Bay of Plenty Regional Active Fault Mapping for Growth Areas

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EXECUTIVE SUMMARY

This report assesses the absence or presence of active faults at 10 sites identified for proposed urban development in the Rotorua, Whakatāne-Opotiki and Western Bay of Plenty areas (Figure 1.1). These sites are referred to in this report as Katikati, Omokoroa (Western Bay of Plenty), Ngongotaha, Pukehangi Road, Eastside, Airport, Peka, Wharenui (Rotorua), Whakatāne, and Opotiki (Whakatāne). Active faults are faults that have ruptured the Earth's crust all the way to the ground surface within the last 125,000 years, or last 25,000 years for faults in Taupo Rift (Langridge et al 2016). Although faults can often be located accurately (to within a few metres), there is currently no technology to prevent earthquake damage to buildings built across faults (Kerr et al. 2003). For this reason, we recommend the use of the Ministry for the Environment (MfE) guidelines to avoid building across hazardous faults (Kerr et al. 2003). The purpose of this report is to assess the absence or presence of active faults in proposed urban development areas so that development can take place in a manner that mitigates the fault rupture hazard.

Active faults are typically identified by a landscape feature of a fault scarp (elongated bump, step or groove in the ground). To identify active faults in the areas of this study, we examined high-resolution topography (LiDAR) and used existing knowledge of active fault locations and landform age information. The following summarises our assessment of active faults at the proposed urban development areas:

- No active faults were identified at the Katikati, Omokoroa, Ngongotaha, Pukehangi Road, Airport, Wharenui, Opotiki sites.
- The Coastlands site (Whakatāne) is almost certainly underlain by the Whakatāne fault but its exact location remains highly uncertain. We have reviewed all mapping of the Whakatāne fault and the most recent and reliable fault mapping shows the Whakatāne fault projecting toward the Coastlands site, but its precise location remains highly uncertain due to the young geological landforms at the Coastlands site. In addition to the uncertainty in fault location, the recurrence interval of the Whakatāne fault is also poorly constrained. We have reviewed information on the Recurrence Interval (RI) of the Whakatāne fault and consider the Whakatāne fault should be treated as potentially having a recurrence interval of <2000 years and categorised as a RI Class I fault. We could not provide a fault avoidance zone for the Whakatāne fault due to the large uncertainties in the fault location. To more precisely locate the Whakatāne fault under the Coastlands site we recommend the use of near-surface geophysical methods to assess where the fault is located.
- At the Eastside site (Rotorua), two north-trending topographic lineations have been identified, the scarps may be active faults scarps or former shorelines of Lake Rotorua. Based on the current data available, we cannot determine if the lineations in the Eastside area are active fault traces or not, and due to this uncertainty, we treat the lineations as possible active faults and place fault avoidance zones around the fault traces in accordance with the MfE Active Fault Guidelines. It may be possible to undertake field investigations to resolve whether the lineations are active faults or not, and we have provided recommendations on methods that could be used.

- The Peka site (Rotorua) has several active fault traces. At the northern boundary of the Peka site is a scarp of the Horohoro fault, which is a RI Class IV fault (RI >5000 - <10,000 years). On the eastern side of the Peka site is an unnamed fault scarp, and two other short (<500 m) fault traces have been identified in the Peka site. There is less certainty that the short fault traces are actually active faults, so we assign them “likely” and “possible” certainties. We have placed fault avoidance zones around the fault traces in accordance with the MfE Active Fault Guidelines.

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1.0 INTRODUCTION

Bay of Plenty Regional Council has identified areas for proposed urban development. GNS Science has been commissioned to assess the absence or presence of active faults on a total of 10 sites in the Rotorua, Whakatāne-Opotiki and Western Bay of Plenty areas (Figure 1.1). These sites are referred to in this report as Katikati, Omokoroa (Western Bay of Plenty), Ngongotaha, Pukehangi Road, Eastside, Airport, Wharenui (Rotorua), Whakatāne, Opotiki (Whakatāne). This report maps and identifies active fault hazards that may be present in these areas.

Sites at Omokoroa and Katikati (western Bay of Plenty) and Pukehangi Road (Rotorua) have already been assessed and results are attached in letter reports in Appendices 4 and 5, a summary of these results are provided in Section 6. The remainder of the sites are described in detail in this report.

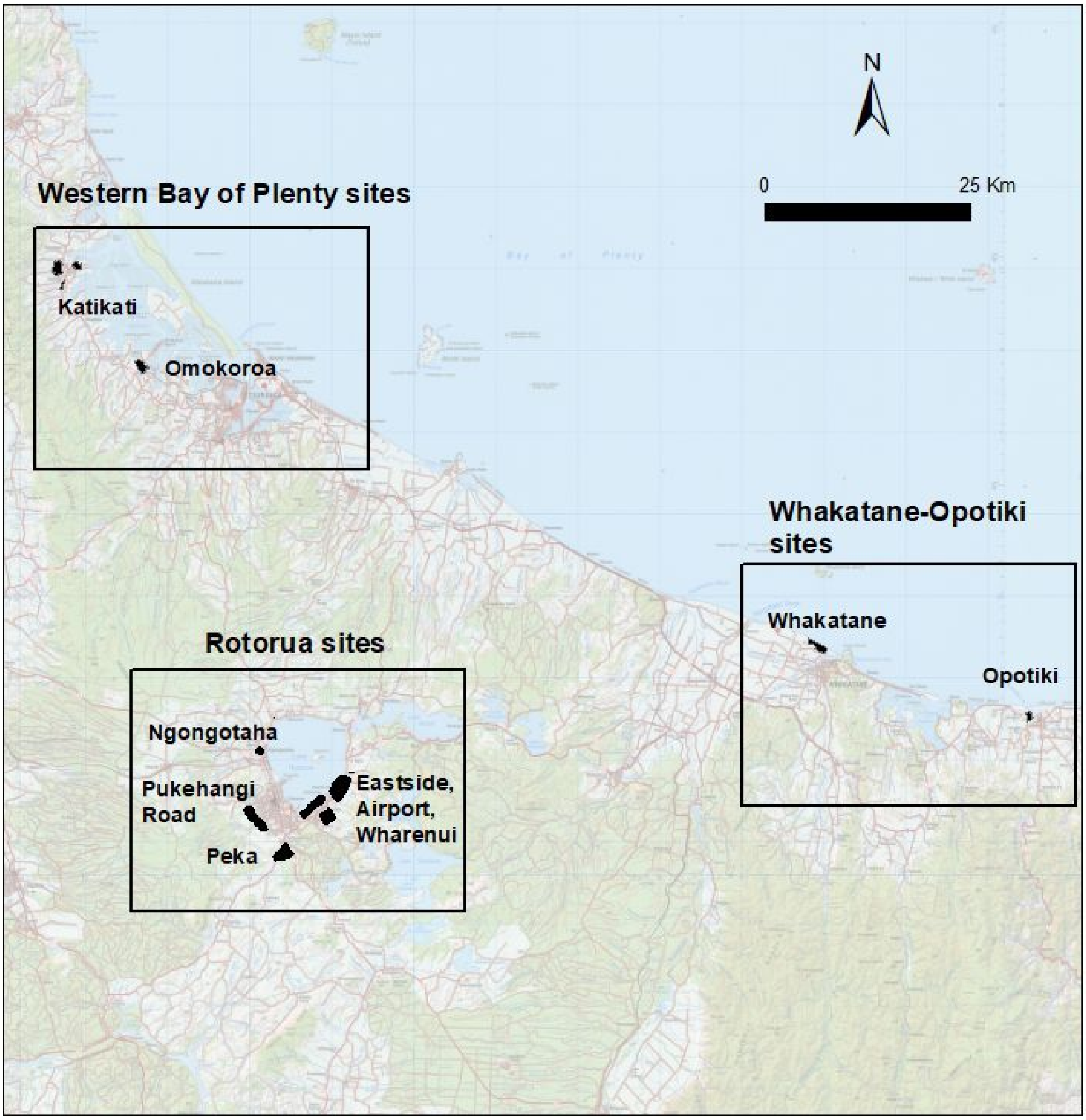

Figure 1.1 Location map of the proposed urban development sites (black polygons). There are 3 separate sites at Katikati and 2 sites at Pukehangi Road.

1.1 Active Faults and Their Hazards

Active faults, in the context used in this report, are faults that rupture the Earth's crust all the way to the ground surface. Surface rupture of an active fault in a large earthquake (usually ≥M_w 6) will result in a zone of intense ground deformation as opposite sides of the fault move past or over each other during an earthquake. Property damage can be expected, and loss of life may occur where buildings, and other structures, have been constructed across the rupturing fault. The 2010 Darfield (Canterbury) earthquake and the 2016 Kaikōura earthquakes provide recent examples of the impacts of ground surface rupture along faults (Van Dissen et al., 2011, 2018). If faults have ruptured in the recent geological history, they are defined as active and treated as faults that have the potential to rupture again in the future. The New Zealand Active fault database defines a fault as active if it has ruptured within the last 125,000 years, and for the Taupo Rift (also known as Taupo Volcanic Zone, TVZ), if it has ruptured within the last 25,000 years (Langridge et al 2016). This latter definition is related to the fast evolution of tectonic faulting in the TVZ (Villamor et al. 2017).

Key fault parameters that are relevant to this study are the fault rupture recurrence interval (RI), fault slip rate and single event displacement (SED). The RI is the time between large, ground-surface rupturing earthquakes on a particular fault and it is a measure of how active a fault is. The slip rate is another measure for fault activity and it represents its "velocity". It is usually expressed in mm/yr but in reality, the fault moves in jumps of several cm to several meters per rupture every few hundreds to thousands of years. The amount of displacement of the ground per rupture is referred to as the SED. This represents the amount of permanent deformation that occurs along a fault trace when it ruptures and it is the hazard that will impact buildings located on the fault.

1.2 Tectonic Setting: The Taupo Rift and the North Island Dextral Fault Belt

New Zealand sits astride the boundary between two tectonic plates, the Australian Plate and the Pacific Plate, where relative plate motion is obliquely convergent across the plate boundary at rates of 48–40 mm/year from north to south (Wallace et al. 2007) (Figure 1.2). East of the North Island, the plate boundary is defined by the Hikurangi subduction margin; this is a collisional plate boundary where the Pacific Plate dives beneath the Australian Plate (Figure 1.2). The Hikurangi subduction margin dominates the tectonics of the North Island and there are three components of the plate boundary present in the Bay of Plenty: The Extensional Western North Island Faults domain, the Extensional Havre Trough — Taupo Rift and the North Island Dextral Fault Belt (Figure 1.2). These tectonic domains have been defined based on geographic groupings of active faults that have similar geometries and kinematics (Litchfield et al, 2014; Stirling et al. 2012). The tectonic domains are described in greater detail below.

