Figure 7 Lateral spreading and damage to bridge abutments as a result of liquefaction, Christchurch, February 2011. Photo: R.D. Beetham, GNS Science.

Figure 8 Damage to Hillside Road, Manapouri, Southland, resulting from the 2003 Fiordland earthquake. The road is raised on an embankment. Disaggregation of the embankment fill by ground shaking has caused a lateral spreading failure of the margins of the embankment. The existence of the embankment reflects the soft and saturated nature of the ground here, which probably exacerbated the earthquake shaking and consequential damage to the road. Photo: R Cook.

Figure 9 Damage to underground services as a result of liquefaction, Christchurch 2011.

3.2 THRESHOLDS FOR THE OCCURRENCE OF LIQUEFACTION

Because liquefaction is caused by overpressuring of pore water within a sediment, it can be caused by a variety of factors (e.g., Ishihara 1985; NRC 1985; Youd et al., 2001; Orense 2010), but the most common triggering mechanism is vibrations from strong earthquakes. Figure 10 shows relationships between the distance from the source of an earthquake of a particular magnitude and the occurrence of liquefaction. Although factors other than earthquake magnitude are known to be important, such as the frequency of the earthquake waves and the duration of shaking (Obermeier et al., 2005), magnitude and distance are simple and easily measured parameters. This diagram highlights that susceptible sediments may liquefy in response to a moderate earthquake centred nearby, or a larger earthquake centred farther away.

The Modified Mercalli Scale Intensity (MM) is a measure of the strength of ground shaking at a particular location. It is directly related to the earthquake magnitude, the distance from the hypocentre, and the strength of the ground at that location. An intensity of MM VII or greater is typically necessary in order for liquefaction to occur. Actual conditions at a particular location, including the nature and sensitivity of the sediments to vibrations, and the depth to groundwater, will greatly influence whether liquefaction occurs, and its severity.

Instrumental measurements of ground shaking by seismometers show that liquefaction generally becomes evident at a peak ground acceleration (PGA) of 0.25 g or more (1 g is the acceleration due to the force of gravity). Cubrinovski & McCahon (2011) reported that severe liquefaction occurred in Christchurch at PGA of about 0.5 g or more. A more detailed study by Quigley et al. (2013) found that in areas of highly susceptible materials in eastern Christchurch, slight liquefaction became evident at PGA of 0.057 g and that more extensive liquefaction became apparent at PGA of more than about 0.2 g.

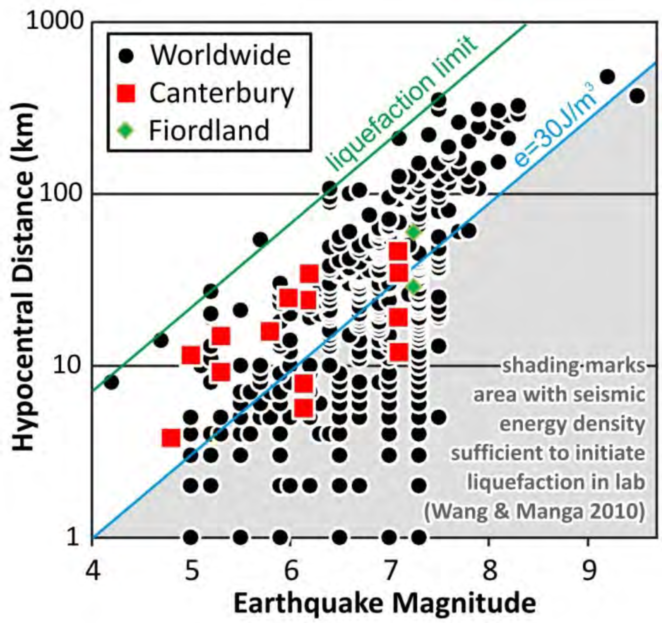

Figure 10 Relationship between the straight-line (hypocentral) distance from the sources of earthquakes of different magnitudes and occurrences of liquefaction. It shows that a M5 earthquake is about the smallest that can generate liquefaction, and only within 10 km or so of the earthquake hypocentre (see Appendix 1). In contrast, a M7 earthquake can generate liquefaction up to as much as 100 km or so from the hypocentre. The plot includes data from the 2010–2011 Canterbury earthquake sequence and the 2003 Fiordland earthquake. Diagram adapted from Wang & Manga (2010).

3.3 LIQUEFACTION IN THE DUNEDIN DISTRICT

There have been no recorded instances of liquefaction in Otago since at least the mid-1800s, when European settlement and written record-keeping began (Murashev & Davey 2005). No liquefaction was reported during the 1974 M 4.9 Dunedin Earthquake (Bishop 1974). That shallow earthquake was centred about 10 km from the city centre, and maximum shaking intensity in South Dunedin was locally as much as MM VII (Murashev & Davey 2005). At that time, there were only two seismometers in Dunedin that could measure ground accelerations. The accelerometer situated at the St Clair telephone exchange recorded a PGA of 0.27 g, while the one at Dunedin Central Post Office recorded 0.12 g (Bishop 1974). The lack of identified liquefaction suggests that the sediments beneath South Dunedin are not as susceptible to liquefaction as those in the most liquefaction-senstive areas of eastern Christchurch. Nonetheless, it is likely that the ground shaking in South Dunedin during the Dunedin Earthquake was close to the threshold for the onset of liquefaction.

3.4 THE IMPORTANCE OF GROUNDWATER

The depth to the groundwater table is fundamentally important in the occurrence of liquefaction, because liquefaction can only occur in water-saturated materials. An upper layer of material that is non-liquefiable, either because it is above the water table, or is a non-liquefiable material such as gravel or clay, has a protective effect. The upper layer (or 'crust') can suppress the ejection of liquefied material to the ground surface, or can influence the extent of ground damage. Studies by Ishihara (1985) and Youd & Garris (1995) showed that where a substantial thickness of liquefiable material exists at depth, the presence of a non-liquefying crust extending to between 3 and 8 m depth prevents subsurface liquefied material from being ejected at the ground surface. The depth of that threshold depends on the degree of shaking and total thickness of liquefying layers below. Generally speaking, the likelihood of liquefaction-related damage decreases as the depth to groundwater increases.

There is good knowledge of groundwater levels and their fluctuations in Canterbury on account of a dense network of monitoring wells and hundreds of piezometers installed by the Earthquake Commission (EQC), Environment Canterbury and Christchurch City Council (van Ballegooy et al., 2013). The distribution of liquefaction and/or consequential damage that occurred during the 2010–2011 Canterbury earthquakes has been mapped in detail (Brackley 2012; Tonkin & Taylor 2012). Comparison with depths to groundwater highlights that liquefaction was almost entirely restricted to areas where the unconfined groundwater table was shallower than 5 m, and was most prevalent where depth to groundwater was less than 3 m (Tonkin & Taylor 2012; van Ballegooy et al., 2013).

It has been suggested that the Christchurch situation was exacerbated by the presence and release of artesian groundwater pressure (Cox et al., 2012; Gulley et al., 2013), and this is a topic of ongoing research.

4.0 LIQUEFACTION HAZARD ASSESSMENT

4.1 ASSESSMENT METHODS

There are different approaches to assessing liquefaction hazard. A common goal is to establish the liquefaction susceptibility of the subsurface. Liquefaction susceptibility is a term that relates to the physical state of materials, in regard to whether they have the “ability” (suitable physical characteristics) to liquefy. Assessing liquefaction susceptibility requires information on the nature of the soil materials, and their degree of water saturation.

The extent to which liquefaction susceptibility can be classified depends on whether the assessment is site-specific for a particular structure or is a more generalised assessment that is intended primarily to aid regional-scale land use planning and hazard minimisation. Site-specific assessments generally require geotechnical investigations (see Appendix 1) and collection of subsurface information from test pits, probes or bore holes. General assessments are usually office-based and draw upon existing information from geological maps, soil maps, landform maps, groundwater level measurements, and bore hole records where available.

Where there is a sufficient level of geotechnical and other relevant data, such as the observed effects of damaging previous earthquakes, more quantitative general assessments can be attempted. One example is the delineation of Technical Category areas (TC1, TC2, TC3) that was undertaken for parts of the Christchurch urban area (see Appendix 1). Particularly important for such assessments are sediment strength measurements from Standard Penetration Tests (SPT) or Cone Penetrometer Tests (CPT). A number of specific indices relating to the liquefaction susceptibility of the ground can be calculated from SPT and CPT data, such as Cyclic Resistance Ratio (CRR), Liquefaction Severity Index (LSI), or Effective Stress Analysis (e.g., Seed & Idriss 1971; Iwasaki et al., 1978; Youd & Perkins 1987; Robertson & Wride 1998; Youd et al., 2001). Liquefaction Severity Number (LSN) is a new index developed following the Canterbury earthquakes to assess liquefaction induced vulnerability (Tonkin & Taylor 2012).

The assessment of lateral spreading hazards is generally based on observations of damage from other earthquakes (e.g., Hamada et al., 1986; Youd et al., 2002). The assessment of lateral spreading requires information not only on the ground strength and liquefaction susceptibility, but also on the form, nature and height of nearby ‘free-faces’ (e.g., a river bank). This necessitates complex analytical modelling. One rule of thumb is that lateral spreading can occur at a horizontal distance 20 times the channel depth, or height of the free face. Unfortunately, this is possible only at site-specific scales, and is well beyond the scope of a general assessment, because there are few reliable measurements of channel depths from regional scale data, such as topographic map contours. Furthermore, lateral spreading can occur in association with former channel edges that have been buried by younger sediment and are therefore hidden from view. Areas that are assessed as having liquefaction susceptibility should also be considered to have lateral spreading susceptibility in areas close to free-faces. Where features such as embankments are built on weak ground, failures akin to lateral spreading can occur (see Figure 8). The degree of this hazard is influenced by the cohesiveness of the material forming the embankment. For example, an evaluation of the stability of the floodbanks of the Taieri Plain included some quantification of the materials from which they are constructed (Tonkin & Taylor 2005). This sort of information could be used to aid more detailed assessment of flood bank stability under earthquake shaking.

As far as the authors of this report are aware, there has only been limited geotechnical testing undertaken in the Dunedin district, and no general collation of geotechnical data exists. Instead this project takes a commonly-adopted approach of using subsurface lithological and groundwater information where available, together with geological and geomorphological criteria to provide a regional overview of those areas that may be susceptible to liquefaction.

4.2 ASSESSING LIQUEFACTION HAZARD – THIS PROJECT

4.2.1 Geomorphological-based approach

The form and origin of the ground surface (geomorphology) generally reflects the nature of underlying geological materials, whether solid rock or a variety of poorly consolidated or loose sediments. Although records from the drilling of water bores, geotechnical probes or excavations provide direct information on subsurface materials, each of these points of information may lie a considerable distance apart. Thus, geomorphologic information provides an area-wide, general indication of what lies beneath the near-surface, e.g., within 10 m or so of the ground surface, as well as providing insights into the processes such as erosion and deposition that have shaped the ground surface.

The nature of soils developed on the landforms is an expression of the underlying near-surface geological materials (growRural Dunedin). Furthermore, the maturity of soils is a function of the age of the landform, and the activity of processes that may modify landform surfaces. Soil maps are based on intensive field surveys, and have been an important resource used to aid the geomorphologically-based mapping in this report.

A key aim of the geomorphological approach, in concert with geological information, is to define the extent of areas that were flooded at the culmination of the post-glacial sea level rise (Section 2), and have subsequently been filled in by the accumulation of young marine or estuarine sediments that are commonly susceptible to liquefaction.

4.2.2 Liquefaction hazard assessment methodology

The liquefaction hazard evaluation reported here is a regional-scale susceptibility assessment, using a methodology similar to that applied in eastern Canterbury (Brackley 2012). It differs from a full susceptibility assessment, which would require detailed information on the geotechnical properties of near-surface sediments. Therefore, the focus of this project has been on identifying areas that, from geological and geomorphological considerations, are likely to be underlain, at least in part, by the types of sediments that are liquefaction-susceptible, and where groundwater levels are sufficiently close to the surface to make liquefaction a possibility. For that reason, the areas shown on the maps and contained in the accompanying GIS dataset (Appendix 4) are described as 'liquefaction susceptibility domains'. The mapping does not identify hazard zones as such, but rather identifies **areas where there may be the possibility of a liquefaction hazard**.

4.2.3 Liquefaction susceptibility domains

The domains identified on the maps accompanying this report are:

- **Domain A**. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring;
- **Domain B**. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B;
- **Domain C**. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

What the domains mean:

Domain A:

- The geological nature of the ground is such that future earthquakes are unlikely to cause land damage from liquefaction;
- Other geohazards are likely to be more dominant, if present at all (see Appendix 1);
- The land in this domain would most likely be classified as TC1 were it to be assessed using the TC methodology (see Appendix 1).

Domains B and C:

- The geological nature of the ground is such that future earthquakes may possibly cause land damage from liquefaction;
- There is no information on the extents of potentially liquefiable ground within these areas. Our assessment is that areas mapped as Domain B have a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the area. Domain C is estimated to have a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the area;
- Collectively, Domains B and C represent what may be termed 'liquefaction awareness areas'.
- It is likely that within both Domain B and Domain C, some land would be classified as TC1, and some land would be classified as TC2 or TC3, were it to be assessed using the TC methodology (see Appendix 1).
- A salient objective for future planning and hazard minimisation should be to undertake reconnaissance geotechnical testing of the areas mapped as Domain C in particular to establish the presence or otherwise of potentially liquefiable materials, and if present, their general pattern of distribution.

4.2.4 Mapping procedure and limitations

Liquefaction susceptibility domains have been mapped based on the information sources listed in Section 1.3. The weighting of the various components of geological, geomorphological and hydrological information used to map the extent of domains is indicated in Section 5 and Appendix 3.

Lithological and groundwater information from bore holes, where available, was then examined. International historic experience suggests that liquefaction that results in ground surface deformation due to water and sediment ejection, subsidence or lateral spreading, is related to subsurface materials within 10 m or so of the ground surface. In considering bore hole lithological information, the choice was made to focus only on the interval down to 10 m depth.

Groundwater information is quite sparse in the Dunedin district compared, for example, to the Canterbury Plains. Furthermore, the groundwater surveys that have been undertaken in the district tend to have focused on deeper boreholes/water-supply aquifers, rather than the shallow water table (Hanson 1997; Irricon & Royds Consulting 1994; Rekker & Houlbrooke 2010). In the first instance, places where depth to groundwater is known or suspected to be less than 6 m were considered of interest for reviewing liquefaction susceptibility. This threshold of 6 m is conservative given the less than 3 m depth to groundwater predominantly associated with liquefaction occurrence in Christchurch, but allows for possibilities of greater shaking, differences in ground strength, and greater uncertainties in the Dunedin district groundwater data.

Finally, based on all these considerations, the domain boundaries were drawn. In areas of lidar coverage, high-resolution digital elevation models generated from the lidar data were used for precise elevation control to aid in the positioning of the domain boundaries. This is because in many instances, a specific elevation above sea level was used to define the placement of domain boundaries.

The accuracy of the mapping of boundaries between domains needed to be considered in two ways. First, the positioning of a boundary between domains, as described in Appendix 3 for each area, is considered to be accurate to plus or minus 50 m. In other words, even though the boundary line, when viewed in the GIS dataset, is placed at an exact location, that boundary line should be treated as being 100 m wide, centred on the exact location where the line is drawn.

Second, it is important to appreciate that there is considerable uncertainty in the exact nature of the subsurface sediments whose character defines the extent of Domain B and C. The mapped extents of each domain represent best estimates based on the interpretation of geological and gemorphological information, but the uncertainties are difficult to quantify from available data. For this reason, it is important that the GIS map of liquefaction susceptibility domains be seen only as providing general guidance for planning and development. In particular, the dataset should not be used in isolation for any purpose that requires site-specific information.

5.0 DESCRIPTION OF THE AREAS MAPPED

A district-wide overview of the liquefaction susceptibility mapping is provided in Figure 11. Most of the district is underlain by basement schist or cover rocks (see Section 2), which have no possibility of being liquefied. Only areas of Quaternary sediments have any potential for liquefaction. There is no prospect of widespread damaging liquefaction where those sediments are dominated by gravel or groundwater levels are not close to the ground surface. Note, however, that the district-wide geological information is from QMAP (see Section 1.3), and is therefore highly generalised. Considerable localised variability exists within the Quaternary sediments, and there may well be patches of soft sediments within areas mapped as gravel-dominated Quaternary sediments. Those areas mapped as basement or cover rocks may also have localised accumulations of soft sediments, on the floors of stream valleys for example, that were too small to be shown on QMAP. Domain A is therefore characterised as having little or no potential for damaging liquefaction. One cannot, however, rule out the possible existence of localised pockets of liquefaction-susceptible sediments that may warrant consideration in regard to liquefaction at site-specific scales.

Domain C encompasses those areas that were flooded by the sea during the post-glacial sea level rise, and therefore are underlain by young marine or estuarine sediments. These areas typically have shallow groundwater. It is, however, by no means certain that all of the sediments in areas mapped as Domain C may be susceptible to liquefaction. For example, they may include substantial areas underlain by gravelly material that is not liquefiable. Domain C is therefore categorised as having a moderate to high likelihood of containing some areas of liquefaction-susceptible sediments, but the presence and location of such sediments can only be confirmed by specifically designed geotechnical investigations.

Domain B encompasses areas underlain by accumulations of river or stream sediments adjacent to the shoreline at the culmination of the post-glacial sea level rise. Domain B also includes other areas where there may be extensive sandy or silty river sediments with shallow groundwater. Similarly to Domain C, it is uncertain to whether, and to what extent, the sediments in areas mapped as Domain B may be susceptible to liquefaction. Domain B is categorised as having a low to moderate likelihood of saturated, liquefaction-susceptible sediments being present in some parts of each area mapped as Domain B. However, as with Domain C, further investigation would be needed to establish whether or not this is the case at specific localities.

The remainder of this section contains a general description of the liquefaction awareness areas (Domain B or C) that have been mapped in the Dunedin district. Appendix 3 contains detailed description of the criteria used for defining the mapped limits of Domains B and C in each of the areas discussed below.

5.1 DUNEDIN URBAN AREA

Two main areas in the general vicinity of the Dunedin urban area may be susceptible to liquefaction (Figure 12). One is the South Dunedin coastal plain, the other is Kaikorai Lagoon and the lower reaches of the valleys of Abbotts Creek and Kaikorai Stream (Appendix 3).

The area referred to here as the South Dunedin coastal plain includes all low-lying areas up to the edges of the hills, and the lowest reaches of the Water of Leith valley. Included are extensive areas of reclaimed land around the margin of the harbour north to Ravensbourne.

