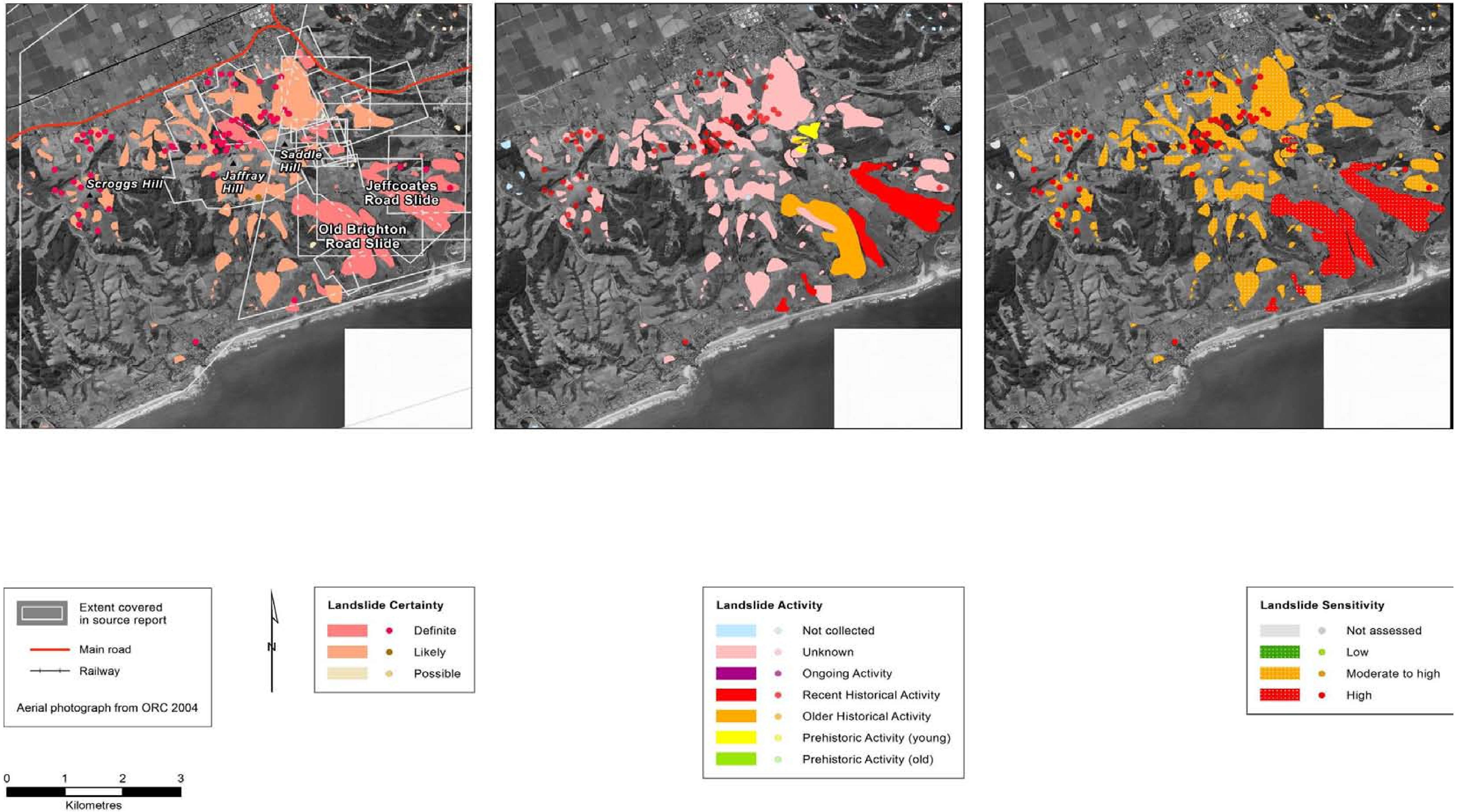

Figure 8 Saddle Hill to Brighton: Landslide Certainty, Activity, and Sensitivity.

3.4 OTAGO PENINSULA

In total, 24 large landslides, represented by polygons, and about 600 small landslides, represented by points, have been mapped or recorded on the Otago Peninsula (Leslie 1974; Stewart 1996; Figure 9). The mapped landslide areas (polygons) comprise about 7.5% of the assessment area, but most of these are classified as possible; landslide areas classed as definite or likely comprise only 0.9% of the assessment area. Landslides represented solely by points have a mean density of 1.2 per square kilometre (Table 6).