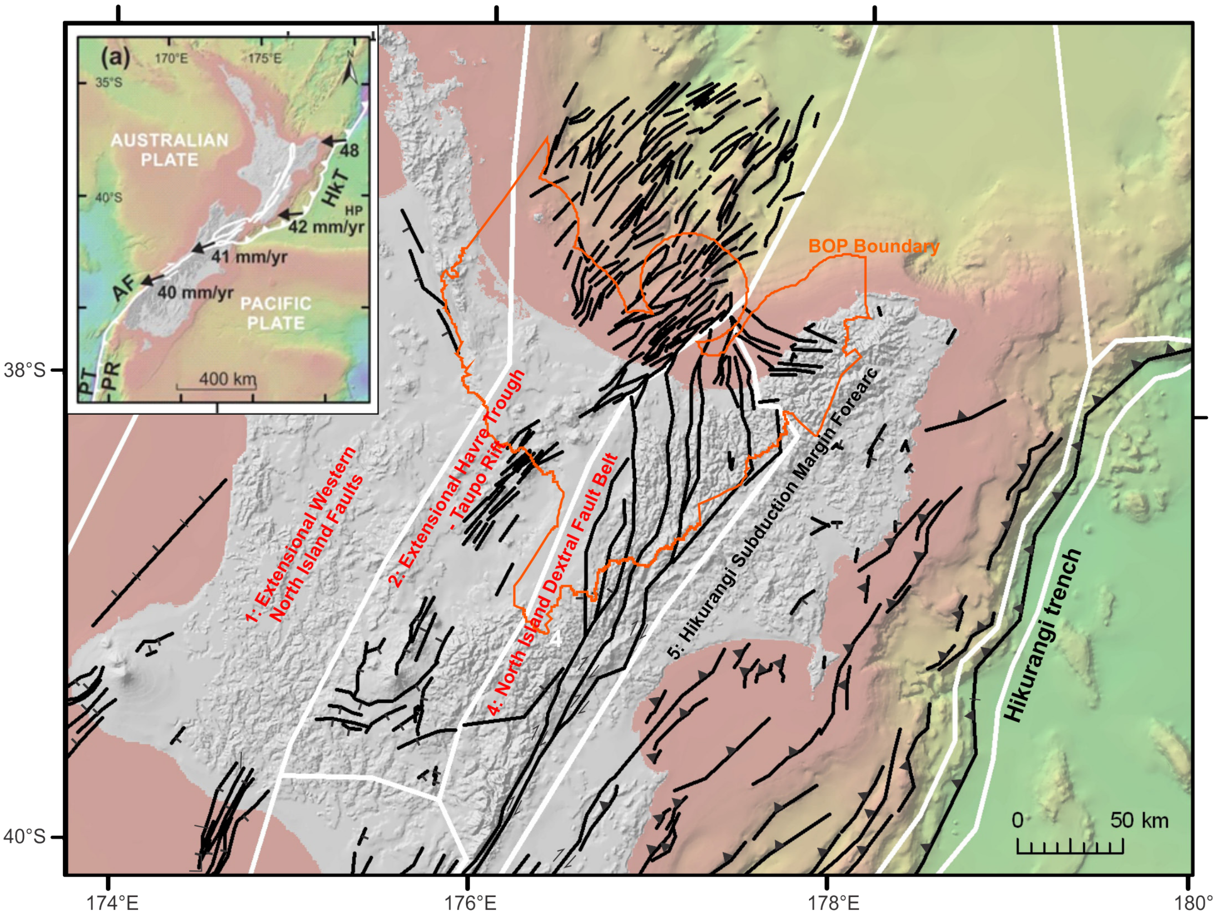

Figure 1.2 (a) New Zealand plate boundary setting (black arrows are plate motion sense and rates from Wallace et al., 2007). HkT: Hikurangi trench, AF: Alpine fault, PT: Puyesgur trench, PR: Puysegur Ridge. (b) Groupings of active fault sources into tectonic domains as per Stirling et al (2012) and Litchfield et al. (2014) The black lines represent fault sources used in the model of active faulting in New Zealand (Litchfield et al., 2014). The Bay of Plenty Regional Council Boundary is shown in orange. The study sites of this report fall into three tectonic domains (highlighted in bold red, boundaries defined by the white lines): The Extensional Western North Island Faults domain, the Extensional Havre Trough — Taupo Rift and the North Island Dextral Fault Belt.

1.2.1 Extensional Western North Island Faults

The Extensional Western North Island fault domain has very few active faults and the active tectonics of this domain is related to back-arc extension. In the present day, most active back-arc extension is concentrated in the Taranaki Region and the Hauraki plains. The western North Island faults have very low rates of activity (0.1–1.5 mm/yr; (e.g., Nodder et al. 2007; Townsend et al. 2010). The Katikati and Omokoroa sites are located within the Extensional Western North Island fault domain (Figure 1.2) and no active faults have been previously mapped in that area.

1.2.2 Extensional Havre Trough — Taupo Rift

The Rotorua growth sites are located in the onshore part of the Taupo Rift domain, also referred to as the Taupo Fault Belt (Grindley 1960). It is situated within the active volcanic arc, the Taupo Volcanic Zone (e.g., Cole et al. 1995; Rowland & Sibson 2001). Fault zones within the Havre Trough - Taupo Rift mostly strike northeast and are typically short (c. 4–33 km) and closely spaced. All appear to have a normal sense of movement (Figure 1.3). Net slip rates on individual fault zones are thought to range from 0.05 to 4 mm/yr (Villamor & Berryman 2001, Lamarche et al. 2006). A northward increase in extension rates in this domain has been previously recognised, from 2.3 ± 1.2 mm/yr south of Mount Ruapehu (Villamor & Berryman

2006), to 4.4 +2.4/-1.9 mm/yr near Rotorua (Villamor & Berryman 2001) to 13 ± 6 mm/yr immediately north of the Bay of Plenty coast (Lamarche et al. 2006). Typical SEDs for the area range between 20 cm to 2.3 m and typical RIs between 200 and 14,000 years (e.g., Berryman et al. 2008; Nicol et al. 2010; Stirling et al 2012).

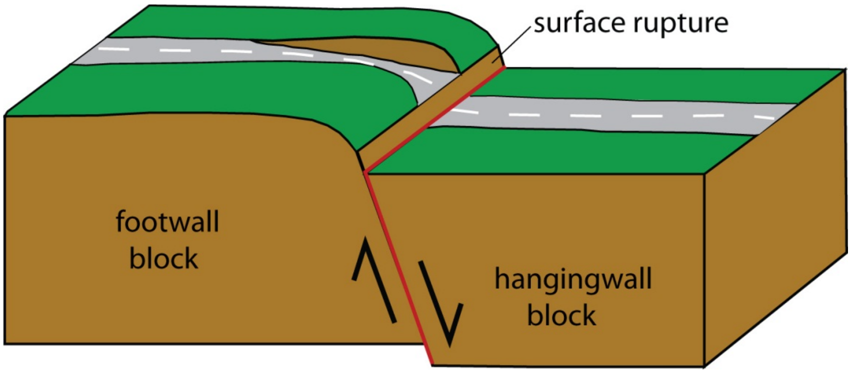

Figure 1.3 Block model of a normal dip-slip fault, typical of the Taupo Rift faults. The relative movement of the blocks is vertical and in the dip direction of the fault plane. The hanging-wall block has dropped down, enhancing the height of the fault scarp.

1.2.3 North Island Dextral Fault Belt

The Whakatāne and Opotiki sites are located within The North Island Dextral Fault Belt (Figure 1.2, also referred to as the North Island Fault System, Mouslopoulou et al., 2007). The Coastlands near Whakatāne is actually located at the boundary between the Taupo Rift and the North Island Dextral Fault Belt (NIDFB). The NIDFB is a c. 470 km long series of faults within and along the eastern margin of the North Island's axial ranges (Figure 1.2). Fault zones within the system typically strike north-northeast and are predominantly dextral strike-slip at the ground surface, that is the blocks on each side of the fault mainly move sideways (Figure 1.4). Further north, the faults bend to the north and fault displacement becomes progressively more oblique with an increasing component of normal faulting. In the Bay of Plenty region, the faults of the NIDFB are predominantly normal faults, with a subordinate strike-slip component. Accompanying the northward change in the style of faulting is a decrease in overall slip rate (Van Dissen & Berryman 1996; Beanland & Haines 1998; Mouslopoulou et al. 2007). Net slip rates on individual fault are up to 11 mm/yr (dextral) in the south near Wellington (Carne et al. 2011) but are no more than 2.5 mm/yr (dextral-normal) in the north (Mouslopoulou et al. 2007). Typical SEDs for the area range between 0.5 to 5m and typical RIs between 400 to 14,000 years (e.g., Mouslopoulou et al. 2007; Stirling et al. 2012).

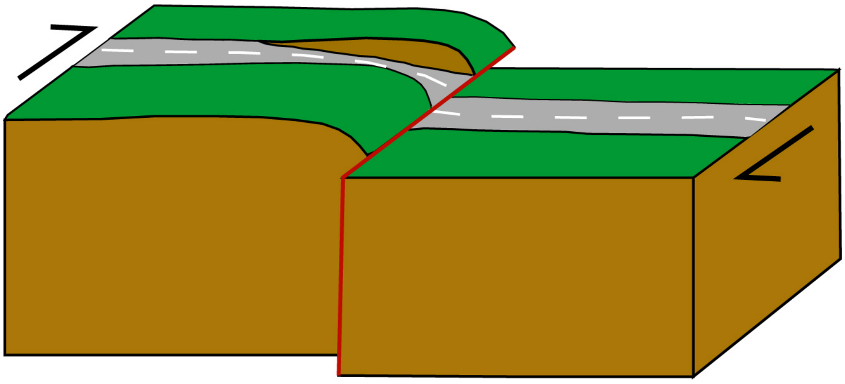

Figure 1.4 Block model of a section through a strike-slip fault (red line) that has recently ruptured. The fault is a right-lateral fault as shown by the black arrows and by the sense of movement across the two blocks and a right separation across the road.

1.3 Local Geologic Setting

To assess the activity of faulting (i.e. the slip rate and when the fault last ruptured in a large earthquake), it is important to understand the age of the landscape across which the faults lie. Figure 1.5 shows a generalised geological map of the areas surrounding the proposed development sites. The various pink shades of colour that dominate the map represent volcanic rock that have intermittently erupted from volcanic centres in Coromandel and other areas of the central North Island since around 11 million years ago.

The light-yellow colours delineate areas of young (12,000 years and younger) river and coastal sediments. The green-blue colours towards the bottom right of the figure represent sandstone and mudstone (greywacke) and are the oldest rocks in the area (100–200 million years).

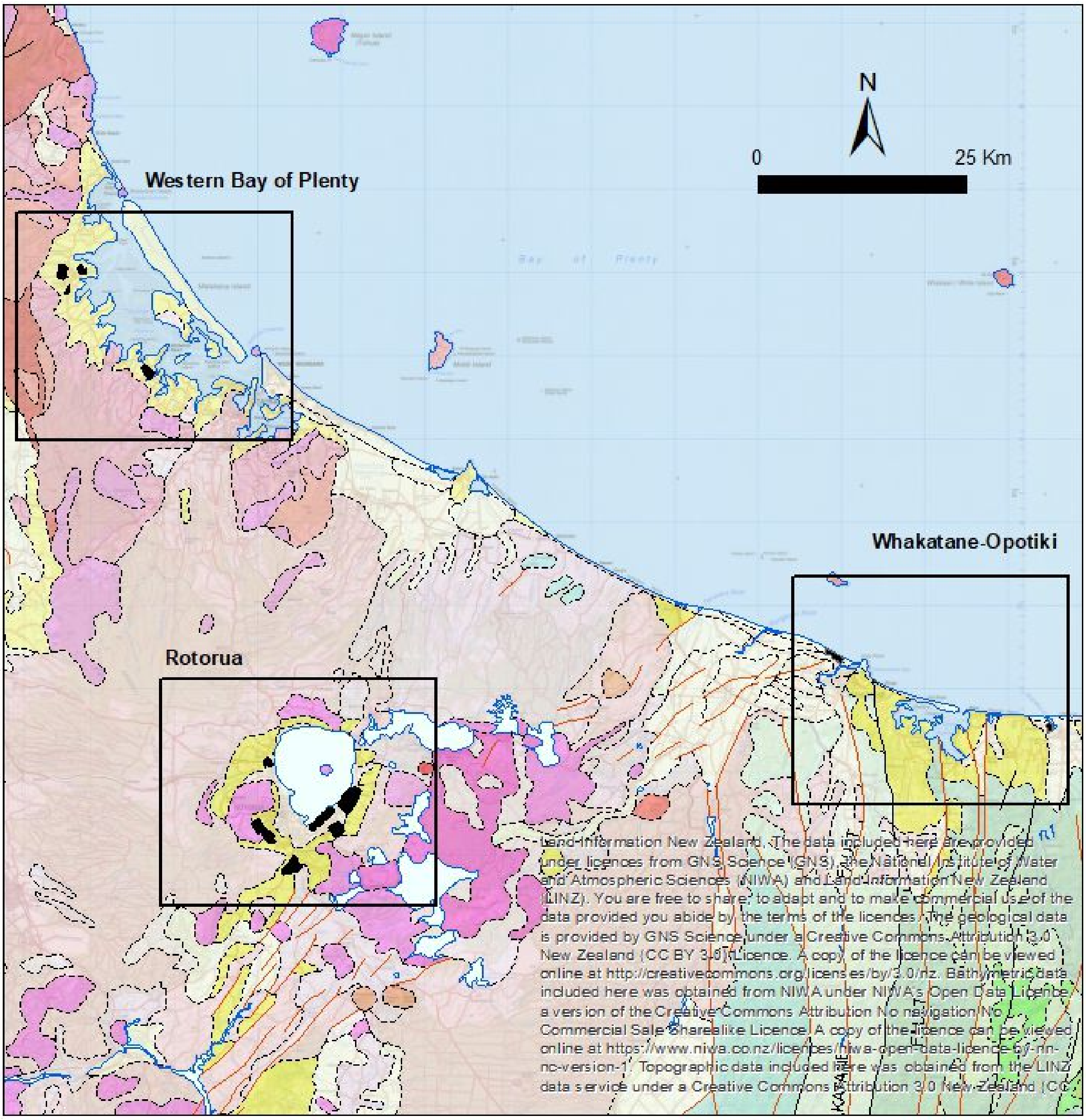

Figure 1.5 Simplified geological map of the Western Bay of Plenty-Rotorua-Whakatāne region (from Edbrooke et al. 2014). Proposed development areas are coloured black. The area is dominated by volcanic rock (pink shades). Lake and coastal areas are surrounded by lake and river or marginal marine deposits (yellow shades). Greywacke sandstone and mudstone south of Whakatāne (green-grey) form the oldest rock units in the area.