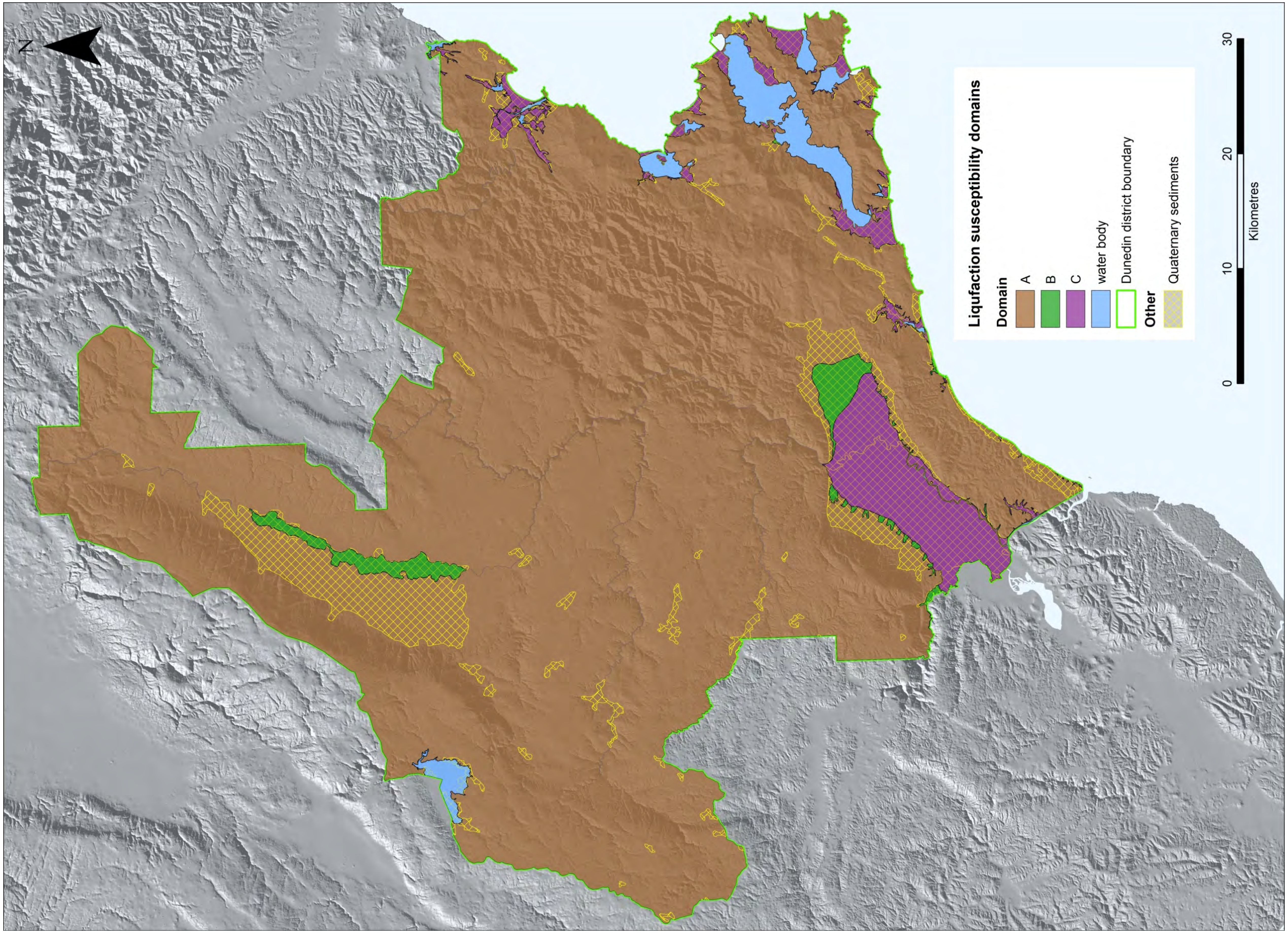

Figure 11 Overview map of liquefaction susceptibility domains for the Dunedin district.

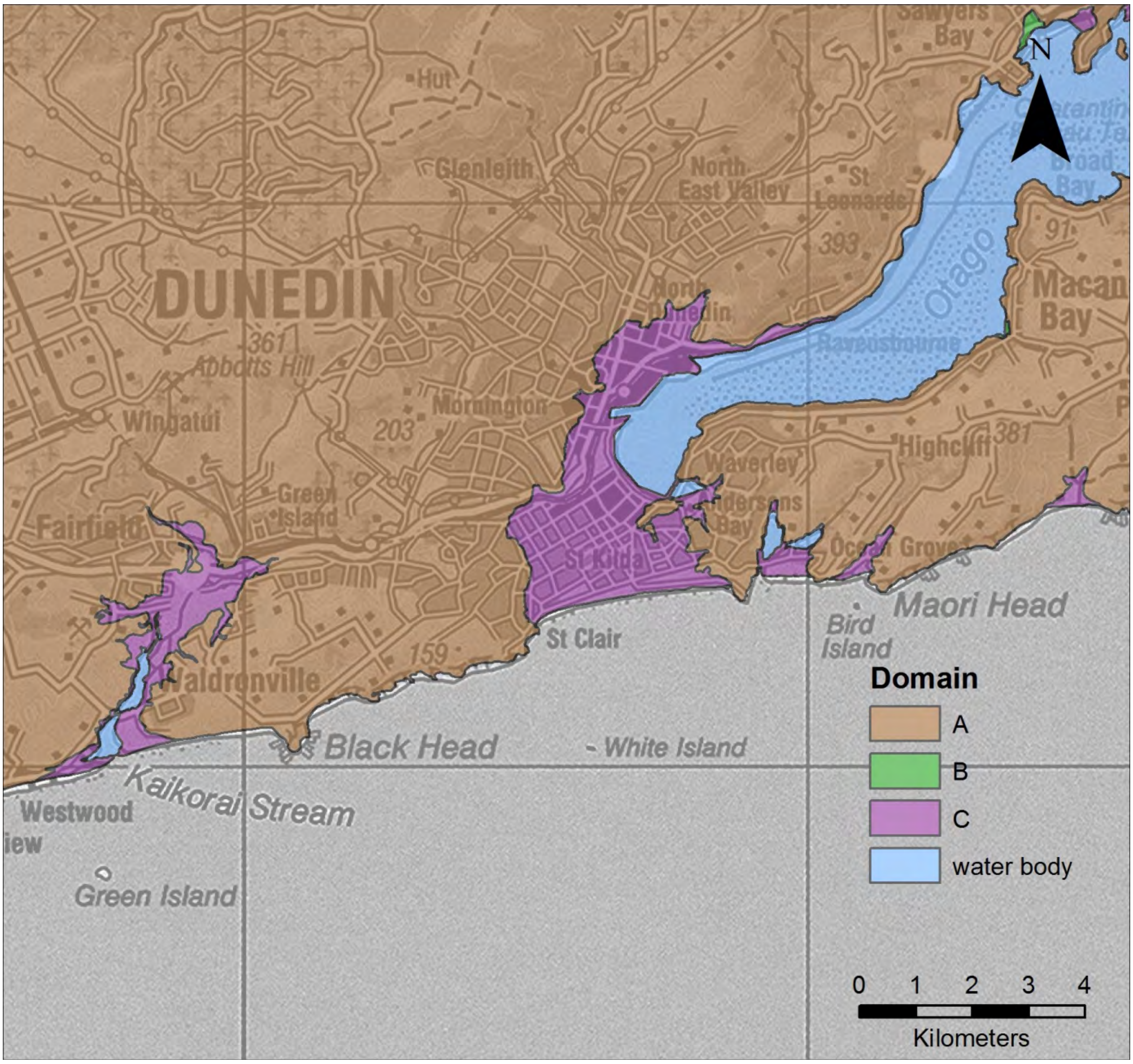

Figure 12 Map of liquefaction susceptibility domains for the Dunedin urban area.

At the culmination of post-glacial sea level rise, the peninsula was an island, separated from the mainland by an ocean passage (now Otago Harbour) that extended from St Clair – St Kilda through to Aramoana. Evidence for this is provided by the relict cliffs cut at the base of the hills at Tainui and Andersons Bay, including the cliffs around the Sunshine hill (Appendix 3). The size and abruptness of these cliffs suggest they were, for some time, subjected to powerful wave action, prior to formation of the St Clair – St Kilda dune barrier. After that barrier formed, fine sediments accumulated in the sheltered water at the head of the harbour, eventually forming the South Dunedin coastal plain. A consequence of the relatively high hills forming the inner margin of the coastal plain from St Clair, through Caversham and around to the Water of Leith is that minor streams and gullies draining from hills have constructed sizeable aprons of alluvial fan sediments out onto the coastal plain.

Extensive fine-grained sediment in combination with a very shallow water table is the reason that this area has been classified as Domain C. It would useful to clarify the extent and degree to which these sediments have material properties, including strength and density, which would make them susceptible to liquefaction. Given the intensive urban and industrial infrastructure in this part of Dunedin, further assessment, including collation of existing geotechnical data, would enable a better appreciation of liquefaction hazards in this area.

5.2 TAIERI PLAIN

The Taieri Plain is a low-lying basin containing extensive development, including the urban settlements of Mosgiel and Outram, and Dunedin International Airport. Much of the basin was flooded as a result of the post-glacial sea level rise, and following its culmination, an extensive marine inlet formed, and has progressively been infilled by sediment, largely carried in by the Taieri River. Much of this sediment is fine-grained, and known as the Waihola silt/sand (Barrell et al., 1999; Litchfield et al., 2002). The area underlain by Waihola silt/sand has been assigned a Domain C classification, and so the approximate extent of this deposit is denoted by the extent of Domain C on the Taieri Plain shown in Figures 11 and 13. In addition, Silver Stream has constructed an alluvial plain that extends southwest over the Waihola silt/sand, and the numerous minor streams that drain into the basin have formed alluvial fans at the margins of the alluvial plain (Barrell et al., 1999; O'Sullivan et al., 2013; Barrell 2014). The lower reaches of the Silver Stream alluvial plain, including the downstream portions of adjacent fans, have been mapped as Domain B (Figures 11 and 13).

5.3 STRATH TAIERI PLAIN

The Strath Taieri Plain lies in a basin on the southeastern side of the Rock and Pillar Range (Figure 14). The Taieri River flows in a broad valley, flanked to the northwest by remnants of old river terraces, underlain by weathered gravel, and an array of alluvium formed by streams draining from the Rock and Pillar Range. Much of the alluvium is gravelly, but the modern valley of the Taieri River has developed a meandering course in places, and these areas of meander channels/bars may potentially include substantial accumulations of sandy or silty sediments, and the groundwater table is likely to be close to the ground surface. Accordingly, Domain B has been mapped in the incised valley of the Taieri River (Figure 14). Specific geotechnical work would be needed to determine the existence, extent, and sensitivity of liquefaction-susceptible sediments, if any, throughout this area.

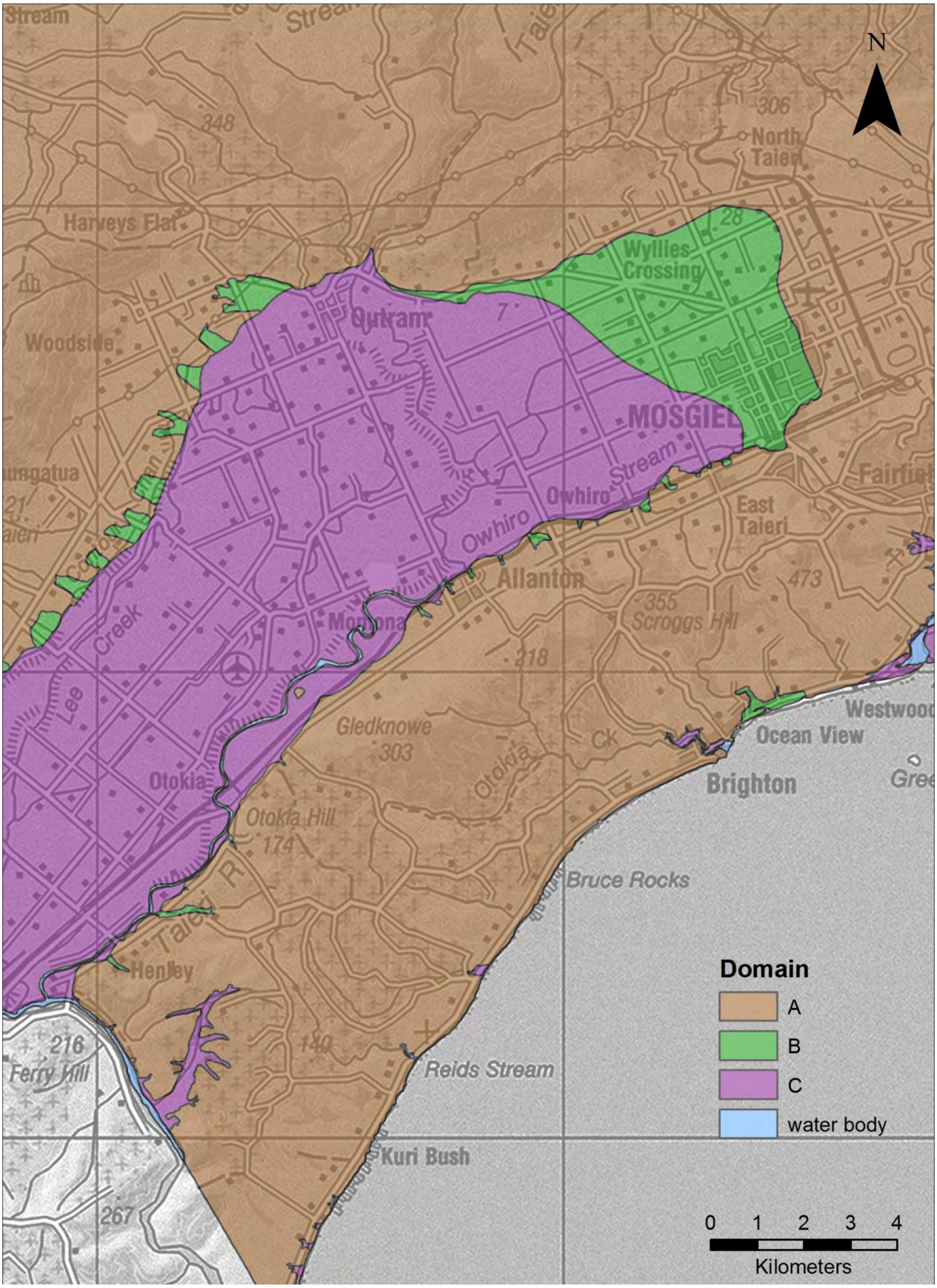

Figure 13 Map of liquefaction susceptibility domains for the northeastern part of the Taieri Plain.

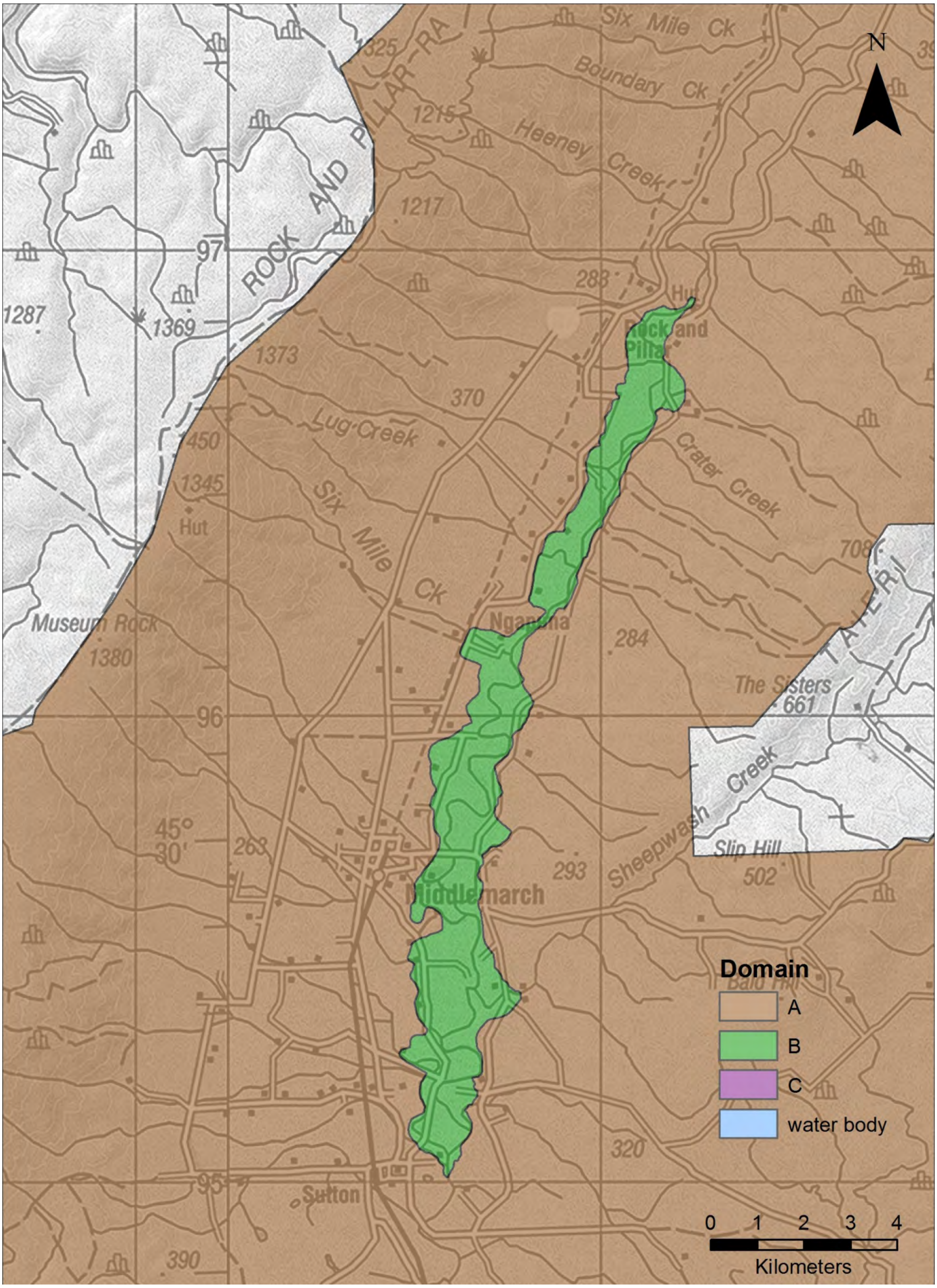

Figure 14 Map of liquefaction susceptibility domains for the Strath Taieri Plain.