The large landslides are all of prehistoric initiation and are thought to be bedrock landslides associated with weak layers within the volcanic rocks. Most have been identified on the basis of landform features that are suggestive of a landslide origin, but have not been investigated directly and so are classified as possible. These suspected landslides are more common where the volcanic strata contain a lot of weak material. The occurrence of historic movements has allowed several of the large landslides to be classified as definite, and two good examples are the Howard St Slide at Macandrew Bay (Macfarlane 1990, Glassey 1995) and the Camp Rd Slide at Broad Bay. Parts of the Howard St Slide have reactivated historically, and have displayed slow movement whose occurrence is associated with rainfall events (Macfarlane 1990, Glassey 1995). The most recent reactivation was in 2013, and occurred despite some remedial drainage having been installed between 1995 and 2013. Such reactivations have caused minor damage to houses. Because of the sensitivity of the Howard St Slide to relatively minor changes in stability factors, most of the large landslides are classified as having moderate to high *sensitivity*, noting of course that most of these are currently only suspected of being landslides, rather than having been proved.

The majority of landslides on the peninsula are shallow surficial earth flows, debris flows and earth slides that have occurred in loess, colluvium and weathered volcanic material that mantle the volcanic bedrock (Leslie, 1974; Stewart, 1996). Most are initiated on slopes of between 12 and 28 degrees (Leslie 1974). Major rainstorms (see textbox, following Figure 9) tend to generate many surficial landslides, some of which are first-time failures while others are reactivated existing landslides. In some cases, surficial landslide material is remobilised as debris flows that, if confined within a stream valley or even minor gully, may travel rapidly for long distances (up to 2 km), and in some cases have caused significant damage to buildings, roads or water/power supplies (e.g. Stewart 1996, Photo 1; reproduced in Figure 10 of this report). Most of the surficial landslides are classified as definite. Those mapped by Stewart (1996) are categorised as having recent historical *activity* and those mapped earlier by Leslie, 1974 as unknown *activity*. All are considered to have moderate to high *sensitivity* to changes to stability factors.

The geological character and widespread moderate to steep slopes of the Otago Peninsula mean that surficial landslides in particular are a hazard warranting consideration. The generally low density of development across the peninsula means that the risk is relatively low, but some damage has occurred historically. Residents and developers alike should be mindful that in many places on the peninsula, moderately to steeply sloping ground can generate relatively fast moving surficial landslides. Risks can be minimised by avoiding adverse modifications to slopes, and not discharging water into slopes. One practical way of improving the safety of existing buildings or other assets in potential landslide run-out zones is by planting a line of trees or a strong hedge to catch or deflect debris.