2.0 METHODS

For this study we followed the methodology outlined by Clark et al. (2017) and Villamor et al. (2010) for active fault mapping in the western Bay of Plenty and Rotorua District. Here we present a slightly modified version of the methods described by Clark et al. (2017). In this study, we follow the MfE Active Fault Guidelines (Kerr et al. 2003) to assess the areas of land development that may need special considerations for building with respect to active fault lines, and the ground deformation hazard they pose. The main considerations are: the location where an active fault plane will rupture the ground; and the level of activity of the fault (measured by the recurrence interval, further explained below), which dictates what type of buildings may, or may, not be permitted on, or near, that fault (Tables A1.1 and A1.2).

2.1 Mapping the Location of Active Faults from Their Geomorphic Expression

Active faults are typically identified by a landscape feature of a fault scarp (elongated bump, step or groove in the ground); the scarps tend to be relatively linear and usually cut across other landforms, such as river terraces (terrace surfaces or risers), hill slopes, old shorelines, abandoned river channels, etc. Often, it's possible to know the age of the main geomorphic features (landforms) in the landscape; therefore, the history of fault activity can be deduced from the age of the displaced features.

Following the MfE Active Fault Guidelines, we map active or potentially active faults in the areas of interest and examine the relationship between fault scarps and the age of the geomorphic surfaces to assess the activity of the fault. In the TVZ, faults have a normal sense of movement, and they typically form clear fault scarps with the land on one side of the fault higher that the other side, resulting from vertical displacement across the fault during rupture (Figure 1.3). Therefore, faults are typically identified as sublinear features that cross geomorphic surfaces and display clear differences in height of the land across it. Fault scarps may cut across surfaces of different ages or only be present on certain age surfaces. They may also be at the boundary between two different geological units (rock types).

To identify faults scarps it is best to use the highest resolution topographic models available, and for this project we have used LiDAR data collected in 2014 and provided by BOPRC. For the analysis, 1 m gridded bare earth LiDAR data was used, and we combined hill-shade and digital elevation models (DEMs) and derived contours to identify landscape features. In addition to the high-resolution topographic models, we have also used geological data that has a bearing on active faults; namely the New Zealand Active Faults Database (Langridge et al. 2016), geological mapping in QMAP (Edbrooke 2001; Leonard et al. 2010; Heron (custodian) 2014; Edbrooke et al. 2014), various journal publications and GNS Science reports. Where the scarp of an active fault has been identified, it has been mapped in a GIS using the most recent set of active fault trace GIS attributes used by GNS Science. In accordance with the MfE Active Fault Guidelines, we place a fault rupture hazard zone around the fault trace and an additional setback buffer of 20 m width in order to construct what is defined in the MfE Active Fault Guidelines as a Fault Avoidance Zone (FAZ). The fault rupture hazard zone is defined by the deformation width of fault; that is, from the line of the fault trace we assess the distance over which fault rupture could reasonably be expected to occur. We typically place the fault line in the middle of a scarp, but fault rupture may occur at the base of a scarp or at the top, and there may be distributed deformation for some distance from the fault line. For very sharp and well-defined fault scarps the fault rupture hazard zone may be as little as 20 m either side of the faults line (total width 40 m) but for less well-defined, more complex or broader faults scarps the fault rupture hazard zone is wider. For a more complete description of the components of a Faults Avoidance Zone, see the description in Villamor et al. (2010).

2.2 Identifying Levels of Fault Activity

The MfE Active Fault Guidelines require the assessment of the recurrence interval (RI; see description above) of the fault as the parameter to evaluate fault activity. This parameter is best evaluated where the fault plane can be exposed (for example, by trenching across a fault scarp). For this study we rely on previously published work to assess the RI of identified faults. Where an RI for a fault has not been previously assessed we can use relationships between slip rate, SED and RI to estimate the RI of a fault. If we can calculate the slip rate and assume a reasonable SED, we can derive a preliminary RI. The MfE Active Fault Guidelines categorise ranges of RIs into RI Classes. In the MfE Active Fault Guidelines these RI Classes are in turn tabulated to show which types of buildings (as defined by Building Importance Class) are permitted for each RI Class (Tables A1.1 and A1.2; Kerr et al 2003).

3.0 COASTLANDS (WHAKATĀNE)

The Coastlands site is located on sand dunes and alluvial sediments on the northern side of the Whakatāne River. Two faults, the Whakatāne fault and the Edgecumbe fault, have been mapped as running through the site or projecting toward the site. However, the fault mapping data sources show variation in the fault locations and it remains highly uncertain exactly where the active fault traces are located due to the young geological landforms that underlie the Coastlands site. In addition to the uncertainty in fault location, the recurrence interval of the Whakatāne fault is also poorly constrained. In the absence of detailed field and geotechnical studies, we cannot provide new estimates for the location and RI of the Whakatāne fault in the Coastlands site, but in this section, we review available data and evaluate the quality of information.

3.1 Geology

The Coastlands site is located almost entirely on a Holocene (<12,000 years) sand dune and beach ridge complex (Figure 3.1). The southern part of the site is located on swamp/alluvial sediments deposited by the Whakatāne and Rangitaiki Rivers. The distribution of volcanic ash across the Rangitaiki Plains allows some constraints to be placed on the ages of the landforms. The shoreline at the time of the Whakatāne tephra deposition (5526 ± 145 years BP, Lowe et al. 2013) was 5 km further inland from the Coastlands site, and the shoreline at the time of the Taupo tephra deposition (AD 232 ± 10 years) was several hundred metres inland from the Coastlands site (Figure 3.2B, Pullar 1985). The shoreline at the time of Kaharoa tephra deposition (AD 1314 ± 12 years) is mapped mostly on the northern edge of the Coastlands site but the detailed cross-sections of Pullar (1985) show the closest site with the Kaharoa tephra is 2 km west of the Coastlands site, so it is likely that the Kaharoa shoreline is inferred through the Coastlands site. All this age information suggests the alluvial and coastal landforms underlying the Coastlands site are <~1700 years old. This is an important constraint because the absence of a fault scarp across the site only implies no fault rupture within the past 1700 years.

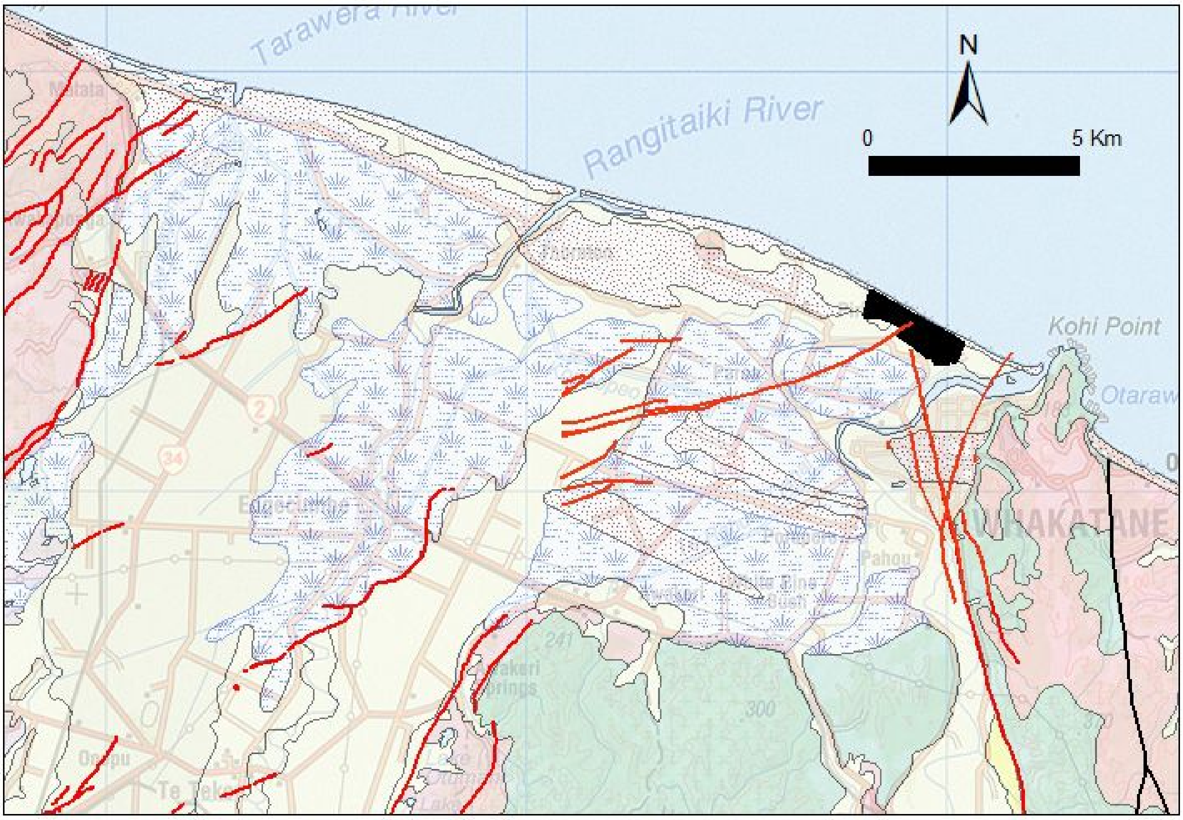

Figure 3.1 The geology around the Coastlands site (black polygon) consists of swamp (blue patterned polygons) and river sediments (yellow). Volcanic rock (pink) and greywacke (blue) border the Rangitaiki plains. Numerous north to northeast-trending active faults (red lines) cut through the plains. Geological map units are from Leonard et al., 2010.