5.4 COASTAL AREAS

5.4.1 Taieri Mouth to Waldronville

From Taieri Mouth to Brighton, the coastline is marked by a post-glacial cliff that is cut into the seaward edge of a narrow terrace. That terrace, typically 100 to 200 m wide and standing several metres above sea level, marks an old shore platform cut by wave action during the last interglacial period, about 125,000 years ago. This 'marine terrace' is underlain by schist bedrock, with a thin cover of weathered gravel, and silt. The larger streams draining from the coastal hills have cut small valleys where they cross the marine terrace. These valleys were flooded during the post-glacial sea level rise, and are likely to contain saturated, poorly consolidated sediments. In a few places, there are dune barriers enclosing these valleys. Northeast of Brighton, the marine terrace is not evident, and the coastal fringe is largely obscured by dunes. Minor streams have constructed alluvial fans over the marine terrace, but are scarcely, if at all, incised into it. All these areas are included in Domain A. Localised areas of Domains B or C are mapped in the lower reaches of the larger streams (see Figure 13).

5.4.2 Otago Harbour and Otago Peninsula

The western side of Otago Harbour and all of the Otago Peninsula is hill terrain formed on cover rocks, predominantly volcanic. The post-glacial sea level rise drowned the broad stream valleys now occupied by Otago Harbour, plus the broad embayments of Hooper Inlet and Papanui Inlet (Figure 15). All drainage comprises relatively minor streams. The streams draining to the harbour have steep courses, and post-glacial sea level rise caused minimal inundation of their lower reaches. On the eastern side of the peninsula, the stream valleys are gentler, probably because they were graded onto the coastal plain now occupied by the continental shelf. Their lower reaches were more affected by inundation by the sea level rise. For example, the Tomahawk Lagoons are former bays within drowned stream valleys, which became lagoons when the sand dune barrier was formed across their mouths. Sand accumulations are substantial on the eastern side of the peninsula, and near the northeastern end of Otago Harbour. Domain C is mapped on the sand flats and in valleys enclosed by dune barriers, and includes reclaimed land at Port Chalmers. A localised area of Domain B is mapped at Sawyers Bay.

5.4.3 Aramoana to Warrington

In this area, hilly terrain is drained by several broad valleys, whose lower reaches form coastal plains enclosed by dune barriers. Purakaunui Inlet and Blueskin Bay are substantial embayments of the sea that have so far escaped being filled in with sediment. Sand flats, dunefields and the lower reaches of valleys draining to the embayments are mapped as Domain C (Figure 15).

5.4.4 Karitane and Waikouaiti

The lower reaches of the Waikouaiti valley and its tributaries, as well as the lower reaches of Pleasant River, were drowned by post-glacial sea level rise, and as a result there are extensive low-lying areas with groundwater close to the ground surfaces, and a significant likelihood of young marine and estuarine sediments in the subsurface. These areas are mapped as Domain C (Figure 16).

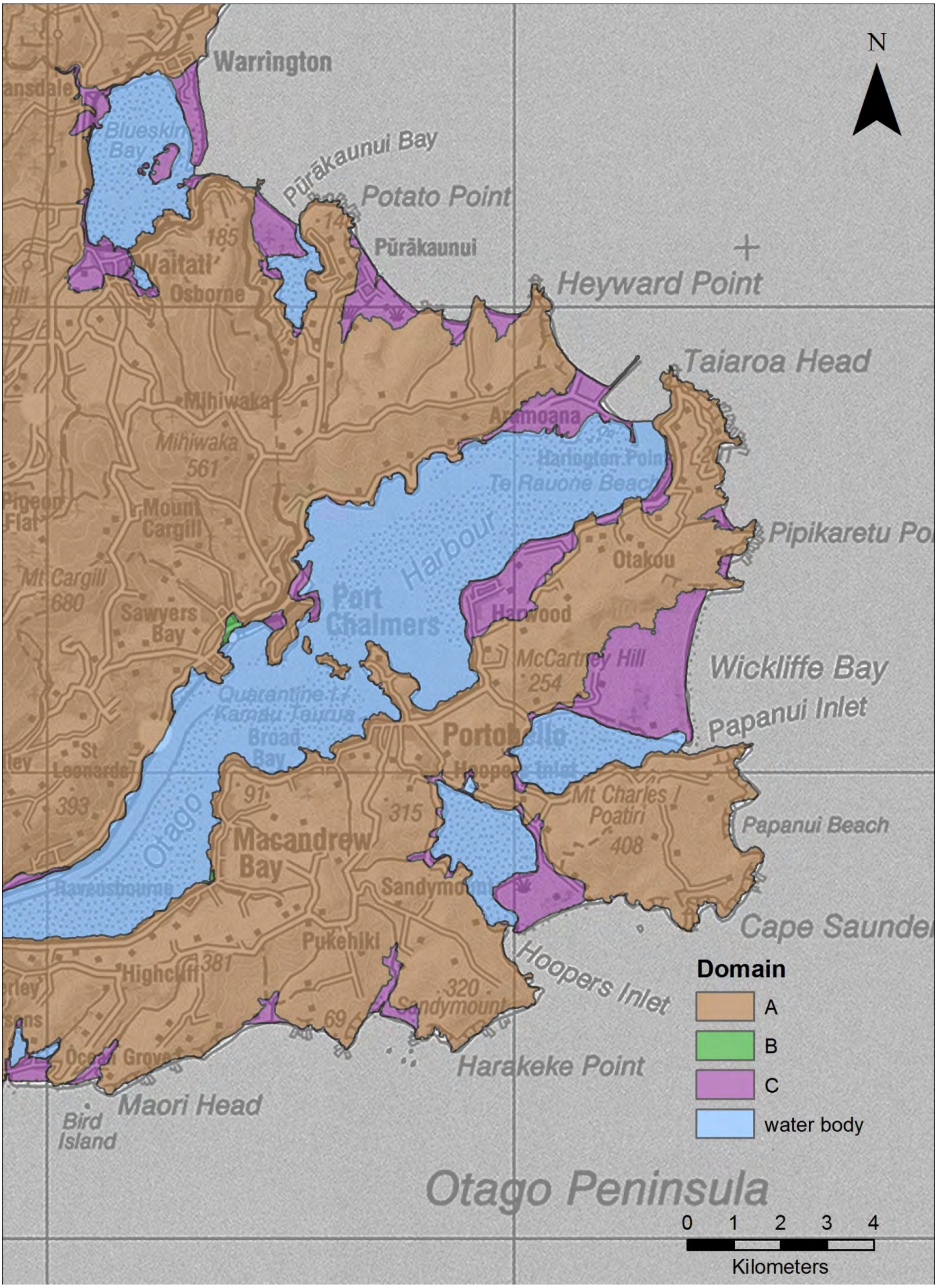

Figure 15 Map of liquefaction susceptibility domains from Otago Peninsula north to Warrington.

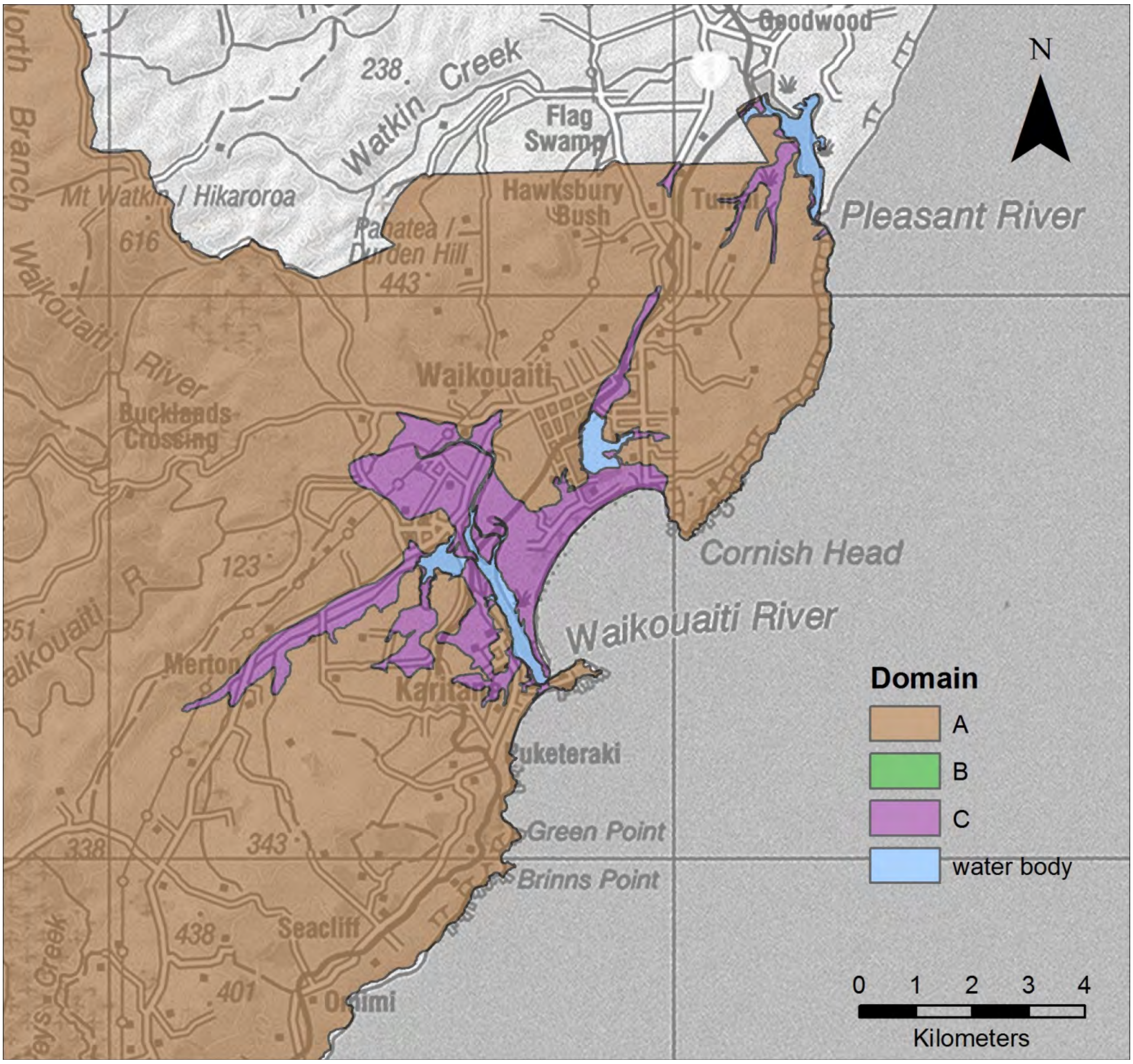

Figure 16 Map of liquefaction susceptibility domains near Karitane and Waikouaiti.

6.0 OVERALL ASSESSMENT

This project has involved an evaluation of information relevant for assessing liquefaction hazards. Being largely office-based, drawing heavily upon regional-scale geological, geomorphological and hydrological information, and not accompanied by subsurface site investigations, the assessment is highly generalised. The information available has been sufficient for the delineation of a three-fold classification of liquefaction susceptibility. These liquefaction susceptibility domains distinguish areas where the geological conditions afford little or no possibility of damaging liquefaction occurring (Domain A), areas with a low to moderate likelihood of being underlain, in part, by liquefiable materials (Domain B), and areas with a moderate to high likelihood of being underlain, in part, by liquefiable materials (Domain C). The uncertainties attending a district-wide evaluation, such as this project, have been highlighted by designating Domain B and C as 'liquefaction awareness areas'. These are not regarded as hazard zones, because the extent and degree of hazard, if any, is yet to be established. As explained in Appendix 1, there is no easy way to relate the domains mapped in this report with the Technical Category classification of green zone land in eastern Canterbury, because the mapping of Technical Categories is based to a considerable degree on the observed effects of damaging earthquakes in Canterbury. Nevertheless, it is likely that Domain 1 land is equivalent to TC1 land, but the extent to which Domain B and C could be differentiated into TC1, TC2 or TC3 equivalents is unknown.

By way of summary, only 12% of the land area of the Dunedin district is underlain by Quaternary sediments, and only some of which will be susceptible to liquefaction. In regard to the liquefaction susceptibility domains, 91% of the district is mapped as Domain A, 1.4% is Domain B, 4.9% is Domain C, and 2.3% comprises large water bodies, including lakes, Otago Harbour and the main bays and inlets. If one compares the overall susceptibility classification map of the Dunedin district (Figure 11) with the liquefaction susceptibility maps presented by Murashev & Davey (2005) (see Appendix 2 – their Maps 20 and 21), they also present a 3-fold classification. The main difference is that their intermediate zone ('low susceptibility') encompasses all areas mapped as Quaternary sediments, whereas Domain B and C of the present report are of much more restricted extent. The reason for this difference is that the Murashev & Davey (2005) 'low susceptibility' zone includes extensive areas of predominantly gravelly, and/or older, sediments that in the present study are placed within Domain A. Looking at the Dunedin main urban area, McCahon et al. (1993) presented a map showing the extent of 'soil types potentially susceptible to liquefaction' (see Appendix 2 – their Figure 6.1). That area is slightly less extensive than Domain C mapped in the present report, and it is likely that the Domain C mapped here is slightly more conservative. The present assessment has been aided by use of highly detailed lidar topographic information.

Areas within Domain B or C that lie close to 'free faces', such as the banks of river or stream channels, may potentially be subject to lateral spreading hazards in the event of an occurrence of liquefaction-inducing earthquake shaking. No attempt has been made to map lateral spreading hazard awareness areas, largely because topographic datasets are too imprecise to undertake a consistent district-wide map of potential lateral spread areas. Another point to consider is that of embankments that are built on potentially liquefiable materials. Although these have not been mapped as part of this project, they do represent a hazard to consider in liquefaction-susceptible areas, especially as many of the embankments relate to important transport routes (road and rail), other infrastructural elements and flood protection (river flood banks).

The designation of Domain B and C as 'liquefaction awareness areas' emphasises that the available data sets lack the detail necessary to quantify the natural variability within potentially-liquefiable geological materials. For example, soft liquefiable sediments may occur in former stream channels, either side of which are non-liquefiable gravel bars. But these features may lie beneath younger sediments. Thus, detailed geotechnical investigations are needed for liquefaction hazard zonation, particularly in order to determine liquefaction hazards to a level sufficient for attempting a classification analogous to the Technical Category approach (see Appendix 1).

The domains identified in this report are not envisaged as being suitable for use in a regulatory or restrictive framework. Rather, they highlight areas where there may be an issue requiring consideration, as well as a 'heads-up' for existing, and in particular, future development. None of the areas mapped as Domain B or C in this report have hard evidence, so far as the authors of this report are aware, for the existence or exact locations of potentially liquefiable ground. Rather, geological factors indicate some likelihood that liquefaction-susceptible ground may exist in parts of those domains. The placing of restrictions on existing or new developments is not justifiable from the information presented in this report. Instead, this report is seen as providing a road map toward improved knowledge. In areas mapped as Domain B, and especially Domain C, that have major existing infrastructure, or if major new development is proposed, it would be desirable, through the collation of existing geotechnical data or the acquisition of new data, to establish the presence or otherwise of potentially liquefiable materials, and if present, their general pattern of distribution.

7.0 CONCLUSIONS

The susceptibility of land to earthquake-induced liquefaction was assessed for the Dunedin City district in an office-based evaluation of geological criteria relevant to liquefaction hazards, supplemented where possible with available borehole lithology and groundwater data. The mapping identifies areas that, from geological and geomorphological considerations, are likely to be underlain by the types of sediments that are liquefaction-susceptible, and where groundwater is at sufficiently shallow depth.

From the available information, a three-fold classification of liquefaction susceptibility has been developed:

- **Domain A**. The ground is predominantly underlain by rock or firm sediments. There is little or no likelihood of damaging liquefaction occurring;
- **Domain B**. The ground is predominantly underlain by poorly consolidated river or stream sediments with a shallow groundwater table. There is considered to be a low to moderate likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain B;
- **Domain C**. The ground is predominantly underlain by poorly consolidated marine or estuarine sediments with a shallow groundwater table. There is considered to be a moderate to high likelihood of liquefaction-susceptible materials being present in some parts of the areas classified as Domain C.

The domains depicted on maps in this report are provided in greater detail in an accompanying GIS dataset. Areas identified as being potentially susceptible to liquefaction are restricted to low-lying places underlain by Quaternary sediments where the groundwater table is less than about 6 m deep. More than 90% of the land area in the Dunedin district is classified as Domain A – terrain underlain by materials that are non-liquefiable, including schist bedrock or cover sedimentary or volcanic rocks, or by gravelly or relatively consolidated Quaternary sediments. There are significant areas mapped as Domain B in Mosgiel-North Taieri and Strath Taieri, along with indications of shallow groundwater. Land classified as Domain C includes the southwestern part of the Taieri Plain, low-lying land in South Dunedin and adjacent to Otago Harbour, and low-lying coastal areas.

The liquefaction hazard evaluation reported here is a generalised regional-scale susceptibility assessment, using a methodology similar to that applied in eastern Canterbury. It differs from a full susceptibility assessment, which would require detailed geotechnical testing of properties of near-surface sediments. The information in this report 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. The liquefaction susceptibility domains delineated in this report are intended to highlight areas where liquefaction hazard may warrant further scrutiny for future planning and development activities. Domains B and C are regarded as 'liquefaction awareness areas', but do not represent hazard zones, as such. The placing of restrictions on existing or new developments is not justifiable from the information presented. Instead, the report provides a road map toward improved knowledge. A desirable future step would be to establish the presence or otherwise of potentially liquefiable materials in areas mapped as Domains B and C, and if present, their general pattern of distribution.

8.0 ACKNOWLEDGEMENTS

We thank Michael Goldsmith and Alex Sims of Otago Regional Council for assistance in developing the project scope and providing information that is held by the council. We are grateful to Rob Garrett of Dunedin City Council for providing lidar and soil data held by DCC. This report has benefited from technical reviews by Hannah Brackley and John Begg of GNS Science.

9.0 REFERENCES

American Society of Civil Engineers 1978. Definition of terms related to Liquefaction. Report submitted by the committee on Soil Dynamics of the Geotechnical Engineering Division of the American Society of Civil Engineers (ASCE). ASCE Journal of Geotechnical Engineering 104, no. GT9, p. 1197–1200.

Barrell D.J.A. 2014. Extent and characteristics of alluvial fans in the northeastern sector of the Taieri Plain, Otago. GNS Science Consultancy Report 2014/45, April 2014.

Barrell, D.J.A.; McIntosh, P.D.; Forsyth, P.J.; Litchfield, N.J.; Eden, D.N.; Glassey, P.J.; Brown, L.J.; Froggatt, P.C.; Morrison, B.; Smith Lyttle, B.; Turnbull, I.M. 1998. Quaternary fans and terraces of coastal Otago. Institute of Geological and Nuclear Sciences Science Report 98/11. Lower Hutt, GNS Science. 36 p. and 2 folded maps.