Otago Peninsula

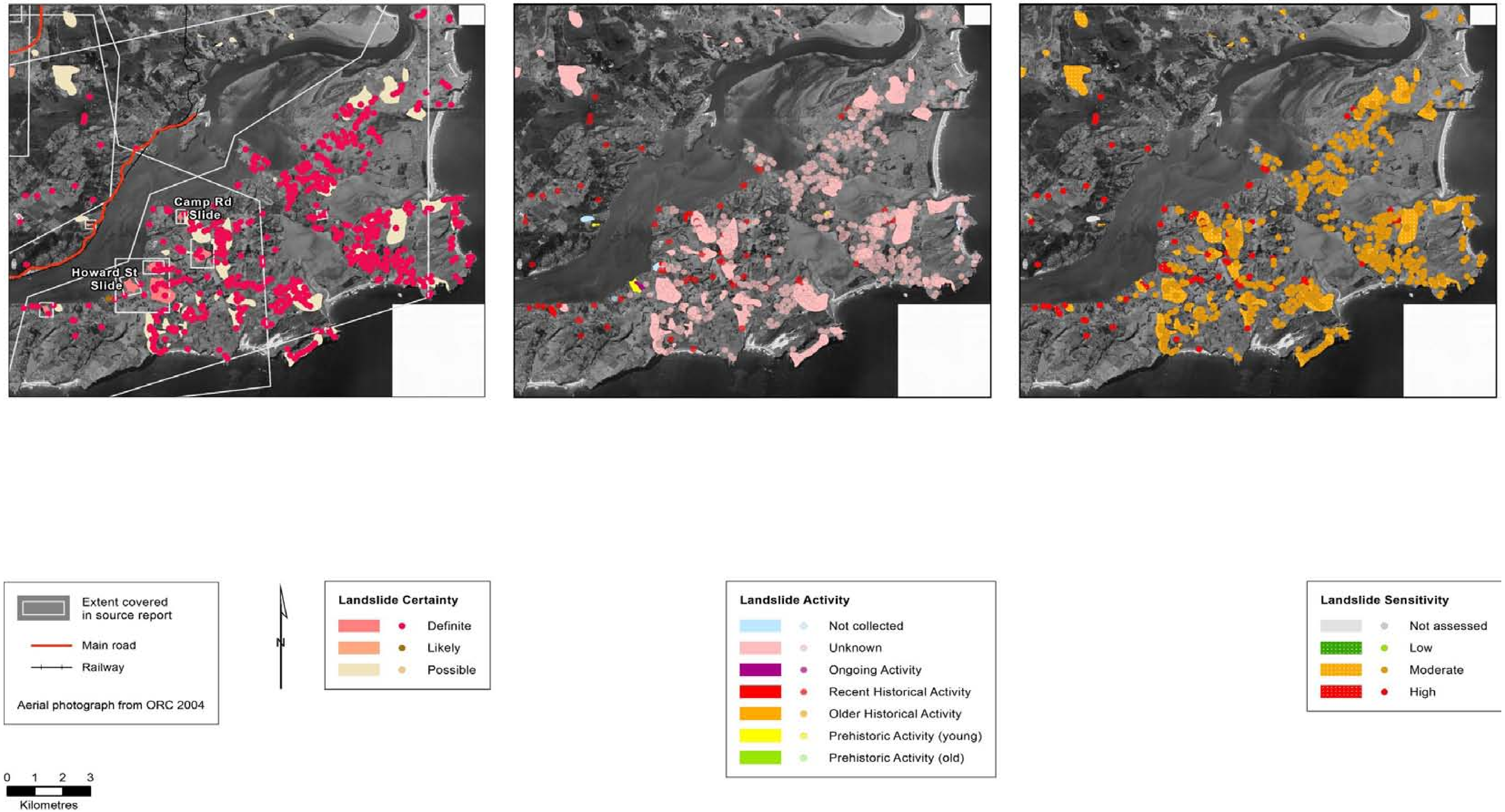

Figure 9 Otago Peninsula: Landslide Certainty, Activity, and Sensitivity.

Figure 10 During the March 1994 rainstorm, a small landslide occurred in the head of a minor gully about halfway up Mt Charles, near Papanui Inlet, Otago Peninsula. The landslide material was mobilised into a debris flow that proceeded rapidly down the gully, crossed Cape Saunders Road and broke through the front gate of a holiday house built in the gully. Debris piled up against the house, which was broken off its foundations by the weight of debris and carried downhill several tens of metres before ending up in the Inlet, as seen in this view, looking north-northeast. The boatshed to the left largely escaped damage. The minor gully down which the debris flow came normally carried a small creek that ran past the house. This photo illustrates the potential hazard of landslide movement inundating a property, even though the landslide was initiated a long way from the property. Photograph courtesy of Otago Daily Times Newspaper, Jane Dawber, March 1994.

Figure 11 A small surficial landslide from this road cut in Margate Ave, Broad Bay, resulted from the March 1994 rainstorm. Flow from the drain at the head of the slide may have contributed to the failure. However, the gabion wall to the left indicates that this slope has previously experienced instability, which the gabions were doubtless installed to remediate. This photo illustrates the potential hazard of landslide movement undermining a property. Photo: GNS Science, I.M. Turnbull, 20 March 1994.

Figure 12 Surficial landslides occurred above Portobello Road, between Challis and Glenfalloch, during the March 1994 rainstorm, and generated debris flows that ran downslope, crossed the road and accumulated in Otago Harbour. The photo was taken after the debris had been cleared off the road, although the debris remains evident on the foreshore (brown) and seabed (pale). Being one of only two access roads to Otago Peninsula, this photo illustrates the potential vulnerability of this key transport route for peninsula residents. Photo: GNS Science, D.L. Homer, CN32057b, 1 May 1994.

3.5 WARRINGTON TO KARITANE

About 50% of the Warrington and Karitane assessment area is mapped as landslide; those landslides classed as definite or likely comprise 41% of the assessment area (Table 6). Large areas of mass movement have been identified between Warrington and Karitane (Figure 14) and some have been documented in detailed drawings or reports (Benson 1940, 1946, McMillan and Reay 1983, Jacobson 1985, Johnson 1987, Glassey 1993b, Glassey 2006).