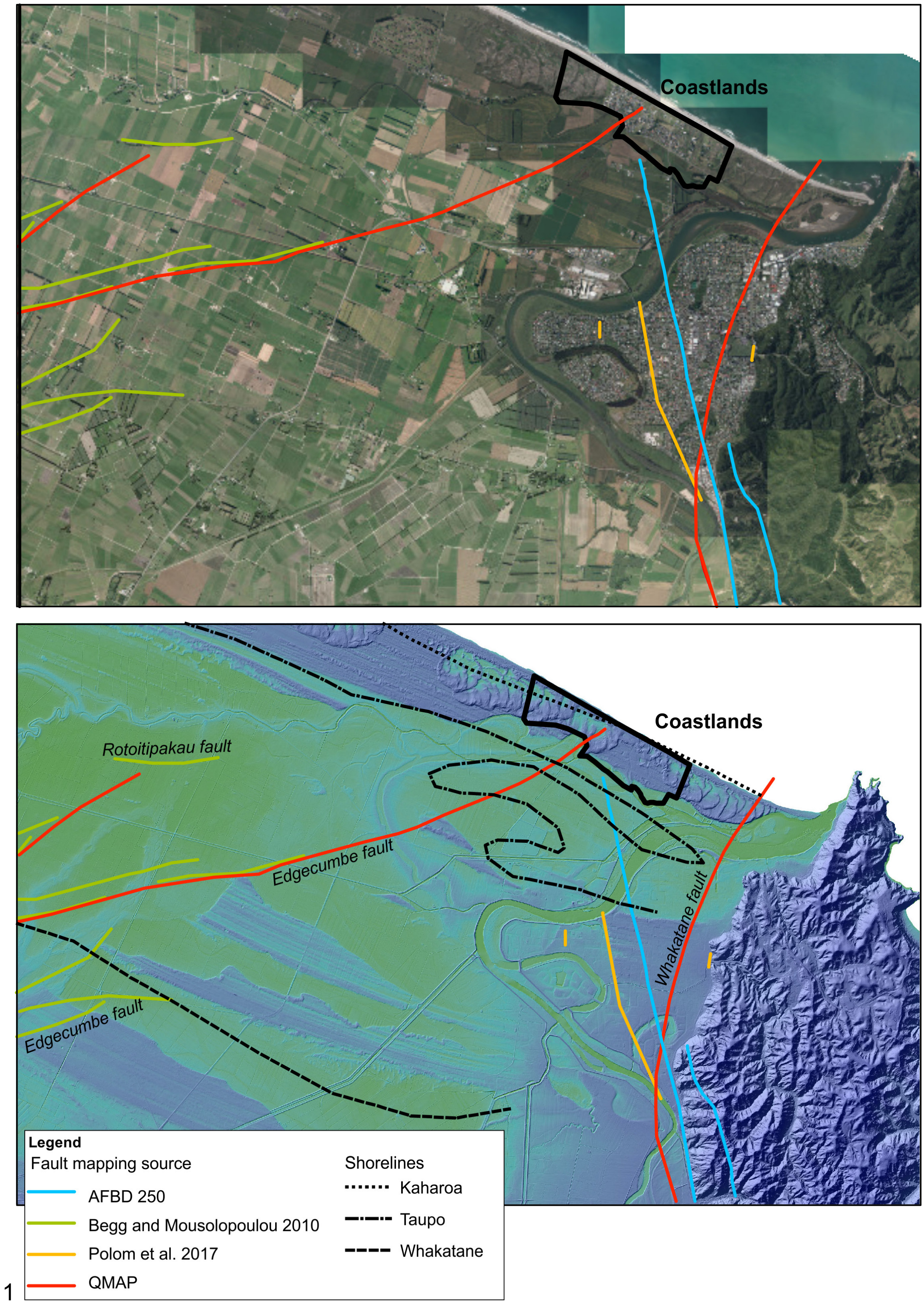

Figure 3.2 (A) Aerial image of the Coastlands site and surrounding areas showing the location of active fault traces mapped by various data sources (AFDB - Langridge et al. 2016; Begg and Mouslopoulou, 2010; Polom et al. 2017, and QMAP geology - Leonard et al. 2010). (B) LiDAR DEM with the same active fault traces as (A) and the position of past shorelines mapped by the extent of tephras (Kaharoa, AD 1314 ± 12 years; Taupo, AD 232 ± 10 and Whakatāne, 5526 ± 145 calibrated years BP, ages from Lowe et al. 2013).

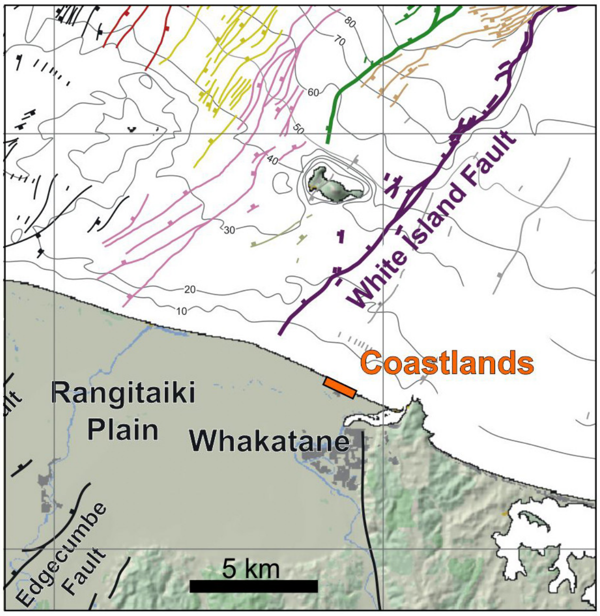

Figure 3.3 Offshore active faults of the Whakatāne Graben; figure adapted from Lamarche et al. (2006). This figure indicates the location of the White Island fault (possibly the offshore continuation of the Edgecumbe fault) relative to the Coastlands site.

3.2 Review of Active Fault Locations

We have compiled the locations of active fault traces from four data sources in Figure 3.2.

- In green are the traces of the Edgecumbe and Rotoitipakau faults mapped by Begg and Mouslopoulou (2010); these traces project toward the Coastlands site but stop within 3 km of the present shoreline. The faults may stop at the mapped location or the faults may continue to the northeast but without a surface expression. The lack of surface expression could be because there has been no fault surface rupture within the relatively short time period since deposition of the alluvial and beach ridge sediments (since 5500 – 1700 years BP). The traces of the Edgecumbe fault shown in Figure 3.2 did not rupture in the M 6.5 1987 Edgecumbe earthquake. The fault mapping by Begg and Mouslopoulou (2010) is based on lineation identification on LiDAR DEMs; criteria to identify a lineation as a fault scarp included: (1) the lineament formed in the 1987 Edgecumbe earthquake; 2) the lineament is a lateral continuation of a scarp that ruptured during the Edgecumbe earthquake; 3) the lineament represents a topographic scarp that trends parallel or sub-parallel to known faults (i.e. NE–SW); 4) the lineament represents a scarp that cuts across depositional or erosional surfaces (such as beach ridges, abandoned stream channels and alluvial fans) at a high angle.
- In red are traces of the Edgecumbe, Rotoitipakau and Whakatāne faults, as mapped by Leonard et al., 2010, although these traces have been largely superceded by more recent work, particularly the AFDB described below. The Edgecumbe fault is mapped as a concealed or inferred subsurface fault into the Coastlands site. The LiDAR topography does not show evidence of a fault scarp so we assign a low certainty to this fault location but acknowledge that continuation of the Edgecumbe fault into the Coastlands site is a possibility. The Edgecumbe fault may transfer slip onto the offshore the White Island fault (Figure 3.3). The White Island fault has a slip rate of 1 mm/yr and is located significantly (3–4 km) west of the Coastlands site, suggesting that the Edgecumbe fault does not project toward the Coastlands site, or if it does it only carries a very minor amount of slip as most slip transfers offshore to the Whaite Island fault.The Whakatāne fault, as mappped by Leonard et al.(2010) does not run through the Coastlands site.

- The New Zealand Active Faults Database (AFDB) maps the Whakatāne fault through the residential area of Whakatāne and its mapped location stops just 100 m south of the Coastlands site boundary (blue lines, Figure 3.2). The fault trace of the AFDB does not follow a surface scarp but it does follow the strike of the Whakatāne fault from its last well constrained location south of Whakatāne where the fault forms a distinct topographic break between alluvial sediments of the Whakatāne floodplain and the hillsides to the east.
- The most recent and best-constrained mapping of the Whakatāne fault (orange lines, Figure 3.2) is by Polom et al. (2017). Polom et al. acquired high resolution shear wave seismic reflection profiles across the Whakatāne fault using a specialised piece of equipment called a land streamer. The land streamer source and receiver technology used in the study was specially designed for use on roads and in built-up areas. The location of the Whakatāne fault identified by Polom et al. aligns with a topographic scarp and is parallel with the fault mapped in the AFBD. The fault trace mapped by Polom et al. (2017) supercedes the mapping in the AFDB and QMAP. Unfortunately, no land streamer profiles were acquired north of the Whakatāne River and the northwards continuation of the Whakatāne fault toward the Coastlands site is uncertain. It is likely there is not surface expression because the sediments are younger than the last fault rupture.

In summary, none of the fault traces that are currently mapped across or very close to the Coastlands site are based on observed geomorphic features. We do not think the Edgecumbe fault projects throughs the Coastlands site. There are no geomorphic scarps of the Edgecumbe fault near the Coastlands site, and it is likely most slip on the Edgecumbe fault is transferred onto the White Island fault, which lies offshore to the west of the Coastlands site (Figure 3.3). As such, we consider the Whakatāne fault to be of greater significance to the Coastlands site. We consider the Polom et al. (2017) traces of the Whakatāne fault to be the best constrained fault traces. However, the northernmost locations where they were mapped are too far away from the Coastlands the site to be able to rely on simply projecting the fault line to the Coastlands site. Projecting the Whakatāne fault from its last well constrained location toward the Coastlands site will not be useful for the purpose of this study because the uncertainty in the location of the fault will be so large that the resulting fault avoidance zone may occupy most of the study site. We recommend a different approach as described below in Section 3.3.

3.3 Recurrence Interval of the Whakatāne fault

The recurrence interval of the Whakatāne fault is poorly constrained. Data bearing on this comes from two main sources: paleoseismic data and estimates based on the slip rate.

Paleoseismic data: Paleoseismic data has been obtained from fault trenches at Ruatoki North, Wharepora and Ruatahuna. Trenches excavated by Mouslopoulou et al. (2009) at Ruatoki North show the last ground surface rupturing earthquake was at ~600–700 years BP. At Ruatoki North they found evidence for three earthquakes in the past 10,000 years. Dividing the 10,000-year time span by three earthquakes yields an RI of ~3300 years. However, there is a time gap of 4000 years within the 10,000 years' timeframe, so this RI is a maximum. At Wharepora, one paleoearthquake was found in the past ~3700 years. At Ruatahuna, two paleoseismic trenches were studied by Mouslopoulou et al. (2009). They obtained evidence of two earthquakes in the past 2500 years, then a 5000-year hiatus with no ground surface rupturing earthquakes, then another two earthquakes in the interval between 7500 and 9500 years before present. These four paleoearthquakes over 9500 years give a recurrence interval of ~2375 years (= RI Class II, >2000 to ≤ 3500 yr), but if only the two most recent events are considered this yields a recurrence interval of ~1250 years (= RI Class I, ≤ 2000 yr).

Slip rate scaling relationships: The slip rate of the Whakatāne fault is estimated at 1.3–3.1 mm/yr, and using scaling relationships for a fault of this slip rate, the National Seismic Hazard Model (Stirling et al. 2012) has a recurrence interval for the Whakatāne fault of 1500=min; 2400=average, 4425 =max.

As compiled above, the uncertainty in the recurrence interval for the Whakatāne fault suggests that it can either be a Recurrence Class I (<2000 yr) or II (>2000 to ≤ 3500 yr) fault. In the Whakatāne city area, the fault could have displaced the surface (geomorphic scarp along Polom et a. line) which is dated at c 5500 years (based on shorelines shown in Figure 3.2). However, it seems that the fault has not ruptured the plains further north in the area where the surface should be ~ 1,700 years old (based on former shorelines; Figure 3.2). This suggests that the Rangitikei Plains section of the fault may not rupture at the same time as the section in Ruatoki North, as the last event there is dated ~600–700 years BP, and thus extrapolating the data from that site to Whakatāne City can be misleading. It is also possible that the ages of the plains are not well constrained. Also, in the Taupo Rift, there is evidence for faults to behave in a non-episodic way. That is a fault ruptures with small RIs (e.g., 600–1000 years) for a length of time, and then switches to large recurrence intervals (e.g, 3000–10,000 years) for another time period (e.g., Nicol et al. 2010). From the literature review on the Whakatāne fault, we could also interpret that the fault may behave in a non-episodic way. For all these reasons, we consider the Whakatāne fault should be treated as potentially having a recurrence interval of <2000 years and categorised as a RI Class I fault. See some recommendation below to further constrain the RI of the Whakatāne Fault in the study area.

3.4 Recommendations

3.4.1 Locating the Fault Trace at Coastlands

Because the fault has not ruptured the land surface north of the Whakatāne urban area, near surface geophysical methods (methods that image the soil layers below the surface) will need to be used to assess where the fault is located. Within the resources available in New Zealand, we recommend that weight-drop seismic reflection (WDSR) methods are used to assess the location at Coastlands. Ideally two profiles are needed: one along the beach; and a parallel one along the “greenfield” area southwest of the Coastland site. Two profiles will be needed to be able to assess fault strike across the site and appropriately project the fault into the site. This is the ideal method but will also be costly. An alternative less expensive but also probably less effective approach will be to undertake Ground Penetrating Radar (GPR) in two or three profiles that cross the “projected fault” in the section between the Whakatāne River and the Coastlands areas. GPR is inexpensive but unfortunately does not work when strong electrical conductors are present in the ground, such as clay and water. Therefore, the technique will need to be trialled in the environment prior to the survey. A combination of both WDSR and GPR would be ideal.