Barrell, D.J.A.; Forsyth, P.J.; Litchfield, N.J.; Brown, L.J. 1999. Quaternary stratigraphy of the Lower Taieri Plain, Otago, New Zealand. Institute of Geological & Nuclear Sciences Science Report 99/15. Lower Hutt, GNS Science. 24 p.

Barrell D.J.A..; Cox, S.C.; Greene, S.; Townsend, D.B. 2009. Otago Alluvial Fans Project: Supplementary maps and information on fans in selected areas of Otago. GNS Science Consultancy Report 2009/052. Prepared for Otago Regional Council. 19 p. plus appendices.

Benson, W.N. 1968. The W.N. Benson geological map of Dunedin district – Scale 1:50,000. New Zealand Geological Survey Miscellaneous Series Map 1. Wellington, Department of Scientific and Industrial Research. 1 folded map and notes (18 p.).

Bishop D.G. 1974. The Dunedin earthquake, 9 April 1974. Part 2: Local effects. Bulletin of NZ National Society of Earthquake Engineering 7: 123–129.

Bishop, D.G.; Turnbull, I.M. (compilers) 1996. Geology of the Dunedin area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 21. Lower Hutt, GNS Science. 52 p. and one folded map.

Brackley, H.L. (compiler) 2012. Review of liquefaction hazard information in eastern Canterbury, including Christchurch City and parts of Selwyn, Waimakariri and Hurunui Districts. GNS Science Consultancy Report 2012/218. 99 p. Environment Canterbury report number R12/83.

Cox, S.C.; Rutter, H.K.; Sims, A.; Manga, M.; Weir, J.J.; Ezzy, T.; White, P.A.; Horton, T.W.; Scott, D. 2012. Hydrological effects of the M_W 7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand. New Zealand Journal of Geology and Geophysics 55: 231–247.

Cubrinovski, M.; McCahon, I. 2011. Foundations on Deep Alluvial Soils. Technical report by Misko Cubrinovski and Ian McCahon, August 2011. Prepared for the Canterbury Earthquakes Royal Commission, http://canterbury.royalcommission.govt.nz/documents-by-key/2011-09-2354.

Fordyce, E. 2013. Groundwater dynamics of a shallow, coastal aquifer. Unpublished thesis submitted for a Master of Science degree, Geography Department, University of Otago, Preliminary version (December 2013) still under examination. 155 pages.

Forsyth P.J. 2001 (compiler). Geology of the Waitaki area. Institute of Geological and Nuclear Sciences 1:250 000 Geological Map 19. Lower Hutt, GNS Science. 64 p. and one folded map.

Grindley, J.; Cox, S.C.; Turnbull, I.M. 2009. Otago Alluvial Fans Project. Opus International Consultants Limited, Report no. 1205 – Version 2, Reference 6CWM03.58, prepared for Otago Regional Council. March 2009. (Note: updated from the draft report and GIS data sets that were completed in July 2007).

growRural Dunedin. Climate and soil maps for the Dunedin City district (1:25,000 scale). Administered by the Dunedin City Council. < www.dunedin.govt.nz > search word: growrural.

Gulley, A.K.; Ward, N.F.D.; Cox, S.C.; Kaipio, J. P. 2013. Groundwater responses to the recent Canterbury earthquakes: a comparison. Journal of Hydrology 504: 171–181.

Hamada, M.; Yasuda, S.; Isoyama, R.; Emoto, K. 1986. Study on liquefaction induced permanent ground displacement. Association for the Development of Earthquake Prediction in Japan, Tokyo, Japan.

Hanson, C.R. 1997. Groundwater study of the Strath Taieri basin, Otago, New Zealand. Prepared by Stone Environmental for the Otago Regional Council. 60 p.

Irricon & Royds Consulting 1994. Lower Taieri Groundwater, Preliminary study. Report prepared by Irricon Consultants Ltd in conjunction with Royds Consulting for Otago Regional Council. 55 p.

Irricon & ESR 1997. Lower Taieri groundwater study. Report prepared by Irricon Consultants Ltd in conjunction with ESR for Otago Regional Council. ISBN 0-908922-55-8. 118 p.

Irricon & MWH 2004. Strath Taieri groundwater resources study: preliminary report. Report prepared by Irricon Consultants Ltd in conjunction with Montgomery Watson Harza (MWH) for Strath Taieri Federated Farmers. 25 p. and 2 appendices.

Irricon 2005. North Taieri closed landfill: Aquifer contamination risk assessment. Report prepared for by Irricon Consultants Ltd for Dunedin City Council. 44 p.

Ishihara, K. 1985. Stability of natural deposits during earthquakes. Proceedings 11th International Conference on Soil Mechanics and Foundation Engineering. San Francisco pp. 321–376.

Iwasaki, T.; Tatsuoka F.; Tokida K.; Yasuda S. 1978. A practical method for assessing soil liquefaction potential based on case studies at various sites in Japan, in 2nd International conference on microzonation, San Francisco, p. 885–896.

Litchfield, N.J.; Norris, R.J. 2000. Holocene motion on the Akatore Fault, south Otago coast, New Zealand. New Zealand Journal of Geology and Geophysics 43: 405–418.

Litchfield, N.J.; Craw, D.; Koons, P.O.; Edge, B.; Perraudin, E.; Peake, B. 2002. Geology and geochemistry of groundwater flow within the Taieri Basin, east Otago, New Zealand. New Zealand Journal of Geology and Geophysics 45: 481–497.

McCahon, I.F.; Yetton, M.D.; Cook, D.R.L. 1993. The earthquake hazard in Dunedin. EQC Report 91/56 prepared by Soils and Foundations.

McKellar, I.C. 1990. Geology of the southwest Dunedin urban area – 1:25,000. Miscellaneous Series Map 22. Map (1 sheet) and notes (64 p). Wellington, Department of Scientific and Industrial Research.

McMillan, S.G. 1999. Geology of Northeast Otago: Hampden (J42) and Palmerston (J43). Lower Hutt: Institute of Geological & Nuclear Sciences. Institute of Geological & Nuclear Sciences Science Report 98/25. 55 p. and 1 folded map (2 sheets).

Murashev, A.; Davey, R. 2005. Seismic Risk in the Otago Region. Opus International Consultants Limited Report SPT: 2004/23, prepared for Otago Regional Council. 50 p., 27 maps and 2 appendices.

NRC 1985. Liquefaction of soils during earthquakes. National Research Council, National Academy Press. 204 p.

Obermeier, S.F.; Olson, S.M.; Green, R.A. 2005. Field occurrences of liquefaction-induced features: a primer for engineering geologic analysis of paleoseismic shaking. Engineering Geology 76: 209–234.

O'Sullivan, K.; Goldsmith, M.; Palmer, G. 2013. Natural hazards on the Taieri Plain, Otago. Report published by the Otago Regional Council. ISBN 978-0478-37658-6. 102 p.

Orense, R.P. 2010. Assessment of liquefaction potential based on peak ground motion parameters. Soil Dynamics and Earthquake Engineering 25: 225–240.

Orense, R.P.; Pender, M.J.; Wotherspoon, L.M. 2012. Analysis of soil liquefaction during recent Canterbury (New Zealand) earthquakes. Geotechnical Engineering Journal of the SEAGS & AGSSEA 43(2): 8–17.

Quigley, M.; Bastin, S.; Bradley, B. 2013. Recurrent liquefaction in Christchurch, New Zealand, during the Canterbury earthquake sequence. Geology 41: 419–422.

Rekker, J. 2012. The South Dunedin coastal aquifer & effect of sea level fluctuations. Report published by the Otago Regional Council. ISBN 978-0-478-37648-7. 25 p.

Rekker, J; Houlbrooke C. 2010. Lower Taieri groundwater allocation study. Report published by the Otago Regional Council. ISBN 1-877265-95-0. 118 p.

Robertson, P.K.; Wride, C.E. 1998. Evaluating cyclic liquefaction potential using the cone penetration test. Canadian Geotechnical Journal 35: 442–459.

Seed H.B.; Idriss I. M.1971. Simplified Procedure for Evaluating Soil Liquefaction Potential, Journal of the Soil Mechanics and Foundation Division, ASCE, Vol. 97, No. SM9.

Stirling, M.W.; McVerry, G.H.; Gerstenberger, M.C.; Litchfield, N.J.; Van Dissen, R.J.; Berryman, K.R.; Barnes, P.; Wallace, L.M.; Villamor, P.; Langridge, R.M.; Lamarche, G.; Nodder, S.; Reyners, M.E.; Bradley, B.; Rhoades, D.A.; Smith, W.D.; Nicol, A.; Pettinga, J.; Clark, K.J.; Jacobs, K. 2012. National seismic hazard model for New Zealand: 2010 update. Bulletin of the Seismological Society of America 102: 1514–1542.

Tonkin & Taylor 2005. Lower Taieri floodbank system: geotechnical evaluation. Report prepared for Otago Regional Council by Tonkin and Taylor Ltd. 82 pages + appendices.

Tonkin & Taylor 2012. Liquefaction vulnerability study. Report prepared for the Earthquake Commission by Tonkin and Taylor Ltd. 40 pages + figures and appendices.

van Ballegooy, S.; Cox, S.C.; Agnihotri, R.; Reynolds, T.; Thurlow, C.; Rutter, H.K.; Scott, D.M.; Begg, J.G.; McCahon, I. 2013. Median water table elevation in Christchurch and surrounding area after the 4 September 2010 Darfield Earthquake. Lower Hutt, GNS Science. GNS Science Science Report 2013/01. 66 p. + 8 appendices

Wang C.-Y.; Manga M. 2010. Earthquakes and water. ISBN 978-3-642-00809-2. Springer. 225 pages.

Youd, T.; Perkins, D. 1987. Mapping of Liquefaction Severity Index. Journal of Geotechnical Engineering 113: 1374–1392.

Youd, T.L.; Garris, C.T. 1995. Liquefaction-induced ground surface disruption. ASCE Journal of Geotechnical Engineering 121: 805–809.

Youd, T.L.; Idriss, M.; Andrus, R.D.; Arango, I.; Castro, G.; Christian, J.T.; Dobry, R.; Liam Finn, W.D.; Harder (Jr)., L.F.; Hynes, M.E.; Ishihara, K.; Koester, J.P.; Liao, S.S.C.; Marcuson, W.F.; Martin, G.R.; Mitchell, J.K.; Moriwaki, Y.; Power, M.S.; Robertson, P.K.; Seed, R.B.; K. H. Stokoe K.H. 2001. Liquefaction resistance of soils: Summary report from 1996 NCEER and 1998 NCEER/NSF Workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geoenvironmental Engineering 127: 817–903.

Youd, T.L.; Hansen C.M.; Bartlett S.F. 2002. Revised multilinear regression equations for prediction of lateral spread displacement. Journal of Geotechnical and Geoenvironmental Engineering 128:1007–17.

APPENDIX 1: EXPLANATION OF TERMS

Geohazards	Natural ground-related hazards, some examples being: • Landslide or rockfall • liquefaction or lateral spread • strong ground motions from earthquake shaking • earthquake fault ground rupture • soft or compressible ground (e.g., peat) • erosion or sedimentation.
Geotechnical investigations	The process of characterising the ground subsurface conditions at a particular locality. The work must be undertaken or overseen by a ***geotechnical professional***. The work will include examination or measurements of the nature and properties of the ground-forming materials, by means that include: • Examination and documentation of the subsurface materials, exposed in test pits or inspection shafts, or obtained from cored or non-cored bore holes; • Measurements of material properties by means of probes or instruments (e.g., cone penetration tests (CPT) or standard penetration tests (SPT) • Measurements of groundwater conditions, such as standing water levels and piezometric pressures. For house development projects there is a minimum scope of geotechnical assessment work required, as set out in NZS3604:2011 *Timber-framed buildings* http://www.standards.co.nz/default.htm
Geotechnical professional	A suitably qualified or experienced civil engineer, geotechnical engineer, or engineering geologist. Work is expected to be done according to the IPENZ (Institution of Professional Engineers of New Zealand) Code of Ethical Conduct.
Hypocentre	The actual location underground where an earthquake is initiated. The epicentre is the location on the ground surface directly above the hypocentre. The hypocentre is also known as the earthquake focus.
Land zones	Following the Canterbury earthquakes of 2010 and 2011, extensive areas of flat-lying (i.e., not on hills) residential land in the greater Christchurch area have been mapped into land zones. Red zone land is deemed to have been so badly damaged by liquefaction-related phenomena during the Canterbury earthquake sequence that it is uneconomic to repair or rebuild dwellings. Green zone land is generally considered to be suitable for residential dwellings and associated land-use. Green zone land has, in places, been differentiated into Technical Category classes.
Technical categories (TC)	Land in the eastern Canterbury green zone has, in places, been divided into three technical categories – TC1, TC2 and TC3. These categories pertain only to residential land, and boundaries between TC areas are always placed along property boundaries. The mapping of TC areas was based to a considerable degree on the presence or absence of liquefaction occurrence during the Canterbury earthquake sequence, and the severity of the liquefaction effects. Geotechnical investigations involving bore holes, CPTs, and SPTs were also undertaken to assist with the TC mapping.

Technical categories (TC) – continued	The primary objective of the mapping of TC areas is to characterise how the ground is expected to perform in future large earthquakes, and to define foundation design requirements for the repair of existing dwellings or construction of new dwellings. More information can be found at: • http://cera.govt.nz/residential-green-zone-technical-categories#factsheets • http://cera.govt.nz/residential-green-zone-technical-categories Because the observed consequences of strong earthquakes were an integral part of the mapping of TC areas, the TC approach cannot be applied to locations elsewhere in New Zealand that have not experienced large damaging earthquakes historically. For that reason, the liquefaction susceptibility domains mapped in the Dunedin district report do not correlate directly with TC zones. Domain A land is likely to perform similarly to TC1 land as mapped in the Christchurch area, but Domains B and C land are likely to include land that may, from place to place, perform similarly to TC1, TC2 or TC3 land. A considerable body of geotechnical information would need to be obtained from investigations before any attempt could be made to apply a TC methodology to subdividing Domain B or C land into a liquefaction hazard zonation classification.

APPENDIX 2: PREVIOUS HAZARD EVALUATION MAPS

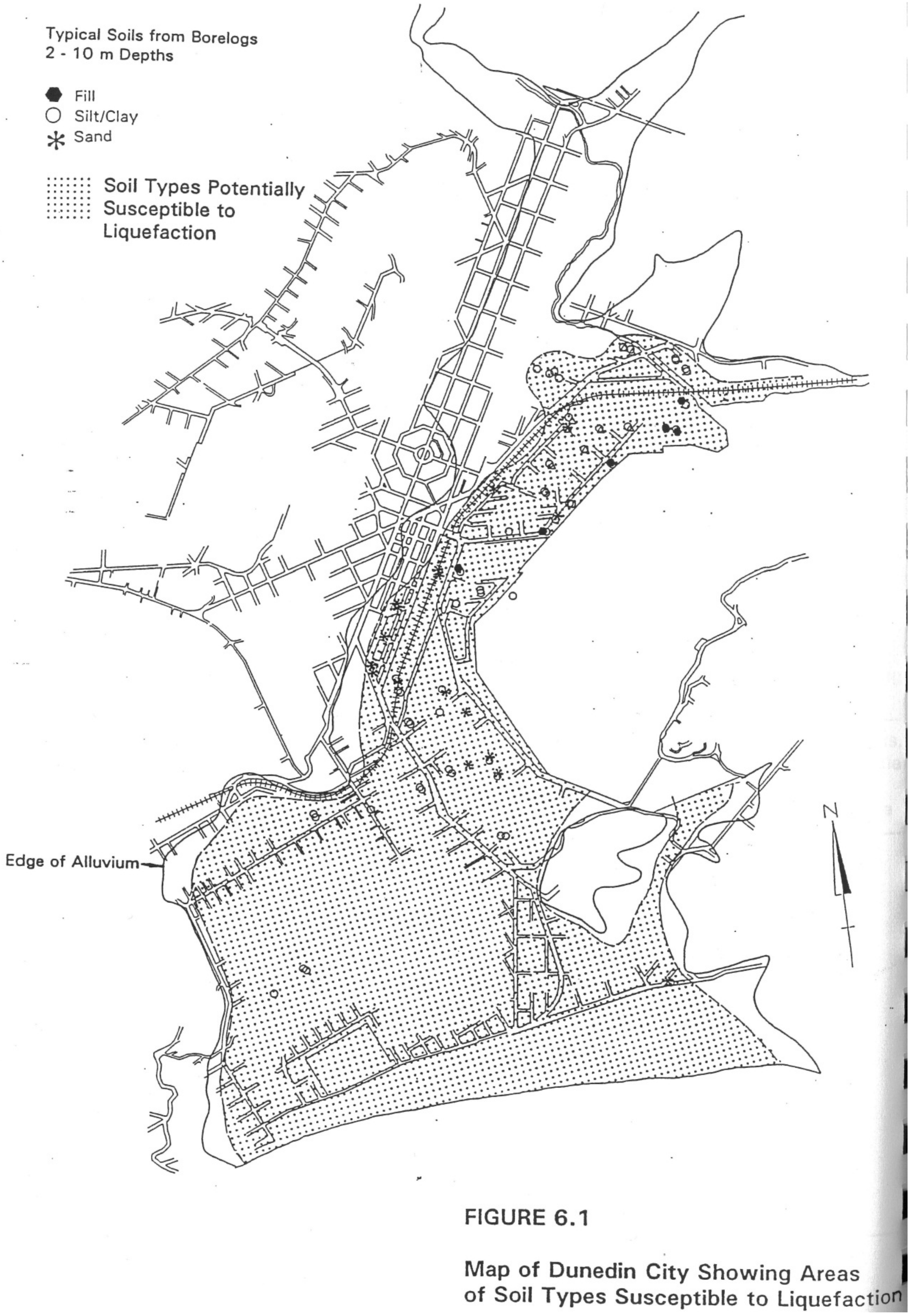

Figure A2.1 Liquefaction-susceptible soils, central Dunedin city (McCahon et al., 1993)

Figure A2.2 Liquefaction and settlement susceptibility, Otago region (Murashev & Davey 2005).