Most of the area that is underlain by Cretaceous-Cenozoic sedimentary rocks has been involved, since prehistoric times, in landslide movement, and in such areas it is difficult to find slopes that do not have the characteristic rumpled or irregular form of landslide terrain (Figure 13). These slides are predominantly earthflows, and historically, slow ongoing movement has been documented, notably where the landslides are crossed by State Highway 1, the Coastal Scenic Highway, and the South Island Main Trunk Railway, such as at the Puketeraki Landslide near Karitane (Lee Paterson, MWH, pers. comm.) and the Site Office Slide (Johnson 1987) and Hammonds landslide (Jacobson 1985) crossing State Highway 1.

At Puketeraki, the original railway tunnel across part of the slide had to be abandoned, as did the Truby King psychiatric hospital at Seacliff (Benson 1940, 1946). The Coastal Scenic Highway and South Island Main Truck railway are in places regularly being disturbed by slow landslide movement requiring a programme of on-going realignment. On State Highway 1, the Site Office Slide, and two smaller slides near Hammonds Hill have undergone major *remediation*, and experience little if any movement these days. Across the general area, future movements are likely to continue at the slow rates seen historically, and similarly disrupting infrastructure as has happened historically. There is no reason to expect any large-scale rapid reactivations, although this cannot be ruled out, especially along parts of the coast where the sea is actively eroding the toes of some of the landslides.

The majority of landslides in this area are considered to have high *sensitivity* to changes in stability factors.

3.6 WAIKOUAITI

All of the landslides in this area have been mapped using aerial photos. Although 37% of the assessment area comprises mapped landslides, those classified as definite or likely occupy only 12% of the overall area (Table 6). A large landslide that has been mapped across much of the Waikouaiti township area (Figure 15) was delineated during regional geological mapping in the 1990s on the basis of irregular topography. However, we consider it likely that this is not a landslide, and the topographic irregularities are more likely to be ancient, long-stabilised, sand dunes. It is retained in the dataset as a possible landslide, and even if it is a landslide, its subdued landform features suggest any past *activity* is older prehistoric and it is classified as having a low *sensitivity* to changes in stability factors.

The landslide at Cornish Head is classified as a definite landslide. Most of those landslides mapped on the slopes in farmland northwest of State Highway 1 north of Waikouaiti township are considered likely to be landslides, while others are classed as possible. There are a few definite small landslides within that area, but these are not differentiated in the database. These landslides are most likely bedrock landslides, developed in the Cretaceous-Cenozoic sedimentary rocks that underlie this area.

Young prehistoric activity is inferred for the slide at Cornish Head and a slide northwest of Waikouaiti. The slide at Cornish Head is considered highly sensitive to stability factors, due to sea erosion of the foot of the slope, while the rest of the landslides mapped in this assessment area are assigned a moderate to high *sensitivity*.

Figure 13 Typical earthflow 'hummocky" terrain Warrington to Karitane. Most of the land between the coast and the flat topped ridge is landslide. The Scenic Coast Road and the South Island Main Trunk railway cross the centre of photo (GNS Science, CN26986-03, Photographer, L. Homer).

3.7 DISCUSSION

There are several noteworthy aspects of the evaluation of landslide characteristics in the six assessment areas. The first is that across all six areas, landslides comprise between one-fifth and one-quarter of the overall land area (21%; Table 6). However, one-third of those landslides are classified as possible (Table 4), and thus it is somewhat uncertain as to whether they actually are landslides. Looking at just the landslides classed as definite and likely, they comprise only about one-eighth (13%) of the overall land area. Some effort to examine the possible landslides and try and refine whether some can be further differentiated to a status of likely or definite, or whether some can be discounted as landslides and removed from the database, would do much to clarify the landslide hazard.

Second, there is much variation in the distributions of landslide points, with Otago Peninsula standing out as having a much higher density than elsewhere. No doubt this is at least partly due to the peninsula having been studied in detail by Leslie (1974), whereas no comparably detailed study has been undertaken in the other assessment areas. It is notable, however, that the peninsula has relatively few large landslides, and leads us to suspect that this may reflect the predominance of volcanic rock, which is not particularly susceptible to instability. The good quality rock may have allowed relatively steep slopes to form over time. Those steeper slopes are in turn more susceptible to surficial landslide development. So we suspect that the relative stability of the peninsula in regard to large bedrock landslides goes naturally in hand with a greater propensity for surficial landslides.