3.4.2 Constraining the Whakatāne fault RI Close to Whakatāne City and Coastlands

The best method to assess the RI of a fault is the excavation of paloeseismic trenches to expose the soil layers and the fault plane. Analysing how the fault deforms the layers and dating the layers that are, and are not, displaced by the fault will help assess how often the fault ruptures. Also dating the surfaces that are displaced, as well as those that are not displaced, by the fault will give some idea of when the fault ruptured last. The location to undertake such a study near the Whakatāne fault are limited because of the built environment and the location of Taneatua Road along the fault trace south the city. However, there are a few places where a trench could be excavated. Because of the difficulty in locating the fault scarp on the LiDAR derived DEM, supporting geophysical investigations (e.g. GPR) would need to be undertaken at the selected sites to better constrain the location of the fault plane.

Also dating of the geomorphic surfaces inside and north of the Whakatāne urban area will help constrain the timing of past fault ruptures. Geomorphic dating can be done in conjunction with the GPR survey suggested for fault location above, supported with a few shallow cores and small exploratory trenches to extract the sediments and date them.

4.0 OPOTIKI

The Opotiki development site is not located close to any known active faults, however it is located on young (<12,000 years) alluvial sediments that could be masking active faults that have not ruptured during the Holocene. Here we review the geology and geomorphology of the Opotiki site and justify our conclusion that there are no active faults underlying the Opotiki development site.

4.1 Geology

The Opotiki township is located on the Holocene alluvial floodplain of the Waioeka and Otara rivers (Figure 4.1). East and west of Opotiki are low flat-topped hills formed of fluvial and/or marine terraces. Opotiki lies at the northern end of the North Island Dextral Fault Belt (NIDFB, see Section 1.2.3). Through the axial ranges south of Opotiki (around the Lake Waikaremoana area), the faults of the NIDFB are dominantly strike-slip but as they head toward the Bay of Plenty, they change fault slip sense to become more normal in style (Figure 1.3), along the way decreasing in slip rate and increasing in recurrence interval. Opotiki is located at the eastern edge of the NIDFB; to the west is the Waiotahi fault and to the southeast of Opotiki is the Koranga fault. Little is known about the slip rates of either of these faults and they have not been the subject of any paleoearthquake investigations. Slip rates of about 1 mm/yr have been obtained on the Waiotahi Fault (Mouslopoulou et al. 2007) and Clark and Ries (2016) have previously assigned the Waiotahi Fault an RI Class of II (>2000 to ≤3500 yr), although this has a high degree of uncertainty. Slip rates have not been obtained from the Koranga Fault but the Koranga Fault is generally less well-expressed in the topography than the Waiotahi Fault, so it probably has a lower slip rate and longer recurrence interval.

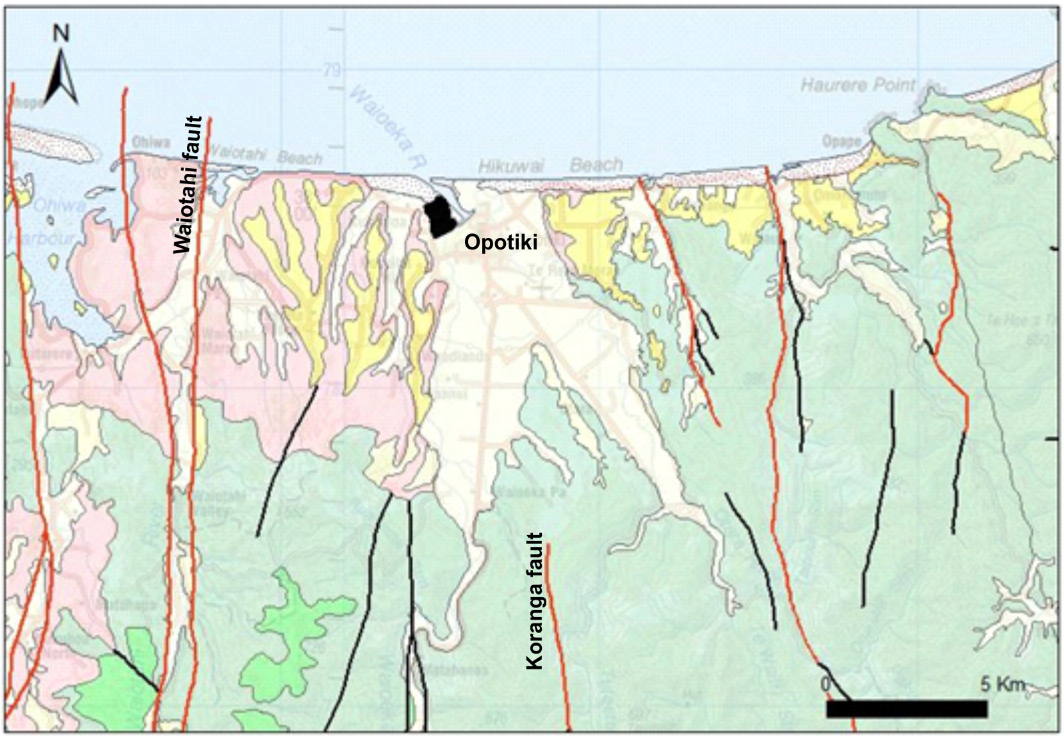

Figure 4.1 The Opotiki site (black polygon) overlies mainly gravel, sand and silt deposited from the Waioeka and Otara rivers (light yellow). Volcanic rock (pink), greywacke (green and grey) and coastal terraces (dark yellow) surround the river plain. Active faults (red lines) and inactive faults (black lines) are predominantly north-striking. Geological units and faults derived from QMAP.

4.2 Active Fault Locations near Opotiki

The Koranga fault has been mapped by QMAP as an active fault to within 10 km of Opotiki but it is only mapped within the steep, forested, hills south of the floodplain, within greywacke basement rocks. There is no geomorphic expression of the Koranga fault across the Holocene floodplain of the Waioeka and Otara rivers. We have examined the LiDAR DEMs in detail across the floodplain and cannot see any evidence of fault scarps or lineations that could be fault scarps. Within the footprint of the Opotiki development area polygon, we do not see any evidence of active faults.

There is a small possibility that an active fault does cross the flood plain of the Waioeka and Otara rivers but that it has not ruptured in the time since deposition of the alluvial sediments. The precise age of the sediment infilling the floodplain is not known but we presume that sediments become younger in a seaward direction, like the Rangitaiki plains (Figure 3.2B). If the Koranga fault does extend northwards then it must underlie the Opotiki floodplain, although projecting the fault northwards on a strike similar to the surrounding faults would place the buried fault on the eastern side of Opotiki, rather than beneath the Opotiki development area polygon. There are two reasons to suggest a buried fault may underlie the Opotiki floodplain: (1) the floodplain is formed in a broad river valley and such valleys are frequently fault-controlled; (2) active faults have been identified offshore of Opotiki (see Opo-01, Opo-02 and Opo-03 in Figure 3.3, Lamarche and Barnes, 2005). The offshore fault traces, called the Opotiki faults, have a maximum slip rate of 0.5 mm/yr and estimated mean recurrence intervals of 4600–10875 years. We conclude that although there is potential for a buried fault beneath the Opotiki floodplain, it must have a low slip rate (<1 mm/yr) and long recurrence interval (probably >3500 years), and it is highly unlikely that the buried fault underlies the Opotiki development site because it is more likely to be located on the eastern side of the floodplain.

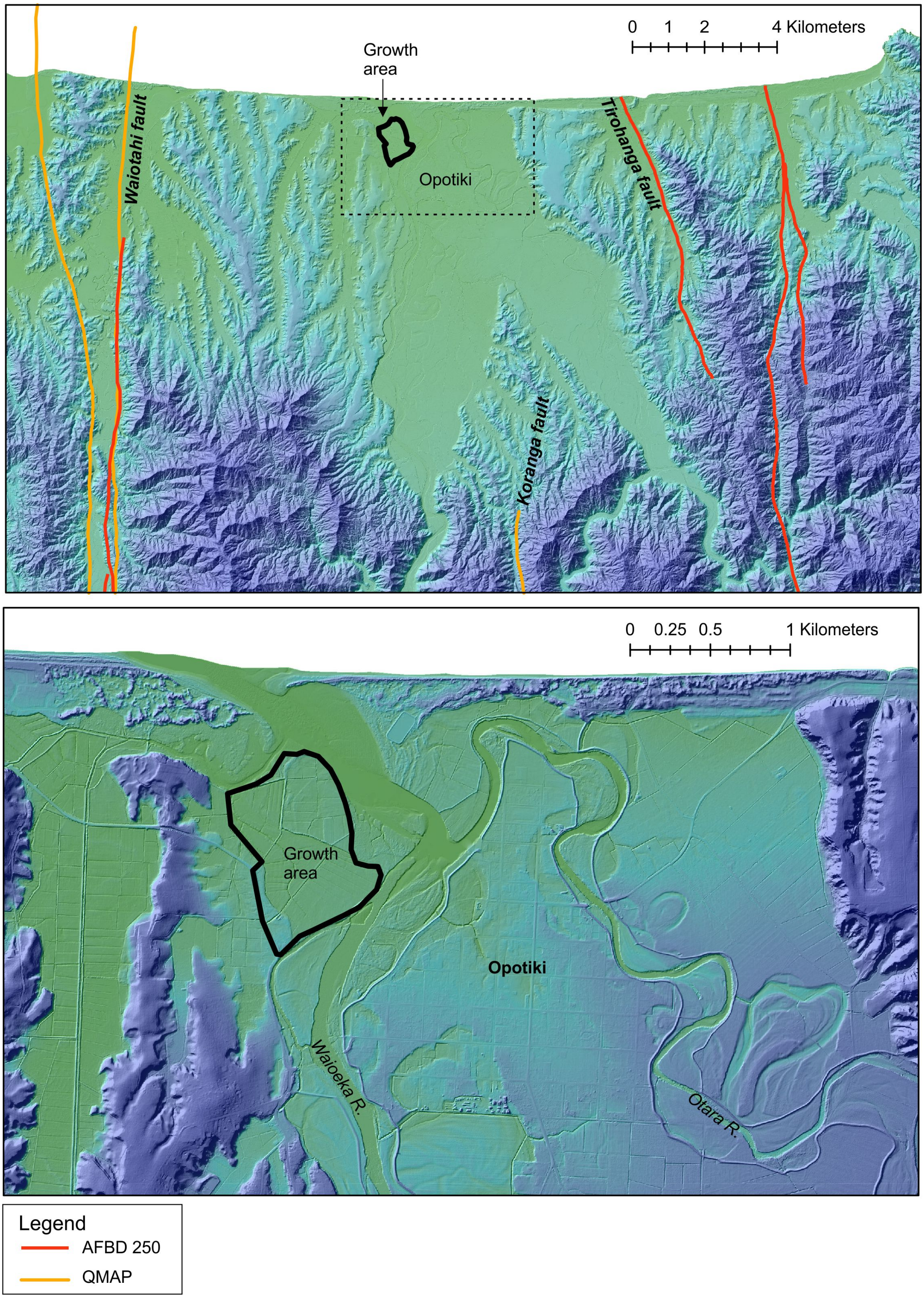

Figure 4.2 LiDAR DEM of the region around Opotiki, including the alluvial floodplain of the Waioeka and Otara rivers (upper image), and a more detailed DEM of the area proximal to the Opotiki development area. No active faults are seen on the alluvial floodplain.

5.0 ROTORUA

Most sites in the Rotorua area are located northwest of the dense zone of previously mapped active faults (Figure 5.1, Villamor et al. 2010). We have reviewed the active fault mapping in the areas of proposed development sites around Rotorua. Detailed reviews of active fault mapping in areas of development are recommended because: (1) previous mapping may have been undertaken at a lower resolution than is useful for site-specific planning; (2) new topographic or bathymetric data may have been acquired; and (3) new knowledge about landscape ages and geological formations may prompt revised interpretations of fault activity. Our review has found no active faults at the Airport, Wharenui, Ngongotaha or Pukehangi Road sites. There are potentially active faults crossing the Eastside site and several active fault scraps in the Peka site.

5.1 Age of the Landscape

The sites around Lake Rotorua are located within the Rotorua volcanic caldera. The caldera formed around 240,000 years ago by collapse of the ground after the eruption of the voluminous Mamaku Formation (Milner et al. 2002; age of the Mamaku Formation from Gravley et al. 2007). A large lake occupied this subsided area after the caldera formed (Marx et al. 2009). Since its formation, Lake Rotorua has reached different topographic levels as a consequence of blockage and establishment of lake outlets responding to the tectonic and volcanic activity around the lake. The modern lake shoreline is at 280 m above sea level (asl). Understanding where the former shorelines were at different times is helpful to understand: (1) if some lineaments detected in the topographic maps are former lake shores rather faults; and (2) to assess the age of the landscape surfaces where the study sites area located, which in turn help us understand fault activity (e.g., if a fault has ruptured a landscape surface that we know is 3000 years old, then we can say that the fault has been recently active and it’s RI is at least 3000 years). In Appendix 3, we summarise the various Lake Rotorua shorelines that have been described in the literature and we show how they spatially relate to the sites for potential development. We have used the information on lake shoreline elevations and landscape age to assess active fault activity at many of the Rotorua sites.