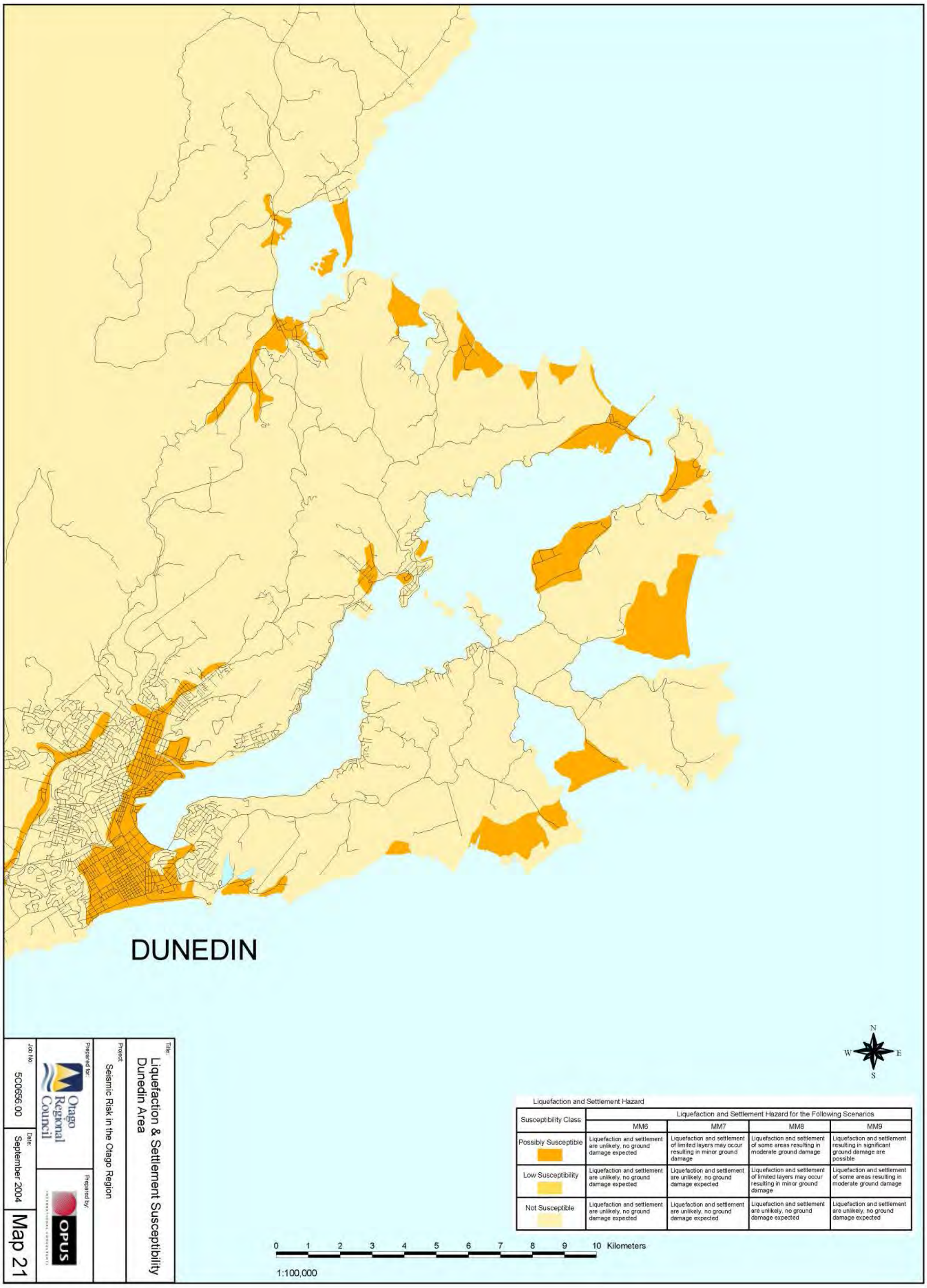

Figure A2.3 Liquefaction and settlement susceptibility, greater Dunedin area (Murashev & Davey 2005).

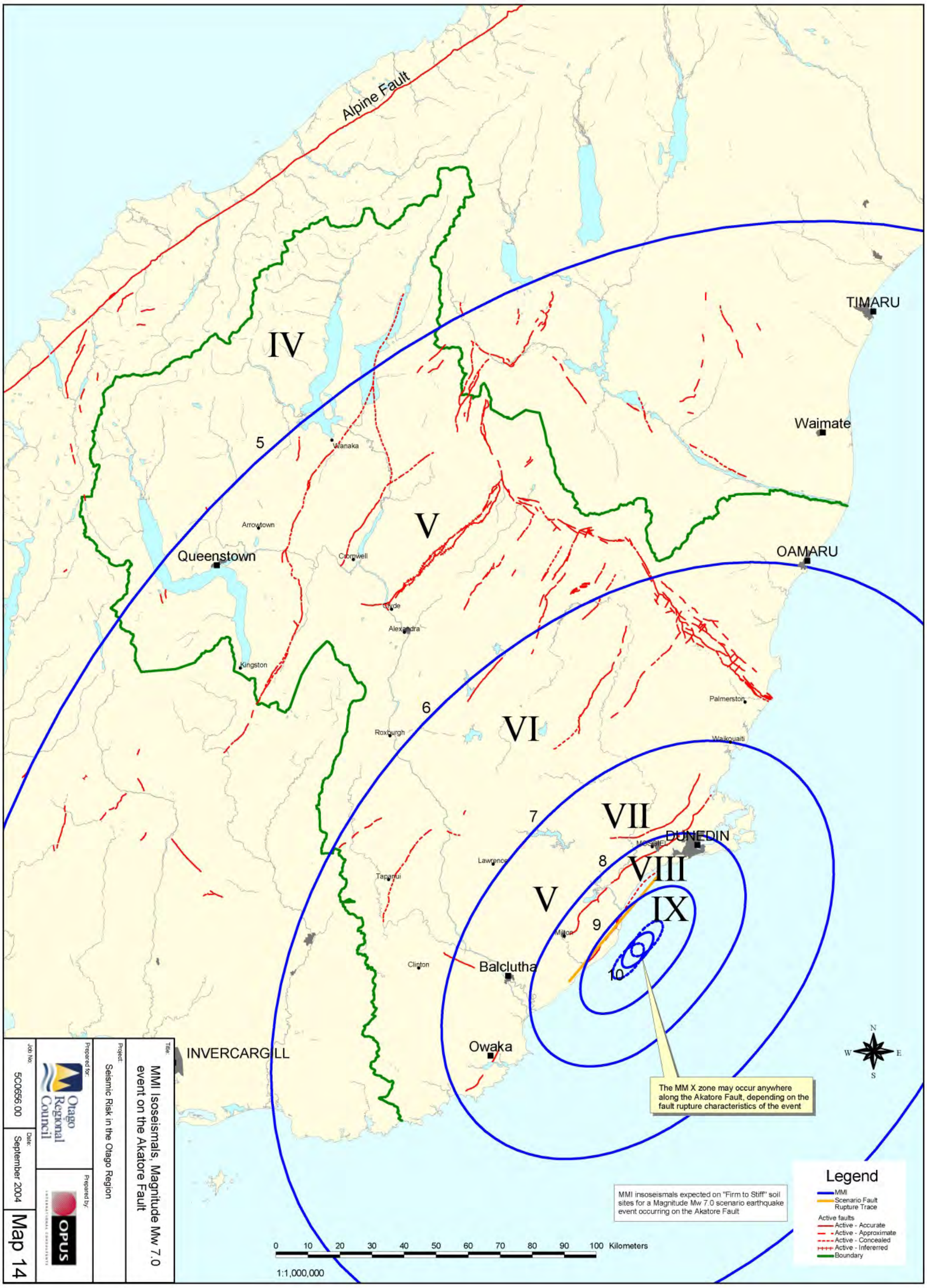

Figure A2.4 Estimated ground shaking, expressed in Modified Mercalli intensity classes, for a magnitude 7 earthquake centred on the Akatore Fault (Murashev & Davey 2005). Intensities of VII and VIII would be expected in coastal sectors of much of the Dunedin district, and would be likely to generate liquefaction in susceptible locations.

APPENDIX 3: DESCRIPTION OF THE MAPPED EXTENTS OF LIQUEFACTION SUSCEPTIBILITY DOMAINS B AND C

A3.1 DUNEDIN URBAN AREA

Mapping was aided by full coverage of lidar data.

Bore records from South Dunedin indicate substantial thicknesses of sand and silt, ranging from about 10 m to as much as 65 m thick (Fordyce 2013). Much of the land surface is within 1 m of mean sea level and is prone to surface flooding after prolonged rainfall. Groundwater is characterised by an unconfined water table that is very shallow, typically 0.3 to 0.9 m below surface, but shallowing in central St Kilda above an extensive area of silt. There may also be local pockets of perched freshwater within coastal dunes (Fordyce 2013). Groundwater is affected by sea level and tides at the ocean and the harbour, and controlled by rainfall-recharge and drainage through the stormwater and wastewater network (Rekker 2012; Fordyce 2013). Shallow groundwater is expected throughout the low-lying land beside the Otago Harbour as far as Logan Park and Ravensbourne. There is a substantial belt of reclaimed land at the margin of the harbour, from Vauxhall around to Ravensbourne.

The basis on which the Domain C/Domain A boundary was positioned is as follows. In order to account for the alluvial fans that grade out onto the coastal plain, and thus likely overlie soft marine sediments, from St Clair around to the Water of Leith, the boundary was placed at 10 m above mean sea level (a.s.l.) as defined by the lidar data (Figure A3.1a). This includes the lowest reaches of the Leith valley and other streams draining to the coastal plain. The 10 m a.s.l. criterion was also applied from Vauxhall around through Andersons Bay and Tainui to Lawyers Head, there accounting for dune sand aprons that probably mantle the base of slopes, along what was a more exposed part of the former embayment. At Lawyers Head, the boundary has been connected to the shore platform rock outcrops. From Logan Park around the reclamation area to Ravensbourne, the boundary was also positioned at 10 m a.s.l.

The Kaikorai Lagoon area is a largely tidal wetland. A major long-standing land-use has been as a landfill area. A sand flat and dunefield at the lagoon mouth was included in the area mapped as Domain C (Figure A3.1b). Lidar coverage runs out at the northwestern edge of the lagoon. The 1:25,000 geological map of McKellar (1990) was used to aid the positioning of the boundary of the Domain C area. The boundary was positioned at 6 m a.s.l., as defined by lidar data, around the lagoon perimeter, and in the valley of Abbotts Creek. It includes all areas of filled and reclaimed land, even though some of those areas stand well above 6 m. The reasoning for a 6 m altitude criterion is that Kaikorai Lagoon has well-defined margins eroded into bedrock terrain, without large catchments draining in. Its intricately multi-branched perimeter suggests that it is a drowned valley with relatively little sediment infill. At Brighton Road, Kaikorai Stream is fast flowing on a gravel bed, suggesting that the sea level rise culminated at about that location. Mapping here was hindered by the extensive embankments associated with the motorway interchange. To be conservative, the boundary of Domain C was extended up the floor of Kaikorai valley to 10 m a.s.l.

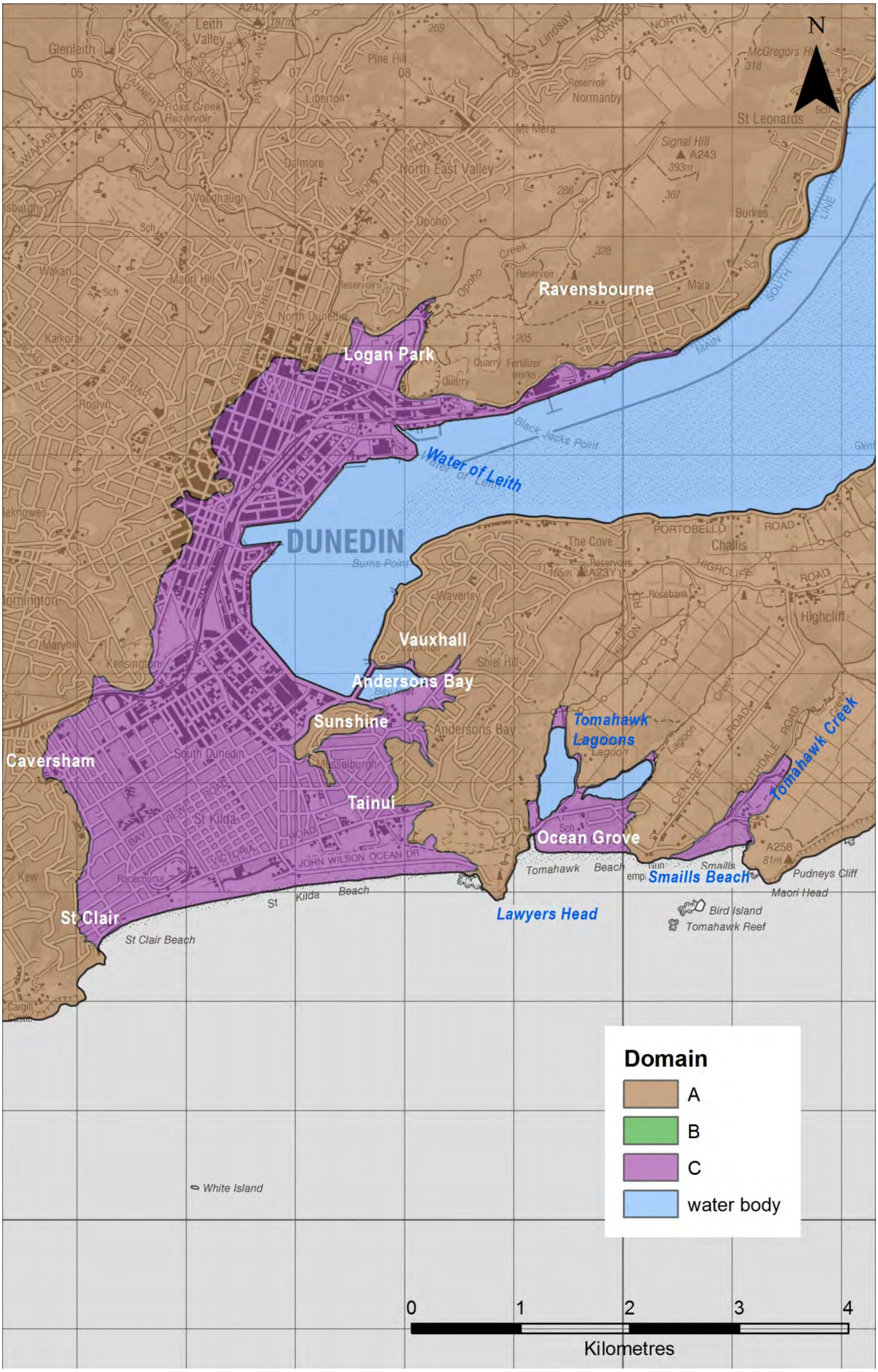

Figure A3.1a Location map for liquefaction susceptibility domains in the Dunedin urban area.

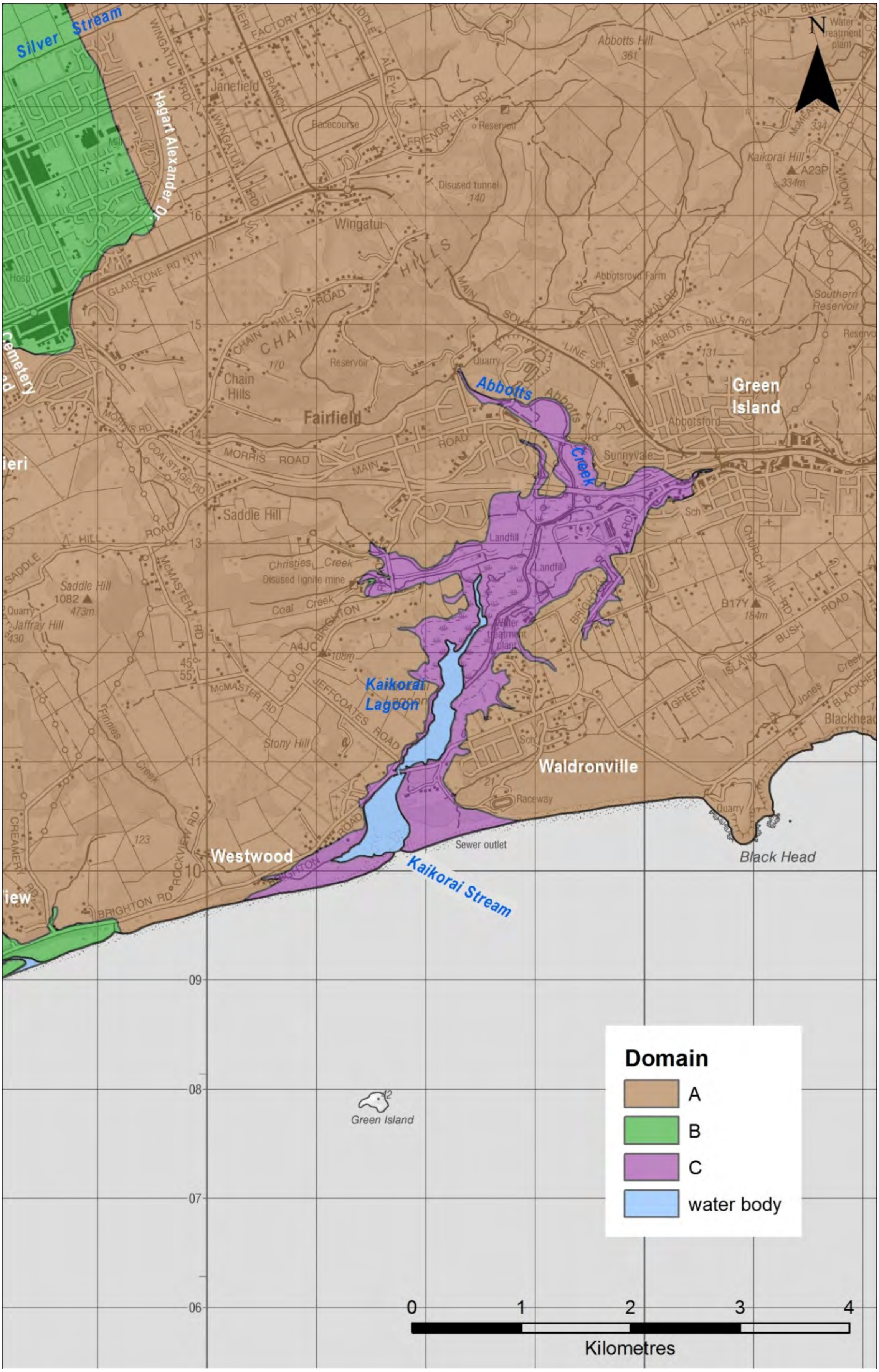

Figure A3.1b Location map for liquefaction susceptibility domains in the Kaikorai Lagoon area.