Third, we see considerable value in further analysis of the landslide inventory data in regard to variables such as geology, slope angle and slope aspect, for example, to improve knowledge of key factors controlling slope instability from place to place in the Otago region.

Fourth, we consider that the conceptual differentiation of bedrock landslides from surficial landslides is a valuable tool, because they have different hazard implications. Bedrock landslides are mostly natural prehistoric features of the landscape, and while some remain active, and new ones may form, their triggering factors and behaviour are difficult to estimate. Surficial landslides are in contrast readily correlated to slope angle and thickness of surficial materials, and commonly form, or reactivate, in response to precipitation, or slope modification. Surficial landslides pose hazards that are relevant on a decadal timeframe.

In regard to the utilisation of the landslide database information, the *certainty* attributes in concert with the *sensitivity* attributes provide an indication of the degree of hazard. A landslide attributed as definite, with high *sensitivity* is of greatest concern for reactivation, whereas a likely landslide of low *sensitivity* is of relatively less concern. We consider that landslides classed as possible cannot justifiably be regarded as identified landslides. Only definite and likely landslides should be treated as identified landslides. In regard to risk reduction of landslide hazards, there remains no substitute for good geotechnical practice, such as avoiding existing landslide areas if possible, keeping slope modifications to a minimum, and not discharging stormwater or wastewater into the ground. It is highly desirable that geotechnical investigations take account of the wider engineering geological context and do not simply focus on the site being investigated and its immediate surrounds.