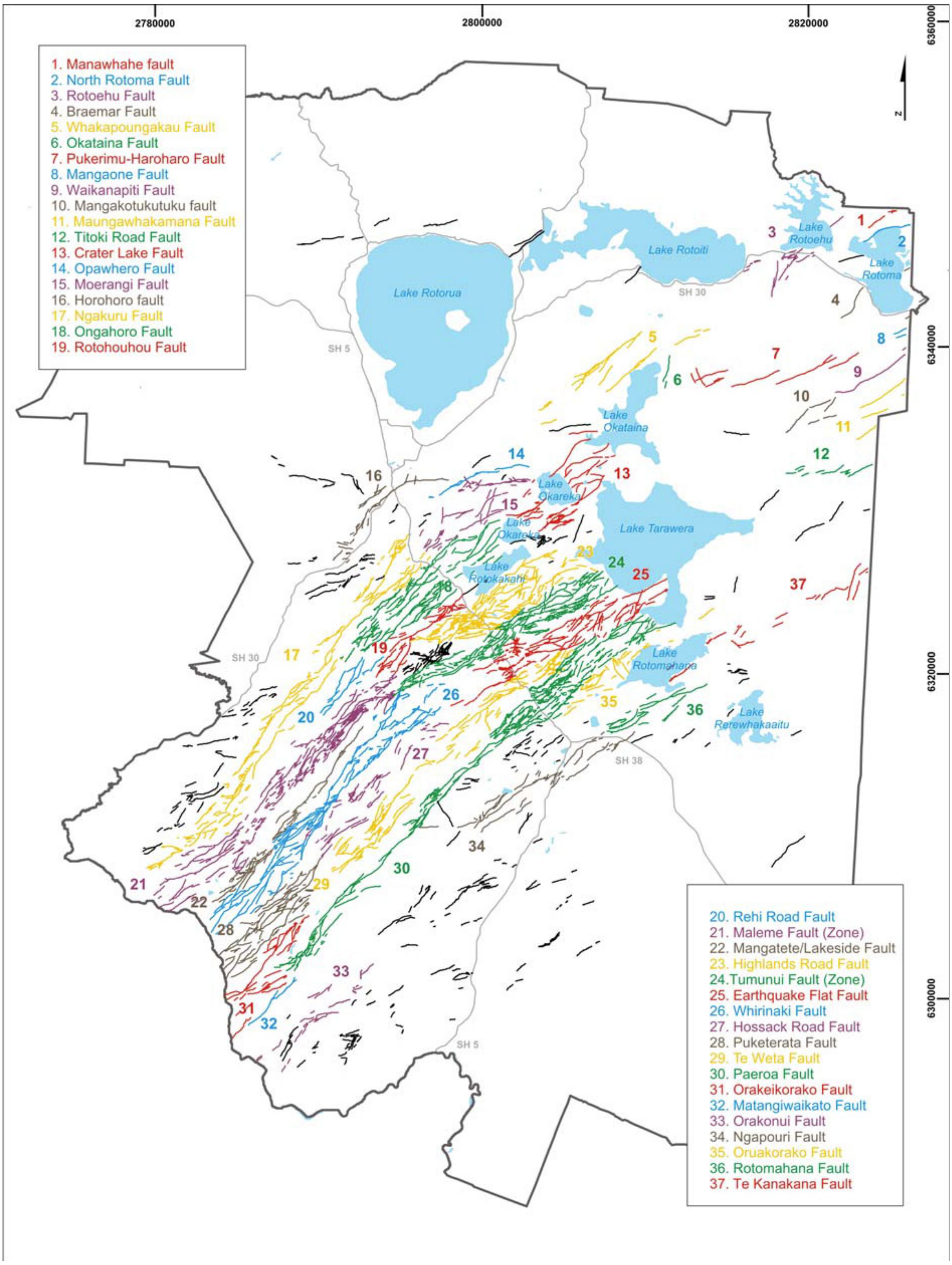

Figure 5.1 Major faults in the Rotorua District that are likely to produce earthquakes with Mw>6.0. Individual surface fault traces merge with depth into major seismogenic faults. Map from Villamor et al. (2010).

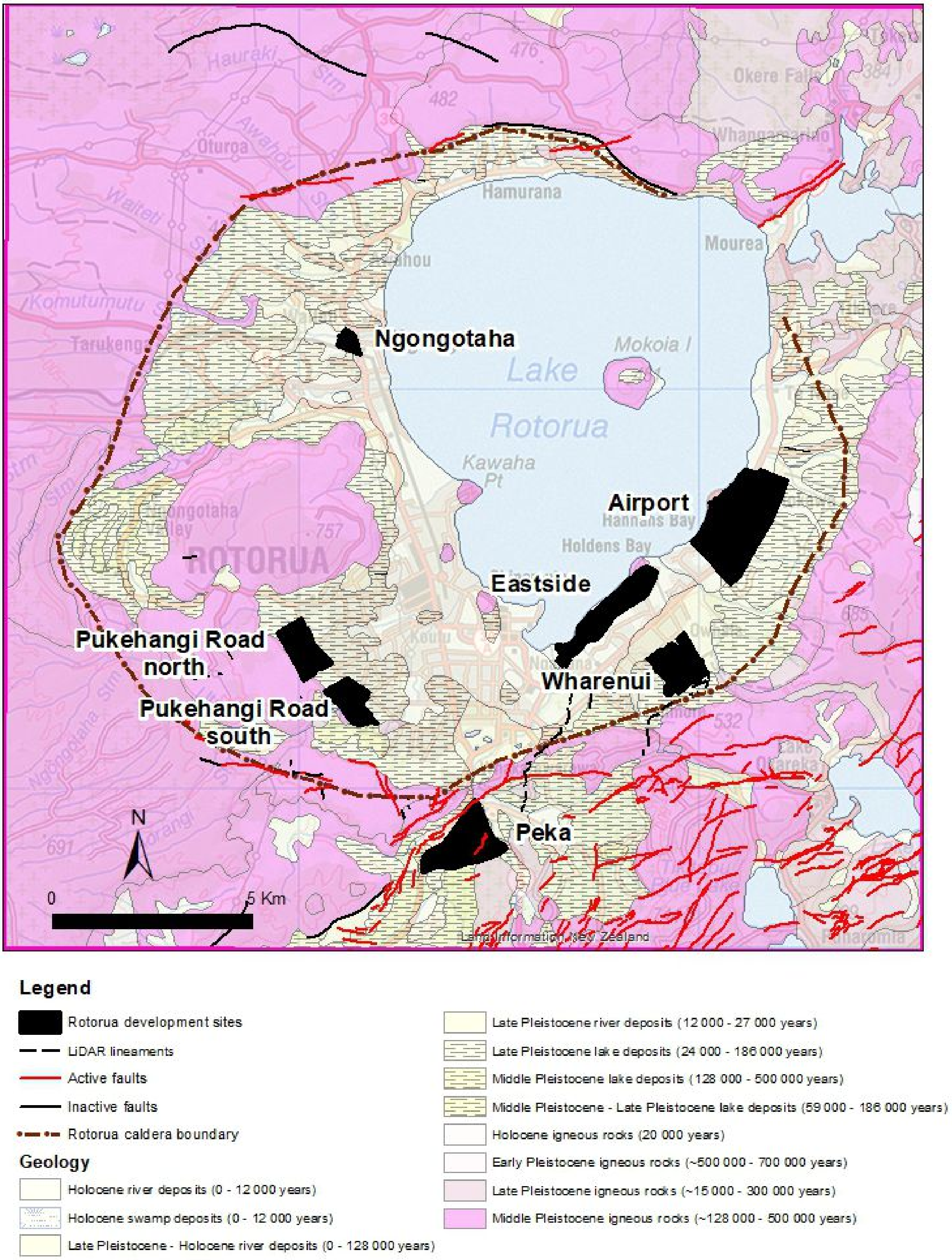

Figure 5.2 A simplified geological map of the Rotorua area. The proposed development sites around Lake Rotorua lie mostly within lake sediments (darker yellow) or river deposits (light yellow). A zone of active faults (red lines) lie mostly away from the sites. The dashed brown line around the lake delineates the edge of the Rotorua Caldera. New fault traces identified from LiDAR are shown as dashed black lines.

5.2 Eastside

The Eastside development area is located on the south-eastern shoreline of Lake Rotorua. The regional scale geological map (Leonard et al. 2010; Heron (custodian) 2014) shows the Eastside site as being situated on young river sediments (~12,000 years and younger; Figure 5.3), the high-resolution topography obtained from LiDAR data shows lake-margin parallel lineations that may be former lake shorelines. This suggests the Eastside site is more likely to be underlain by lake deposits than river deposits.

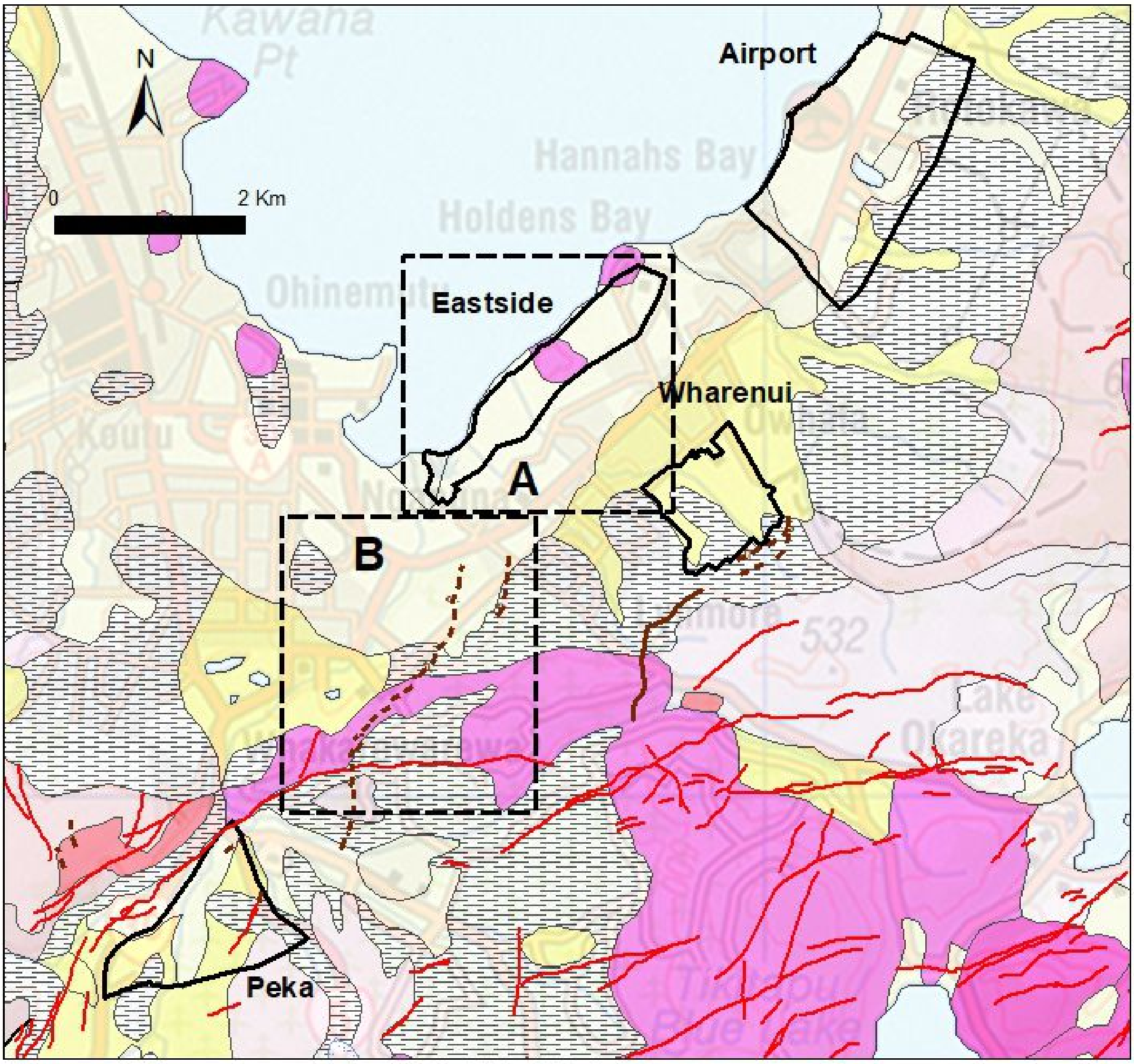

Figure 5.3 A closer view of the mapped geology at the Airport, Eastside Peka and Wharenui development sites (black polygons). Young river sediments (light yellow), older pumiceous river or lake deposits (dark yellow), lake deposits (black dashed pattern) and volcanic rock (pink). Interpretation of LiDAR data show the Eastside site is more likely to be underlain by lake deposits (Inset A, Figure 5.4). Active faults (red lines) have an east-northeast trend and lie south of the sites. New active fault traces (solid brown line) and possible active fault traces (dashed brown lines) are interpreted from LiDAR data (Inset B, Figure A2.1).