A3.2 TAIERI PLAIN AND STRATH TAIERI PLAIN

A3.2.1 Taieri Plain

The boundary of Domain C on the Taieri Plain was positioned to coincide with the limit of the Waihola silt/sand. It is most easily defined southwest of Outram and Allanton (Figure A3.2a), because there is a line of wave-cut terrace edges marking the margin of the former inlet, broken by alluvial fans that have built out onto the plain after the inlet became filled in. Between Outram and East Taieri (Figure A3.2b), the mapping of the extent of Waihola silt/sand was derived from information from bores, but there are relatively few bores that have lithological details. Thus the Domain C boundary has less certainty here, but is aligned with the limit of Waihola silt/sand as mapped by Litchfield et al., (2002). In addition, bores indicate the presence of zones of silt or sand in the subsurface, northeast towards the Mosgiel area. However, there is much variability, with sand or silt recorded from some bores, and yet mostly gravel recorded in other bores nearby. Coupled with the observation that groundwater is close to the surface in that area, an area has been mapped as Domain B which includes Mosgiel (Figure A3.2b). The extent and sensitivity of any liquefaction-susceptible materials in this domain will need to be established by specific geotechnical investigation. Similarly, areas of Domain B were mapped in the lower reaches of the infilled valleys of minor streams that have built alluvial fans out over Waihola silt/sand (all areas underlain by Waihola silt/sand are included in Domain C) (see Figures 11 and 13 of main report).

The positioning of the boundaries of these domains was determined as follows. Apart from parts of the lower Taieri Gorge southeast of Henley, there is complete lidar coverage of the Taieri Plain area. In the valley of the Waipori River upstream of Berwick, the Domain C/A boundary was positioned about 1 km northwest of Berwick (Figure A3.2c). The rationale was that the bore holes in the valley upstream of here show predominantly gravel, while those near Berwick encountered mainly fine-grained material. Northeast of Berwick, the Domain B/C boundary was located at the former shoreline, then interpolated beneath fans that post-date the former shoreline. The Domain B/A boundary was positioned across the floor of each minor stream valley at 10 m a.s.l. to allow for the possibility of saturated fine-grained material at depth. On the southeast side of the basin, the Domain B/A boundary was positioned as far up each valley as the valley floor is broad. The reasoning is that, particularly in the area southwest of Allanton, the base of the Waihola silt/sand, which marks the original land surface prior to sea level rise, is as much as 25 m below sea level. The minor valleys were doubtless graded to that old land surface, and it is very likely that the lower reaches of these valleys were also drowned, and subsequently filled with fine sediment. In the lower Taieri Gorge (i.e., between Henley and Taieri Mouth), the boundary was positioned at the margins of the infilled valley, and extended up tributary valleys as far upstream as each valley is broad (Figure A3.2d). The extensive infilled valley on the northern side of the gorge, and into which Knee Stream and Elbow Stream drain, was mapped using the 1:50,000 scale topographic map, because much of this valley is outside the lidar coverage.

More difficult was the placement of the Domain B/A boundary in the vicinity of Wyllies Crossing and Mosgiel (Figure A3.2b). The area mapped as Domain B includes the bores that encountered significant components of fine-grained materials in the top 10 m, and also encompasses most areas where groundwater is shallower than about 5 m. Topographic elevations were used to position the zone boundary, as follows. East from Outram along the northwestern side of the basin, the Domain B/A boundary was positioned at 15 m a.s.l., but shifted to 20 m a.s.l. near Tirohanga Road, and then shifted progressively to 30 m a.s.l.

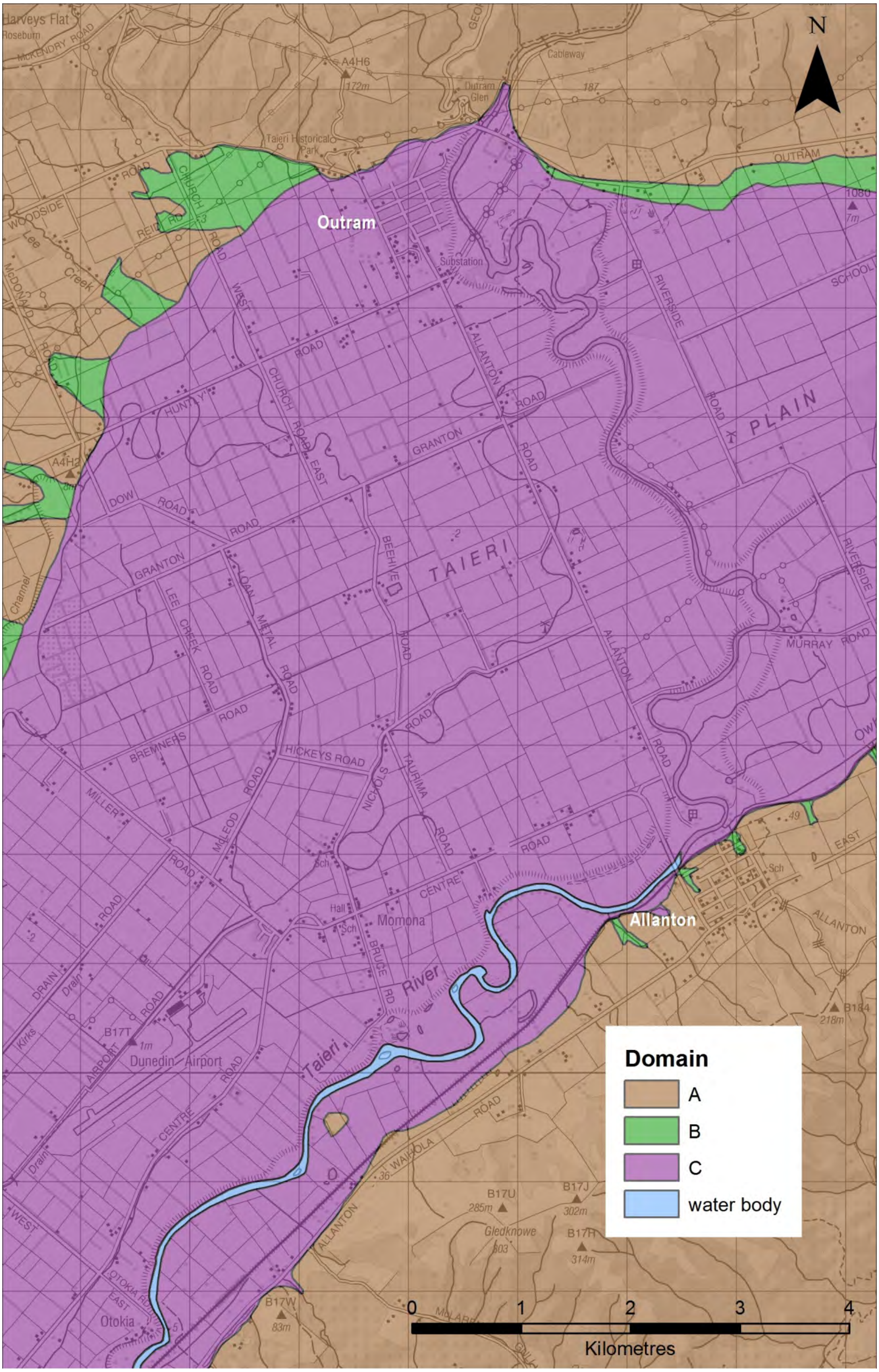

Figure A3.2a Location map for liquefaction susceptibility domains in the central part of the Taieri Plain.

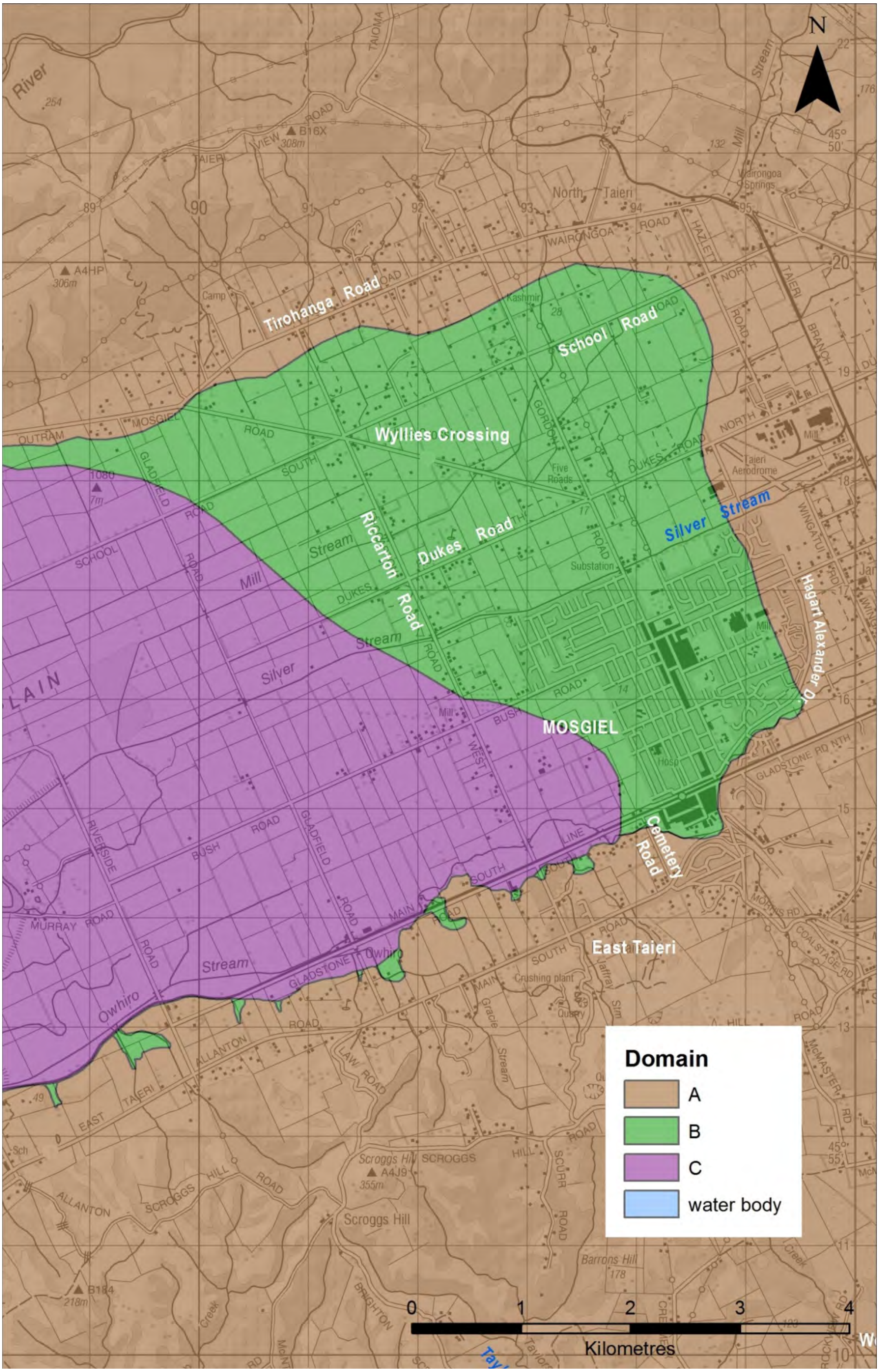

Figure A3.2b Location map for liquefaction susceptibility domains on the northeastern part of the Taieri Plain.

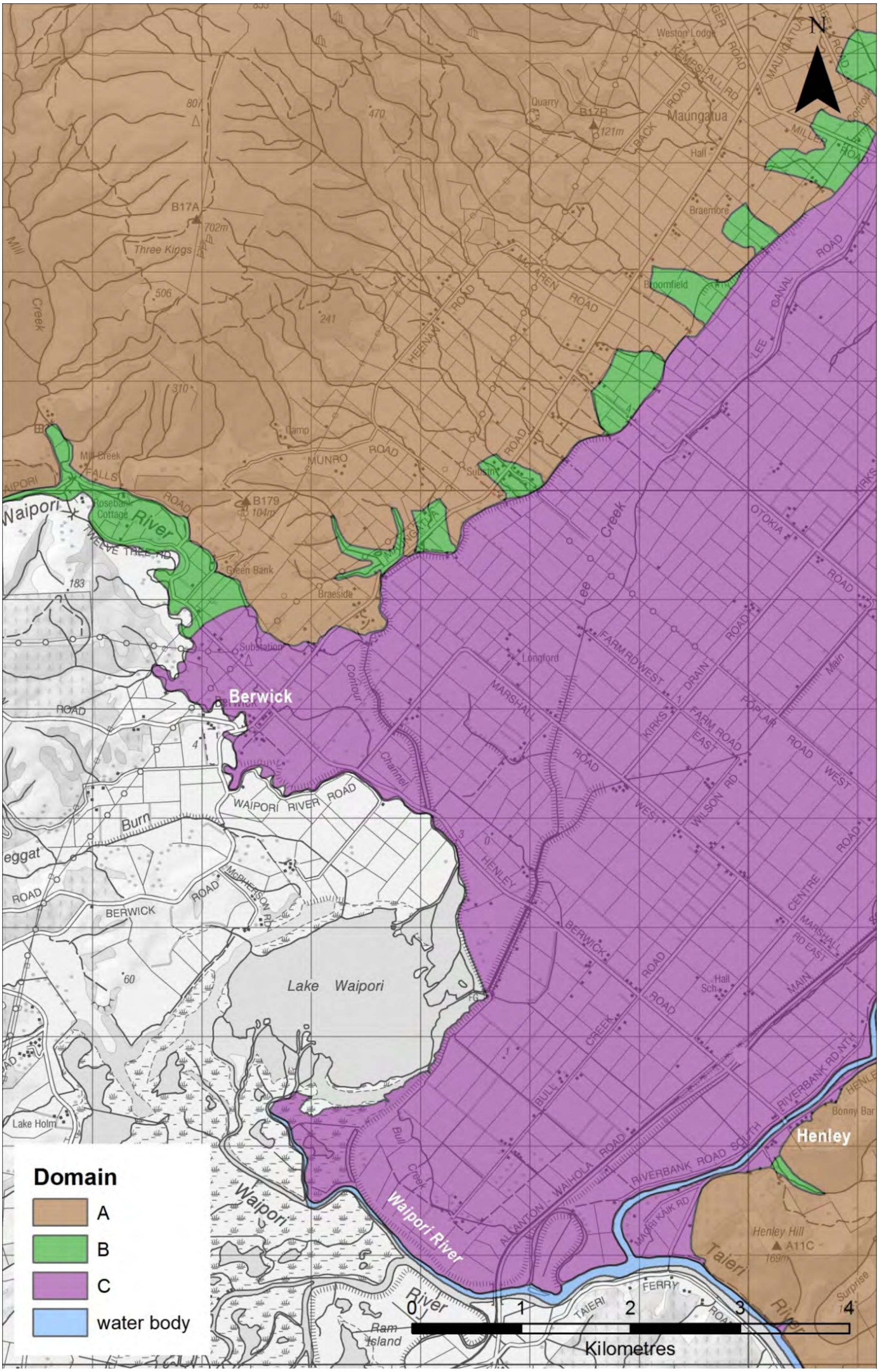

Figure A3.2c Location map for liquefaction susceptibility domains in the southwestern part of the Taieri Plain.

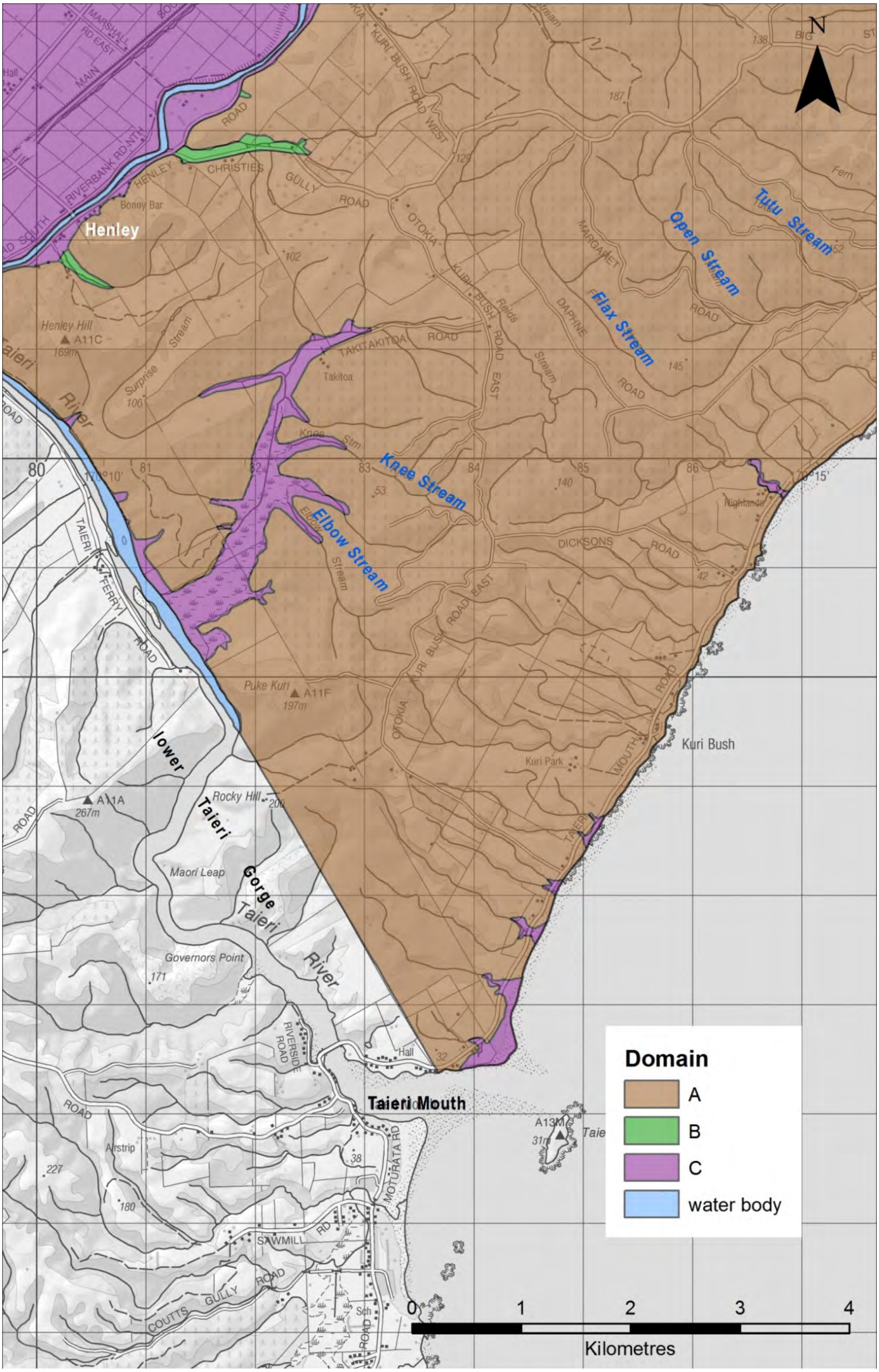

Figure A3.2d Location map for liquefaction susceptibility domains in the lower Taieri Gorge.