Warrington to Karitane coast

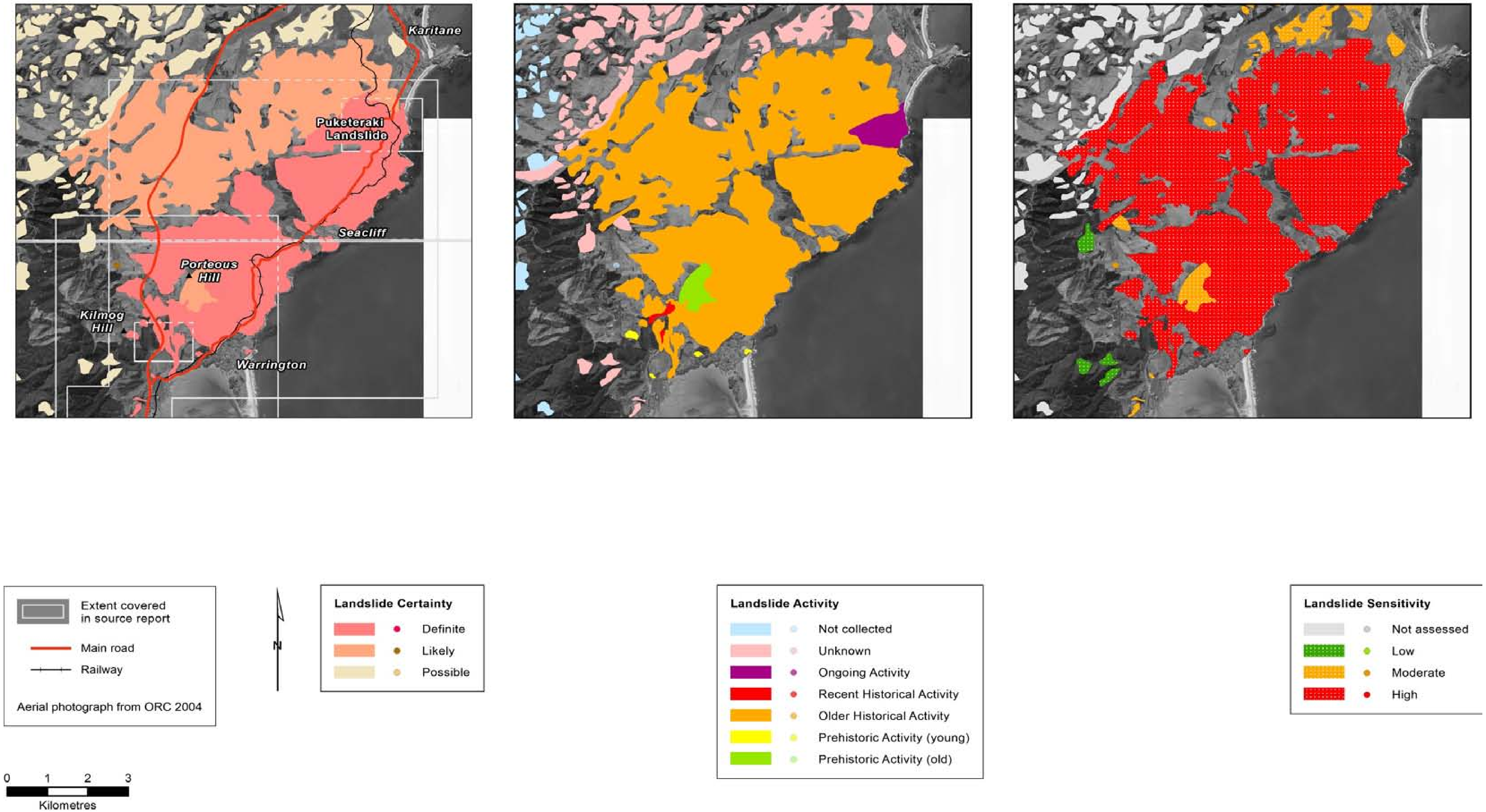

Figure 134 Warrington to Karitane: Landslide Certainty, Activity, and Sensitivity.