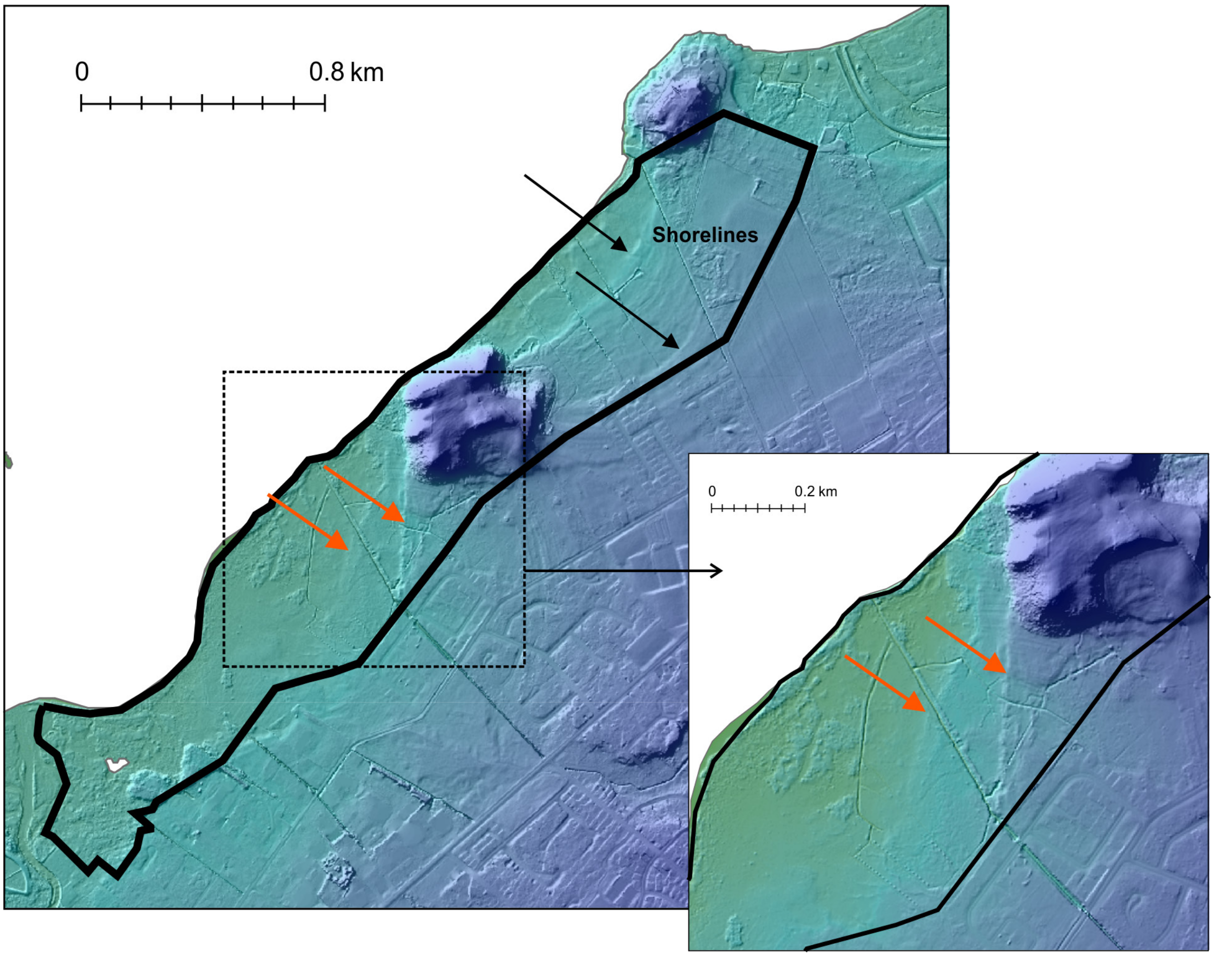

Figure 5.4 LiDAR DEM of the Eastside development area. The arrows show topographic lineations. The topmost arcuate lineations (black arrows) are most likely to represent lake shorelines. The lower, more northerly trending lineations (red arrows) may be either faults or shorelines; more detail on these lineations is shown in the inset map. For more details on shorelines see Appendix 3.

Two potential active fault traces have been identified at the Eastside development area, but they could also be old lake shorelines (Figure 5.4). The difficulty in assessing if the trace is a fault or a shoreline is that a fault line can uplift part of the shore during rupture and change the shoreline to follow the fault scarp. It is thus possible that a lineation could be an old lake shoreline that has formed along an existing fault scarp.

Reasons to suspect the north-striking lineations at the Eastside site are active faults include:

1. *The sharp and straight trace of the lineations:* most former shorelines around Lake Rotorua have curved and/or irregular traces (for example, the curved lineations pointed to in the northern part of the Eastside site in Figure 5.4). The lineations in the southern part of the Eastside side are unusually straight and perhaps more consistent with fault scarps than shorelines.
2. *Their location along strike of an active fault that lies further to south:* our revised mapping of active faults in the area near the Eastside and Wharenui sites has identified two northward-striking active faults south of the Eastside area (Figure A3.1). The lineations identified within the Eastside area are along the strike of these active faults suggesting they are a northward continuation of the same active tectonic structure.

Reasons to suspect the north-striking lineations are former lake shorelines, and not active faults, include (see also Figure A3.2):

1. *A lack of continuity onto the older, higher surfaces to the south:* the lineations within the Eastside area cannot be traced immediately southward onto the higher, older land surfaces. Although there are active faults to the south (Figure A3.1), the scarps cannot be continuously traced. Figure 5.5 shows the lineations cease at around the southern edge of the Eastside development area. If the lineations within the Eastside area were active fault scarps, we would expect the older, higher surfaces to the south to have scarps of equal or larger size upon them. The scarps on the higher surface, however, could have been removed or smoothed over by land development, if they originally existed.
2. *The north-trending orientation of these lineaments are atypical for active faults in this area:* most active faults in the Taupo Rift trend northeast to southwest (Figure 5.1) but the lineations identified at the Eastside site trend north-south. The trend of the lineations therefore are unusual for active faults in this tectonic environment but there are a few other examples of north-south trending faults.

Based on the current data available, we cannot determine if the lineations in the Eastside area are active fault traces or not. Due to this uncertainty, we are treating the lineations as possible active faults and placing fault avoidance zones around the fault traces. We also provide recommendations for future work that may help to resolve if they are active faults or not.

5.2.1 Fault Avoidance Zones for the Eastside lineations

In accordance with the MfE Active Fault Guidelines, we place a fault rupture hazard zone around the possible fault traces identified at the Eastside site (Figure 5.5), and we place an additional setback buffer of 20 m width in order to construct what is defined in the MfE Active Fault Guidelines as a Fault Avoidance Zone (FAZ). The fault rupture hazard zone is defined by the deformation width of fault; that is, from the line of the fault trace we assess the distance over which fault rupture could reasonably be expected to occur. For the Eastside site the deformation width is 40 m and with the additional 20 m setback buffer the fault avoidance zones are 80 m wide (Figure 5.5). Where the fault traces merge, the fault avoidance zones become wider.

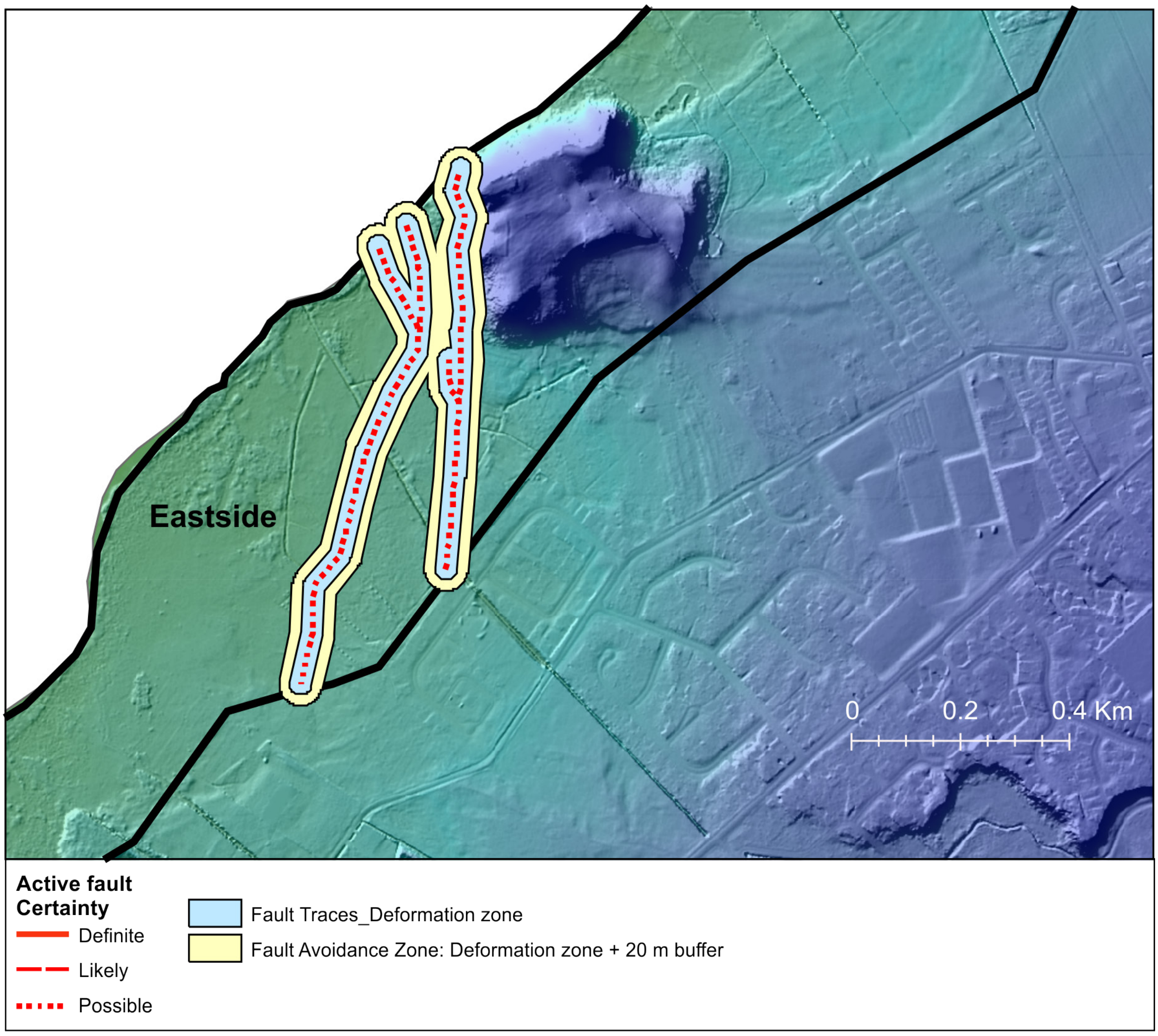

Figure 5.5 Fault avoidance zones at the Eastside site.

5.2.2 Recommendations

If the lineaments are treated as fault lines, we recommend that the MfE guidelines are implemented. In that case, the lineaments should be classed as active faults with a Recurrence Interval Class I, as the age of the landscape surfaces displaced by the fault is <2,000 years old (surfaces are below the 1.8 ka year old shoreline; see Figure A3.2 .).