Southeast of School Road, its altitude was progressively reduced, reaching 15 m at Dukes Road. It was positioned at 15 m a.s.l. along to Hagart Alexander Drive, continuing southeast to the foot of the alluvial fan complex on the southeast side of the basin. The Domain B/A boundary was placed along the edge of the alluvial fans to just past Cemetery Road, where it terminates at the Domain C boundary.

Groundwater levels are also an important consideration for delineating domain boundaries. A number of groundwater studies have been carried out in the area, summarised in Rekker & Houlbrooke (2010). The most definitive groundwater level contour map available for Taieri Basin was a survey of 52 levelled bores, carried out in mid-May 1994 (Irricon & Royds Consulting 1994), updated with new investigation wells and observations in July 1996 (Irricon & ESR 1997). The Waihola silt/sand exerts an important influence on groundwater beneath the Taieri Plain. Where present, west of Riccarton Road, it separates a near-surface unconfined water table from confined groundwater in aquifers below. East of about Riccarton Road, the sediments include greater quantities of gravel and are characterised by a high degree of lithological variability with rapid lateral transitions in grainsize. Groundwater in that area is mostly unconfined. The potentiometric surface conforms approximately with the elevation of topography, with groundwater at higher elevations in the north, decreasing with distance toward the southwest to approximately mean sea level at Henley. Local departures in the general shape of the surface are caused by: pumping at Mosgiel; discharge at School Swamp; emergence of Taieri River onto the plains at Outram; and the west Taieri drainage scheme (Rekker & Houlbrooke 2010).

Available groundwater information comes mostly from deeper bores, which are typically between 15 and 35 m deep, and screened in productive aquifers. There are relatively few bores less than about 10 m deep, but these shallow bores generally show higher groundwater levels than the deeper bores, indicating downward directed vertical pressure gradients (Irricon & ESR 1997). This is important as deep bores, or derived potentiometric contours, cannot be used as an indicator of the free water table and saturation required for liquefaction assessment. ORC records of shallow bore groundwater levels generally show the water table to be less than about 5 m deep across most of the Taieri Plain. Shallow artesian-flowing groundwater is sometimes present near Wyllies Crossing, but may have been reduced by long-term drawdown caused by land drainage (Rekker & Houlbrooke 2010). The greatest potentiometric depths appear to occur from Mosgiel toward North Taieri, but the position of the shallow water table in this area is not entirely clear. A shallow (6.1 m) bore at Roslyn Woollen Mills (now Mill Park Industrial Estate, Factory Road, central Mosgiel) has a median water level ~2 m below ground, with a long-term record of ±1 m variability closely related to rainfall recharge (Collins 1950; Rekker & Houlbrooke 2010). This suggests that saturation levels are sufficiently shallow for the occurrence of liquefaction if liquefaction-susceptible sediments are present.

A3.2.2 Strath Taieri Plain

The Strath Taieri Plain lies in a basin on the southeastern side of the Rock and Pillar Range (Figure 14 of main report). The Taieri River flows in a broad valley, flanked to the northwest by remnants of old river terraces, underlain by weathered gravel, and an array of alluvium deposited by streams draining from the Rock and Pillar Range. The river and fan sediments are probably 200 m thick at most, and are thought to be underlain by schist basement rock. The maximum confirmed depth of the alluvial deposits is 28 m in well H43/0187 located 2 km south of Middlemarch (Irricon & MWH 2004). The fan sediments are predominantly gravelly.

The Taieri River has developed a meandering course in places, and these areas of meander channels/bars may potentially include sandy or silty sediments.

Groundwater assessments by Hanson (1997) and Irricon & MWH (2004) indicate that there is an unconfined groundwater aquifer within the alluvial sediments, within complex interlayering of gravel, sand, silty sand and silt. Bore logs commonly describe “silty fine gravels”, “claybound gravels” or “very sandy claybound gravels” with low specific yields (Irricon & MWH 2004). A survey of 19 wells on 25 March 1997 indicated that the groundwater table was within 5 m of the ground surface over most of the basin, but at Middlemarch was locally less than 2 m below ground (Hanson 1997). Depth to groundwater is greatest within the alluvial fans on the western side of the valley. About Middlemarch, there are iron pans and minor perched water tables, confined aquifer conditions, and channels of preferred groundwater flow (Hanson 1997). The 1997 groundwater survey was carried out in early autumn, when groundwater conditions are likely to have been low. At times the water table immediately to the west of Middlemarch has risen above the ground surface and caused flooding (Hanson 1997).

To acknowledge the possible existence of fine-grained sediments and a likely high groundwater table, Domain B has been mapped in the incised valley of the Taieri River (Figure 14 of main report). As there is no lidar coverage for the Strath Taieri Plain, the Domain B/A boundary was positioned at the margins of the incised valley, using high-resolution satellite photography accessible via the ArcGIS computer software used for the mapping, and the 1:50,000-scale topographic map.

A3.3 COASTAL AREAS

A3.3.1 Taieri Mouth to Waldronville

There is lidar coverage for this entire coastal stretch, which has aided the mapping of domain boundaries.

The lower reaches of several minor stream valleys south of Kuri Bush are mapped as Domain C (Figure A3.2d). Inland boundaries of Domain C are placed as far up-valley as the valley floor is broad. In places, dunes lie seaward of the post-glacial cliff adjacent to these streams, and are also included in Domain C. North of Kuri Bush, areas of Domain C were mapped in the lower reaches of Reids Stream, which includes a lagoon, and in the combined valley of Flax Stream – Open Stream – Tutu Stream. This combined valley has a broad floor but it may conceivably be an alluvial fan pre-dating the sea level rise, so is not necessarily underlain by young marine sediments. It is tentatively classified as Domain C.

At Brighton, Otokia Creek has a broad estuarine reach, and Domain C was mapped here, encompassing the full width of the valley floor, and adjacent sand dunes at the beachfront near the estuary mouth. The inland boundary is placed as far upstream as the valley is broad (Figure A3.3a).

At Ocean View, a broad low-lying coastal plain is enclosed by the dune barrier. The coastal plain, the dune barrier and the lower reaches of Taylors Creek, as far upstream as the valley floor is broad, are mapped as Domain B (Figure A3.3a). This classification reflects the consideration that substantial parts of this area are on dunes, and likely to be well above groundwater level, which here will approximately coincide with sea level. The Domain B

Figure A3.3a Location map for liquefaction susceptibility domains along the coast in the Brighton area.

classification also reflects the possibility that the valley floor may conceivably be an alluvial fan in part pre-dating the sea level rise. To the northeast, the Domain B/A boundary is curved out to meet the coast where the terrain rises up towards Westwood.

From Westwood to Kaikorai Lagoon, low-lying dunes in front of the post-glacial sea cliff are mapped as Domain C, as is the dune/sand plain seaward of the sea cliff on the south side of the lagoon at Waldronville (Figure A3.1b).

A3.3.2 Otago Harbour and Otago Peninsula

There is lidar coverage for most parts of the harbour and peninsula.

Around the margins of both sides of Otago Harbour are extensive road and, on the western side, rail, embankments. These are commonly cut-to-fill constructions. The choice was taken not to map these separately from Domain A, but they may be potentially subject to lateral spreading hazards where the embankments are constructed on top of harbour sediments.

On the western side of the harbour, at Sawyers Bay there is a narrow fringe of low-lying ground, that is probably in part reclaimed land (Figure A3.3b). This was mapped as Domain B, with the Domain B/A boundary positioned at 6 m a.s.l., as defined in the lidar digital elevation model. Reclaimed land at the Port Chalmers port was mapped as Domain C, as was reclamation near Albertson Avenue on the southwest side of Port Chalmers. The inland boundaries of these domains were placed at 4 m a.s.l. Although a Domain C classification was chosen for the port reclamation, because it is built over marine sediments, it is likely that the reclamation has largely been engineered and its foundation on harbour sediment is likely to have been accounted for in the engineering design. At Sawyers Bay, it is unclear to what extent, if any, the area is underlain by soft sediments.

The coastal flat at Waipuna Bay, and the sand flat at Aramoana seaward of the coastal cliff, were both mapped as Domain C (Figure A3.3c). The base of the cliff is sharply defined, and the coastal flats have minimal relief, with negligible accumulation of debris or colluvium at the foot of the cliff, suggesting that the formation of the flats, and cessation of wave action at the base of the cliffs, is relatively recent, perhaps within the last thousand years or so. Due to the sharpness of the base of the cliff, the Domain C/A boundary was placed at 4 m a.s.l., as defined by lidar data. Any sand dunes on the flats that reach above 4 m are included in Domain C.

On the eastern side of the harbour at Macandrew Bay there is a narrow coastal plain, although it is unclear to what extent it is a natural feature, or enhanced by reclamation. It was mapped as Domain B, with the domain boundary positioned at 6 m a.s.l. at the foot of the hill terrain (Figure A3.3b). Farther northeast, there are extensive sand accumulations from Harwood northeast to Harington Point, and these were mapped as Domain C (Figure A3.3c). The mapping was hindered by widespread sand dunes on the costal flats and locally draped against the lower parts of the hill slopes. Generally, the Domain C/A boundary is placed at 6 m a.s.l., as defined by lidar, at the foot of the hill terrain, and interpolated where dunes have accumulated.

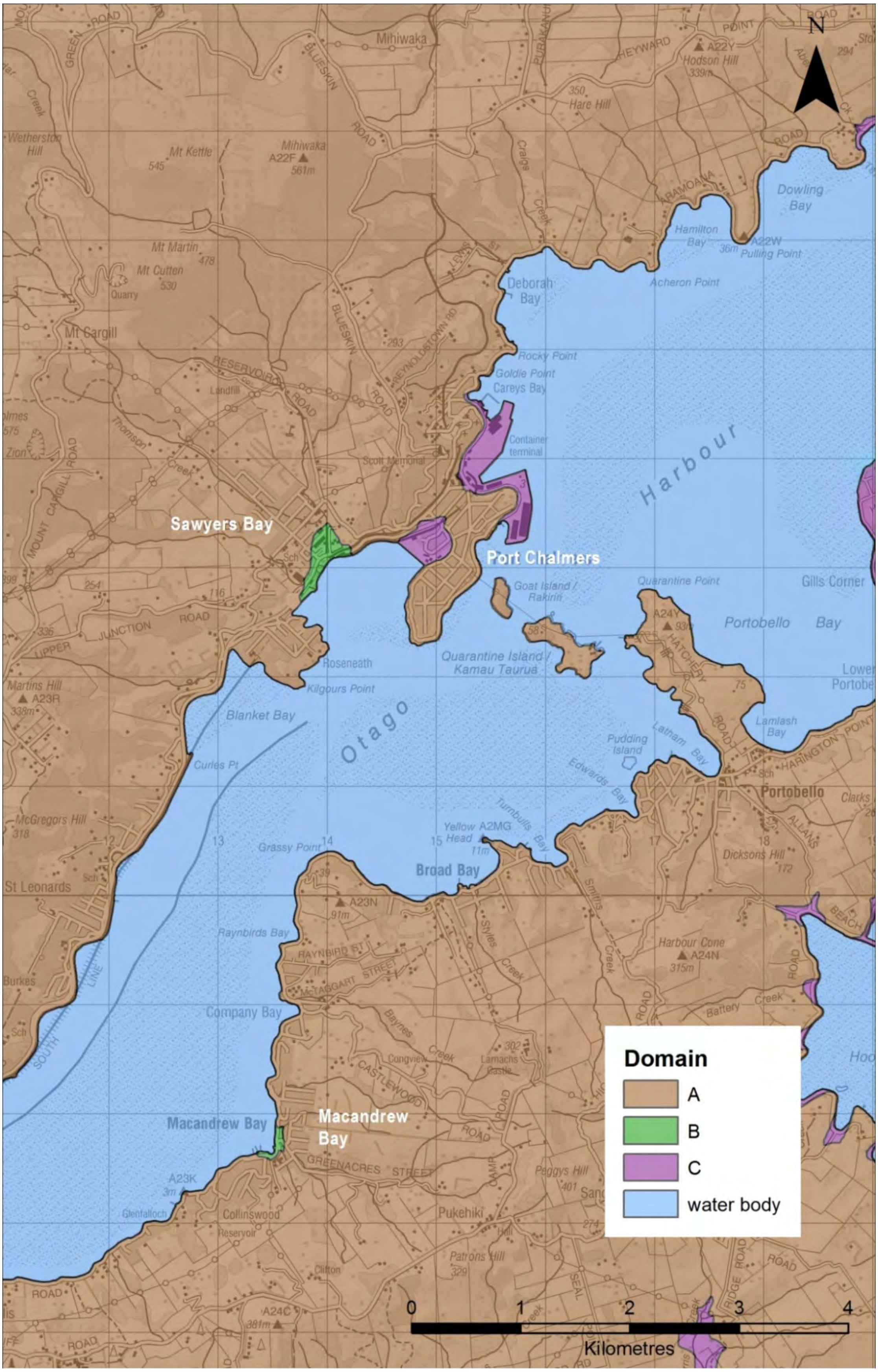

Figure A3.3b Location map for liquefaction susceptibility domains around the middle reaches of Otago Harbour.

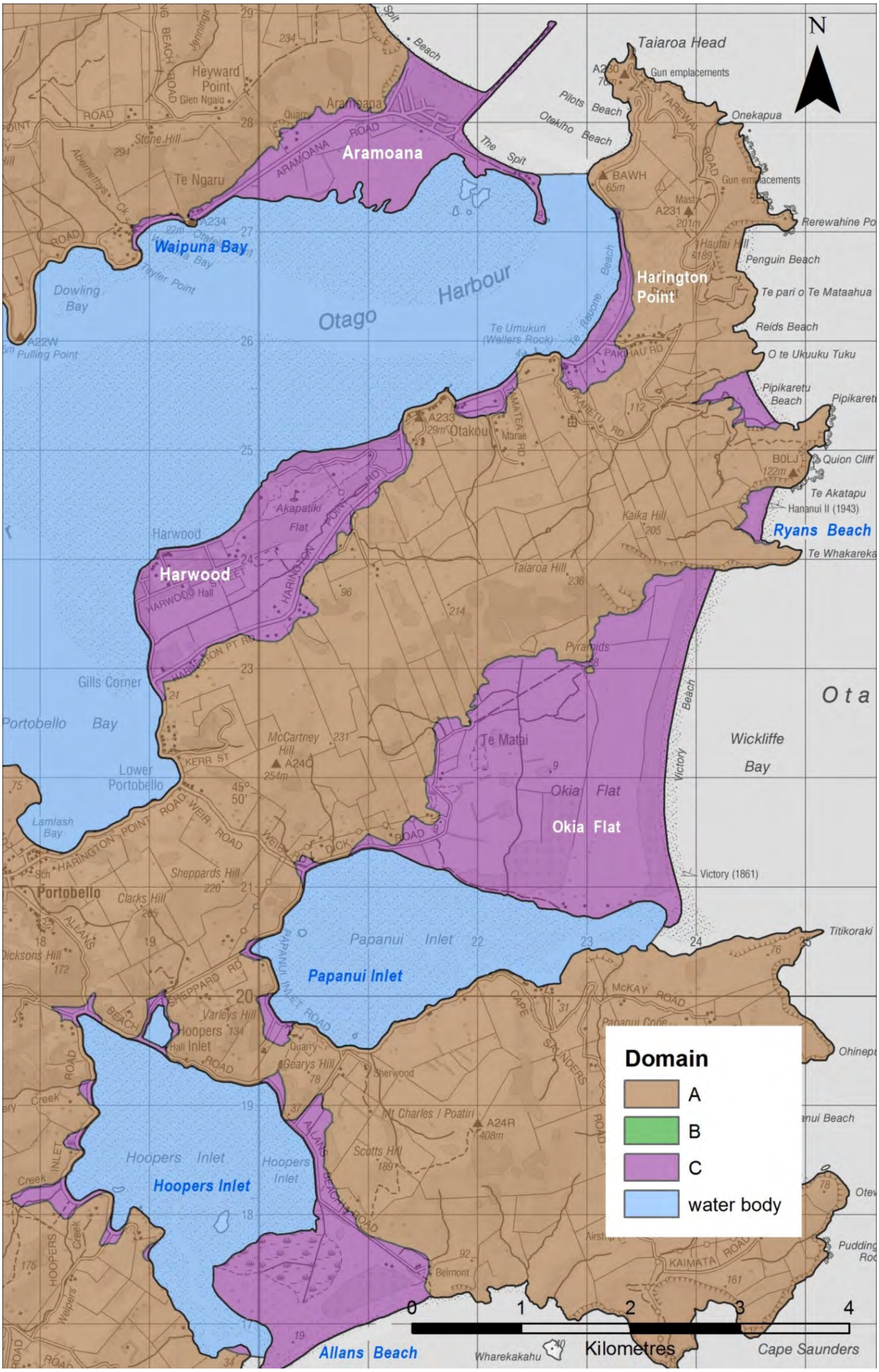

Figure A3.3c Location map for liquefaction susceptibility domains around the northeastern parts of Otago Harbour and Otago Peninsula.

On the eastern side of the peninsula at Ocean Grove, the low-lying margins of the Tomahawk Lagoons, and their enclosing sand dune barrier, were mapped as Domain C (Figure A3.1a). In many places the dunes are more than 10 m high. Where they abut hill slopes either side of the valleys occupied by the lagoons, the Domain C/A boundary was positioned at 15 m a.s.l. Around the perimeter of the lagoons, the boundary was positioned at 6 m a.s.l. The reasoning was that the lagoons have received relatively little sediment infill since culmination of sea level rise, probably reflecting the small size of the catchments that feed them.

At Smaills Beach the broad low-lying valley of Tomahawk Creek, and its enclosing dune barrier, were mapped as Domain C (Figure A3.1a). As this creek has a relatively large catchment, and thus has had a greater sediment accumulation since culmination of the post-glacial sea level rise, the Domain C/A boundary was positioned at 15 m a.s.l., both where the dunes abut the valley sides, and across the valley floor farther upstream.

At Boulder Beach and Sandfly Bay, the bay heads have extensive accumulations of dune sand, and are mapped as Domain C (Figure A3.3d). The inland boundary was placed at 20 m a.s.l., due to the heights to which the dunes mantle the valley sides.