Waikouaiti

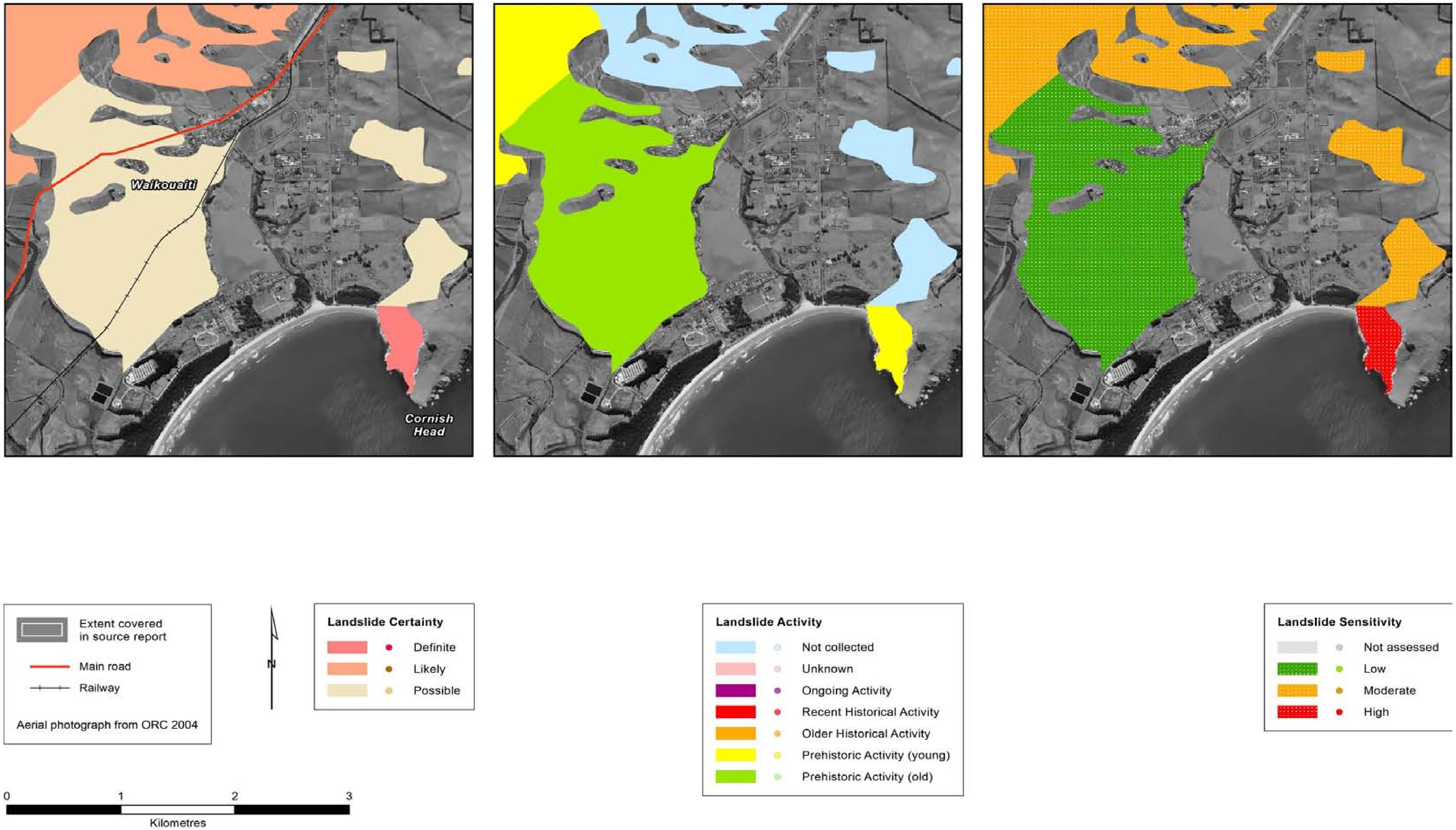

Figure 145 Waikouaiti: Landslide Certainty, Activity, and Sensitivity.

4.0 CONCLUSIONS

The Otago Regional Council landslide database is an inventory of known or suspected existing landslides, and includes a range of attributes that classify the characteristics of the landslides in various ways. This report has added further levels of classification that should help to give a better sense of the significance of the hazard that is posed by the landslides in a particular area. The new information categories describe the level of certainty that a feature has been correctly identified as a landslide, an improved classification of the age and degree of activity of a landslide, an indication of what level (if any) of stabilisation measures have been undertaken at a landslide, and how sensitive a landslide is likely to be to changes that could destabilise it. Although the database provides no direct information that could forecast when or where new landslides are likely to form, the distributions of existing landslides do highlight areas that have been particularly prone to instability in the past, and these are areas where future landsliding should come as no surprise.

Landslides in the Dunedin district, and elsewhere, can be segregated into bedrock landslides, which are developed in the underlying bedrock, and surficial landslides, which are developed in soils that mantle the bedrock. Bedrock landslides are typically large, deep-seated, and in most cases originated in prehistoric times. Bedrock landslides are most prevalent in areas underlain by Cretaceous-Cenozoic sedimentary rocks, notably in the Green Island to Saddle Hill area, and between Warrington and Karitane. Some have displayed recent activity, and their movement rates are typically slow. Because of their large size, and in many cases a lack of investigation to determine their stability condition and key factors driving movement, they are difficult to remediate economically, and any developments on them may require ongoing repairs.

Surficial landslides are developed in soils such as loess, colluvium or extremely weathered zones on top of the bedrock. They typically occur where the surficial materials are thicker than about 1 m, and the slope is steeper than about 12 degrees. They occur in many places and settings throughout much of Otago. They are commonly triggered during heavy or prolonged rainfall, and can move at moderate or rapid rates. Where the debris becomes waterlogged, it can mobilise into potentially damaging debris flows that can flow surprisingly long distances down gullies or small valleys. Locations where surficial landslides could develop are relatively predictable from geological and topographic considerations, and provides a heads-up to the potential hazard, that can guide existing land-use practices, and future developments, in ways that minimise exposure to surficial landslide hazards.

Landslide movement occurs when the forces driving material downslope are greater than those forces that work to resist downslope movement. Existing landslide areas should in the first instance be assumed to be only marginally stable, and relatively small modifications to the slope, or to groundwater conditions, could reactivate instability. Smaller landslides tend to require less change to get them mobilised again than do larger landslides, especially if some of the causative factors no longer exist (e.g. erosion at the toe has ceased). In general, renewed activity of existing landslides in the Dunedin area tends to occur as small periodic movements, often during prolonged or intense rainfall or erosion at the toe of the slide.

There remains no substitute for good geotechnical practice, such as avoiding hazardous areas where if possible, minimising slope modifications, and not discharging water into the ground. Geotechnical investigations should also take account of the wider geological context.

5.0 ACKNOWLEDGEMENTS

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GLOSSARY

Bedrock: A general term for the rock, usually solid, that underlies soil or other unconsolidated, superficial material.

Soil (Engineering): All unconsolidated materials above bedrock.

Loess: A silt deposit formed from wind-blown dust.

Colluvium: A general term for loose or poorly consolidated sandy, silty and gravelly sediments deposited on hill slopes, derived from erosion of bedrock farther upslope.

Regolith: A general term for the mantle of fragmental and unconsolidated material, whether residual or transported and of highly varied character, that overlies bedrock