Coastal flats around Hoopers Inlet, and the sand dune spit forming Allans Beach, were mapped as Domain C (Figure A3.3c). Around the inlet flats, the boundary was positioned at 4 m a.s.l., but in the east, the boundary position was raised to 10 m a.s.l. along the northern margin of the Allans Beach dunefield. On the western and southern shore of Hoopers Inlet, south of Battery Creek, lidar coverage is patchy, and mapping of the Domain C/A boundary relied mainly on interpretation of the 1:50,000 scale topographic map, satellite photography, and Google Earth StreetView along Hoopers Inlet Road.

Around Papanui Inlet, there are localised salt marshes that, along with the extensive Okia Flat dunefield, were mapped as Domain C (Figure A3.3c). The Domain C/A margin was placed at 4 m a.s.l. at the back of the salt marshes, but its position was lifted to 10 m a.s.l. where the dunefield abuts the hill slopes.

At Ryans Beach and Pipikaretu Beach, the bayhead was mapped as Domain C (Figure A3.3c). Along the western and northern margins of Ryans Beach, where the dunes are relatively high, the Domain C/A boundary was placed at 20 m a.s.l.

A3.3.3 Aramoana to Purakaunui

Kaikai Beach and Whareakeake (Murdering Beach) have well defined post-glacial sea cliffs, in front of which are dunefields. These dunefields were mapped as Domain C (Figure A3.3e), with the inland boundary positioned at 10 m a.s.l.

Long Beach lies at the seaward edge of a broad infilled valley enclosed by a sand dune barrier (Figure A3.3e). The post-glacial sea cliff is sharply defined close to the present coast, but otherwise the valley slopes merge with the infilled valley floor, suggesting that the dune barrier formed very shortly after culmination of post-glacial sea level rise, isolating the former inlet wave action. The Domain C/A boundary was placed at 6 m a.s.l. around the perimeter of the valley, and was raised to 10 m a.s.l. where sand dunes fringe the foot of the sea cliff.

At Purakaunui, a prominent post-glacial sea cliff is present only near the western end of the inlet, indicating that, like Long Beach, the dune barrier enclosing the inlet formed shortly after culmination of post-glacial sea level rise. There is minimal fan development at the mouths of the streams draining into the inlet, suggesting that it has received minimal post-glacial sediment infill. One localised area of Domain C was mapped at the Bay Road foreshore reserve, and another in the lower reaches of the Purakaunui Creek valley, with its inland boundary positioned at 10 m a.s.l. The sand flats and dunefields north of Osborne were also classed as Domain C, with the domain boundary at 6 m a.s.l., rising to 10 m where dunes abut the former sea cliff (Figure A3.3e).

Figure A3.3d Location map for liquefaction susceptibility domains around the southeastern side of Otago Peninsula.

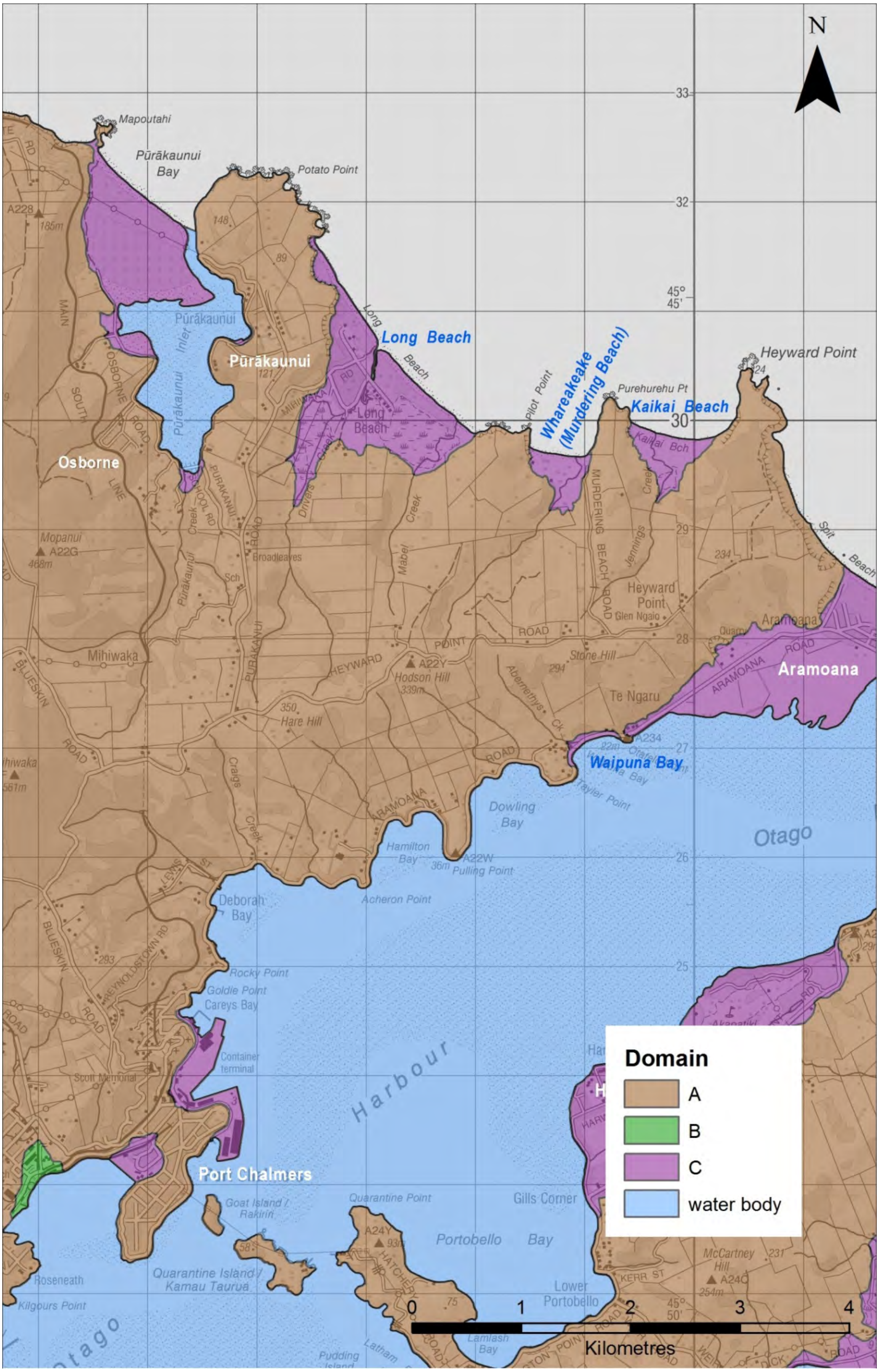

Figure A3.3e Location map for liquefaction susceptibility domains from Aramoana to Purakaunui.

A3.3.4 Blueskin Bay

The Waitati River has built a substantial fan into Blueskin Bay (Figure A3.3f). The river has a gravel bed and flows all the way to the inlet (i.e., it is not tidal). It is likely that this is a post-glacial fan-delta. The fan head is at about 15 m a.s.l., upstream of which the valley is of a uniform width. The broad fan downstream of the fan head was mapped as Domain C, and this domain was extended east around the head of Orokonui inlet, with the inland boundary positioned at 6 m a.s.l. This domain was also extended northeast of Waitati township, along the margin of Blueskin Bay, and includes the road and rail embankments and the lower reaches of minor fans draining to the bay.

At Evansdale, the infilled valley just south of the village appears to be a filled part of the bay, as it does not have a major stream flowing into it. This area and the lower reaches of Careys Creek are mapped as Domain C. The Domain C/A boundary was placed at 6 m a.s.l. rising to 10 m a.s.l. on marginal fans and up the Careys Creek valley.

The Warrington sand spit, and a localised sand flat at Doctors Point, were mapped as Domain C, with the inland boundary positioned at 6 m a.s.l.

A3.3.5 Karitane and Waikouaiti

Karitane and the Waikouaiti beach area have lidar coverage, but elsewhere on the lowland margins of the Waikouaiti River valley, mapping was based on information from soil maps, 1:50,000 scale topographic maps, satellite photography, and Google Earth StreetView.

Extensive remnants of a last interglacial marine terrace (see Section 5.4.1 of the main report) are preserved in the Karitane area. The terrace margins have been dissected by broad low-lying valleys that adjoin the coastal plain fringing the Waikouaiti River estuary. All the low-lying ground was mapped as Domain C (Figure A3.3g), based largely on the extents of Pomahaka, Clutha, Matau, Momona, Berwick and Koau soil groups mapped on the low-lying ground (growRuralDunedin). The area mapped as Domain C includes the swampy unnamed valley that drains the northern side of the Kilmog area (along which SH1 traverses), the Waikouaiti River valley floor upstream to the McGrath Road bridge, the post-glacial beach/dune complex seaward of Waikouaiti township, and low ground fringing the Waikouaiti estuary valley as upstream far as Koau soils are mapped, which includes the racecourse.

At the east-northeastern end of the Dunedin district are several tributary valleys draining to the Pleasant River estuary. The broad floors of these were mapped as Domain C (Figure 16 of main report), guided largely by the presence of the young soils groups mentioned above, as lidar coverage exists only close to the ocean coastline.

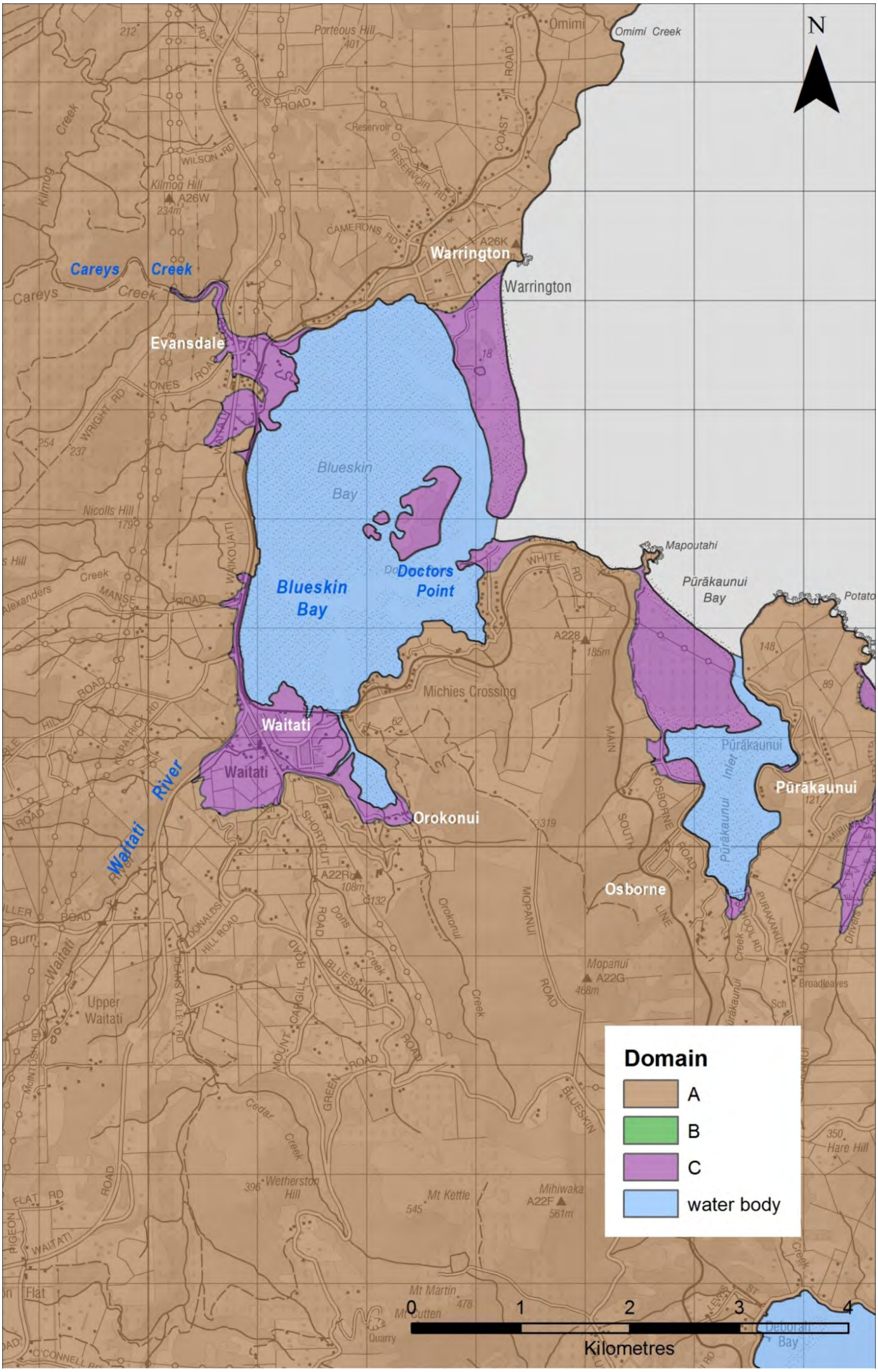

Figure A3.3f Location map for liquefaction susceptibility domains from Purakaunui to Warrington.

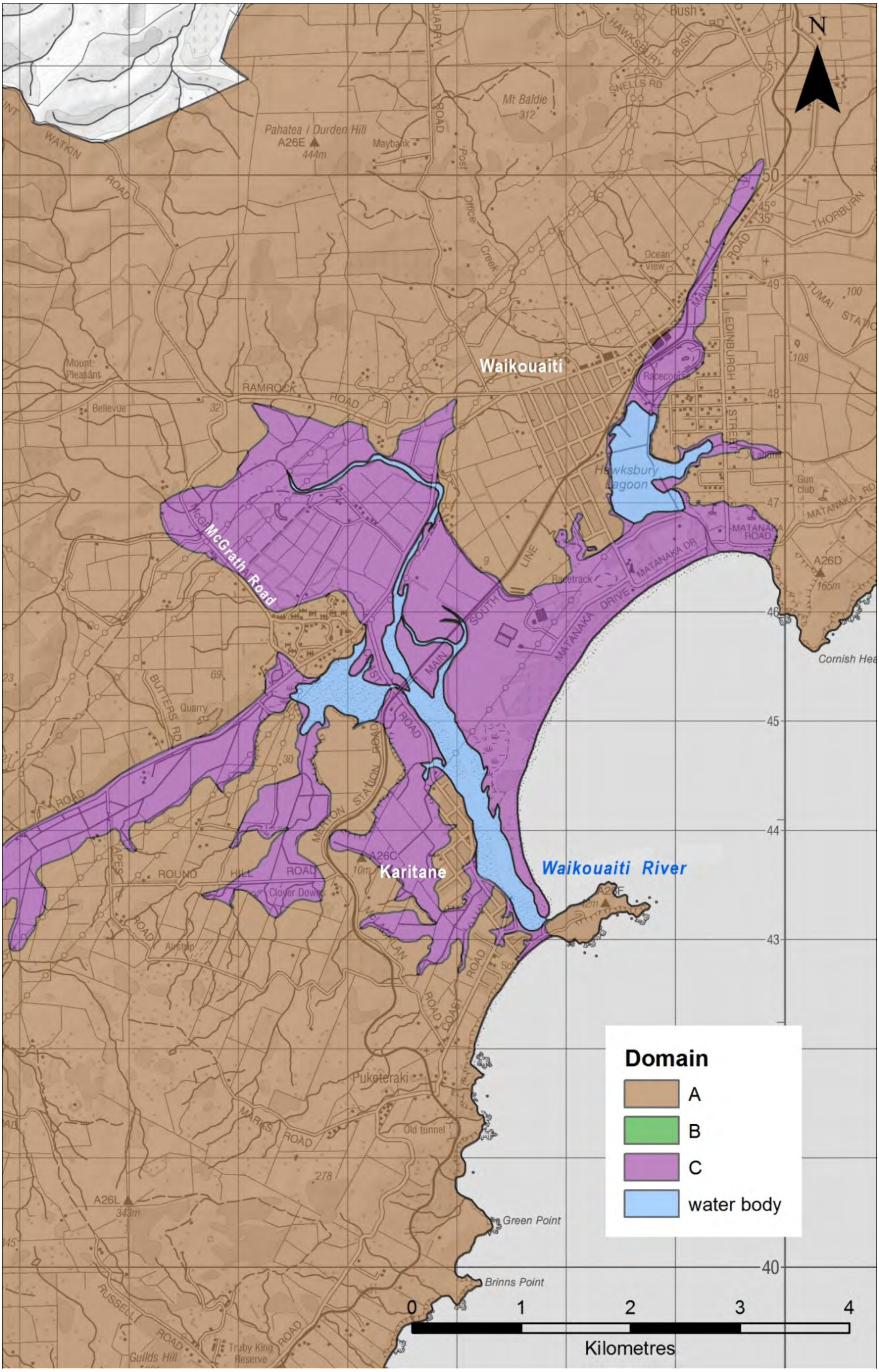

Figure A3.3g Location map for liquefaction susceptibility domains in the Waikouaiti area.

A3.4 APPENDIX 3 REFERENCES

Collins, B.W. 1950. Ground water in the Mosgiel District. Department of Scientific & Industrial Research, New Zealand Geological Survey, Water Resources Division, Hydrological Report No. 36, Christchurch.

All other references cited in Appendix 3 are listed in the reference section of the main report.

APPENDIX 4: DESCRIPTION OF THE GIS DATA SET

The GIS data are provided as an ArcGIS v10.0 file geodatabase:
GNS_Dunedin_liquefaction_study_6May2014

The file geodatabase consists of the polygon feature class: *liquefaction_domain_polygon*

The attribute fields of this feature class are listed below:

Field name	Data type	Field length	Content
Domain	Text	5 characters	A single letter code specifying the liquefaction susceptibility domain assigned to a polygon. Specific list of four values: A, B, C, or W
Description	Text	150 characters	A description of the general geological character of the designated domain. Specific list of three descriptive entries relating to each of domains A, B and C, as defined in Section 4.2.3 of the report. In addition, there is a descriptive entry water body, which is associated with the Domain attribute W.

The Coordinate System for the data is New Zealand Transverse Mercator, based on New Zealand Geodetic Datum 2000.

The boundaries between domain polygons are considered to have a positional accuracy of ± 50 m, related to the generalised topographic and photographic base information upon which the polygons are drawn. In addition, there is considerable geological uncertainty regarding the exact nature and extent of the subsurface sediments whose character defines the extents of Domain B and C. The mapped extents of each domain represent best estimates based on the interpretation of geological and gemorphological information, but the geological uncertainties are difficult to quantify from available data. The GIS map of liquefaction susceptibility domains is intended to provide only general guidance, and should not be used in isolation for any purpose that requires site-specific information.

Also provided is a layer file *liquefaction_domain_polygon.lyr* depicting how the data have been rendered on maps presented in this report.

The file geodatabase and layer file, along with a digital version of the report in PDF format, are provided on a computer disk inside the back cover of the printed report.

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