Should the Council decide to investigate whether the lineaments are active faults or not, we recommend paleoseismic trenching and Ground Penetrating Radar (GPR) is used to assess the presence or absence of fault activity. Paleoseismic trenches could be excavated across the faults to assess the presence of a fault or other tectonic deformation features and the timing of the deformation. Because the ground water table will be close to the surface at the locations of the lineaments, an excavation may not be deep enough to discern the origin of the lineaments. In that case, we recommend that additional investigations using GPR to assess the possible northward extension of the fault located south of the site into the study site.

5.3 Airport

The Airport site lies on the eastern margin of Lake Rotorua and within the development area we do not see any evidence of active faults. As with the Eastside site, the geology at the Airport site is also mapped as being situated on young river sediments and flanked by older lake sediments (Figure 5.3). However, the LiDAR data shows former shorelines indicating the sites is mostly underlain by recent lake sediments, rather than river sediments (Figures 5.6, A3.1 and A3.2).

In the northern part of the Airport we did identify one topographic scarp as a possible active fault, but further investigation showed this was unlikely. The inset map of Figure 5.6 shows the scarp that we studied in more detail. We have concluded the scarp is most likely to be an old, poorly preserved and highly dissected lake shoreline (see Figure A3.1). We examined the height contours around the lake and it is possible that this feature correlates to other shoreline features at the same height around the north shore of the lake and that correspond with a shoreline form between 36,000 to 27,000 years ago (see Appendix 3; Figure A3.1). The shoreline at this elevation is not well preserved at any location, perhaps indicating the lake level was only at this elevation for a relatively short period of time, inhibiting the formation of a prominent shoreline scarp. This is likely the reason why this shoreline is not mentioned in the literature, as it would have been difficult to map without LiDAR derived high resolution maps.

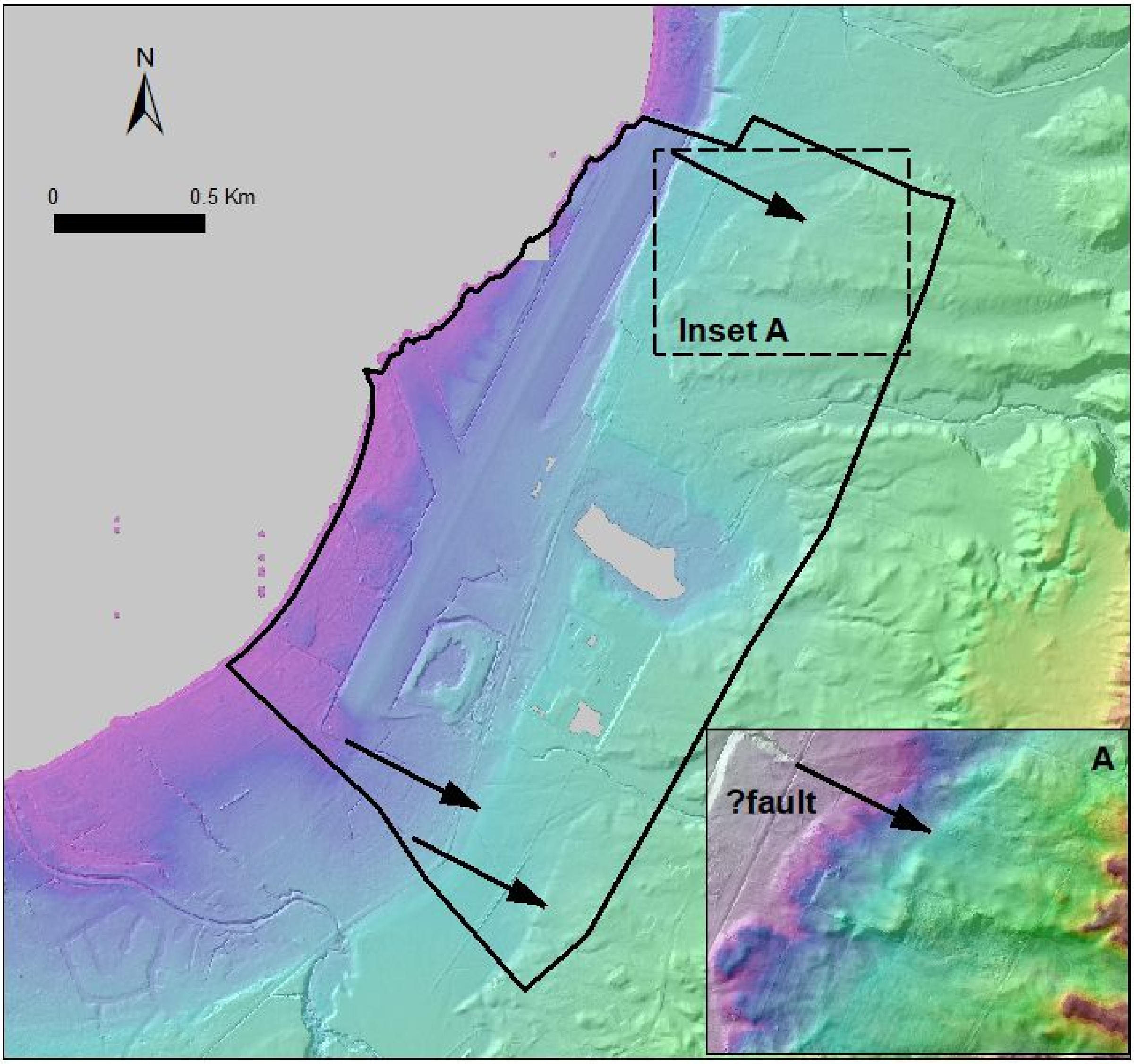

Figure 5.6 Shorelines (unlabelled arrows) are clearly seen from LiDAR data. Inset A shows a sharp lineation that is likely to be an old dissected lake shoreline. For more details on shorelines see Appendix 3.

5.4 Wharenui

Within the Wharenui site, there is no evidence of any active faults (Figure 5.7). The landform surface in the Wharenui area is relatively old and is a highly dissected surface underlain by pumiceous fluvial and lake deposits aged ~12,000 to 186,000 years based on Leonard et al (2010), but could be more constrained 27,000 to 60,000 based on our compilation of shorelines (see Appendix 3; Figure A3.1). Approximately 1 km to the south of the Wharenui site, a possible east-northeast trending active fault has been identified (Figure 5.7). Subtle topographic lineations immediately southeast of the site boundary (dashed lines, Figure 5.7) may relate to the mapped active fault that lies southwest but these do not cross into the Wharenui site footprint.

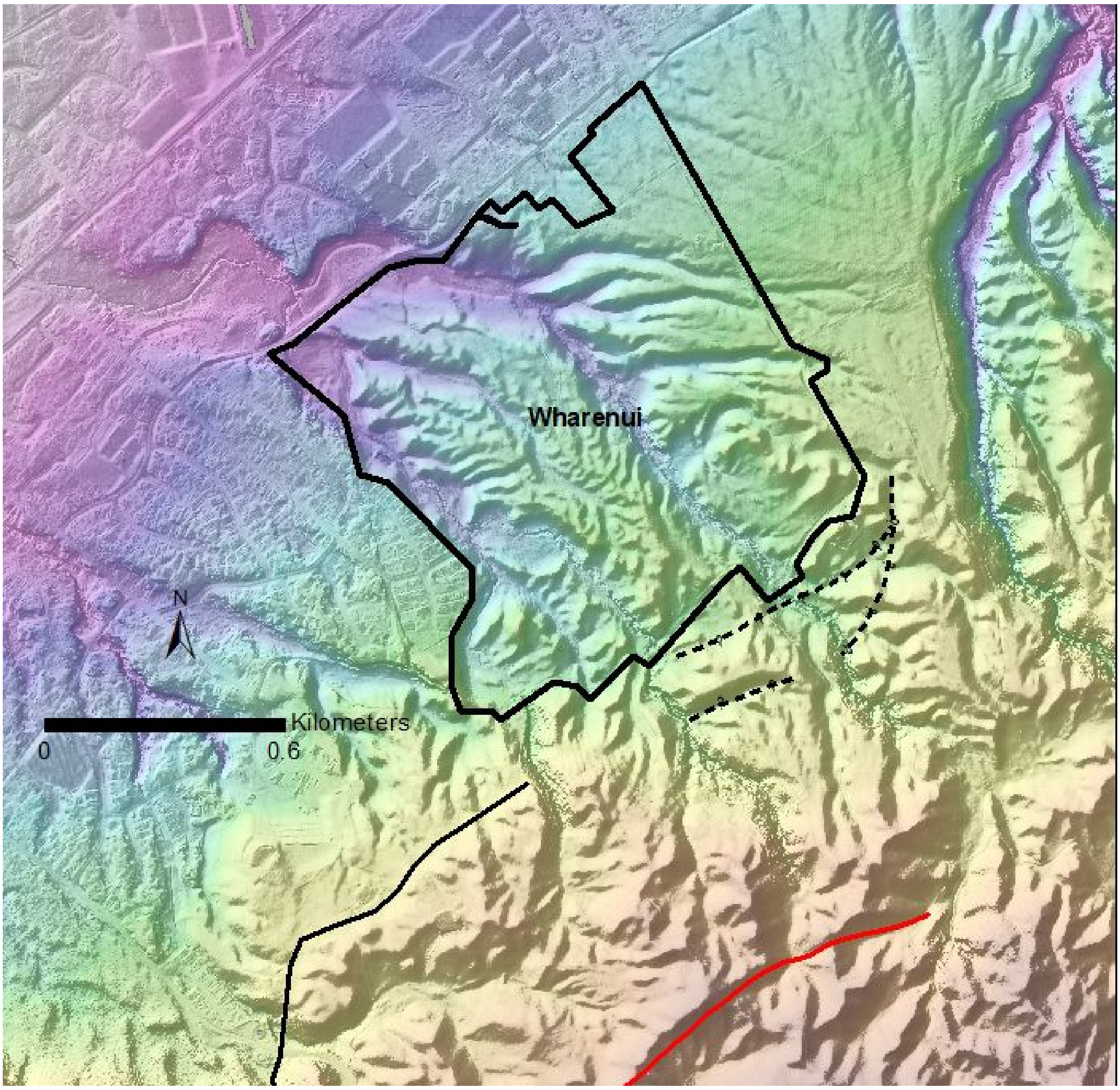

Figure 5.7 LiDAR DEM of the Wharenui site shows an absence of active fault scarps. An active fault trace (red line) lies about 900 m southeast of the site but trends away from the area. An inactive fault (black solid line) trends to the northeast and may correlate to the lineations identified in the LiDAR (black dashed lines).

5.5 Peka

The Peka site is situated south of Rotorua, it lies outside of the Rotorua caldera boundary Figure 5.2) and is the closest site to the zone of dense active faulting associated with the active Taupo Rift (Figure 5.1). The geology of the area is mostly Holocene to late Pleistocene (recent – 128,000 years old) lake or river sediments. A previous report on active fault mapping by Villamor et al. (2010) had identified several traces of the Horohoro fault zone in or near the Peka area (Figures 5.1, 5.8) and this report refines the location of these fault traces and provides updated fault avoidance zones.

At the northern boundary of the Peka site is a scarp of the Horohoro fault, it is somewhat hard to trace across the very low, young fluvial sediments in the stream valley but is well defined on the older surfaces (Figure 5.8). We place a Fault Avoidance Zone (FAZ) around the Horohoro fault trace but because the fault skims on the northern boundary of the Peka site, the FAZ does not cover much of the Peka area (Figure 5.8). We adopt the fault parameters for the Horohoro fault from Villamor et al. (2010) which lists the fault slip rate as 0.17 mm/yr (with an uncertainty range from 0.1 to 0.2 mm/yr) and an RI of 7400 years; most of these fault parameters are derived from a paleoseismic trenching study undertaken by Zachariasen & Van Dissen (2001). According to the MFE Guidelines, the Horohoro fault is a RI Class IV fault (RI >5000 - <10,000 years, Table A1.1).

On the eastern side of the Peka site is an unnamed fault scarp, previously identified by Villamor et al. (2010). We informally name this the Peka fault and our fault mapping agrees with Villamor et al. but we extend the fault scarp about 100 m further to the northeast. We place a FAZ around the Peka fault, but no data is available to assess the slip rate and RI of the fault. We suggest the fault is likely to have a similarly low, or lower, slip rate as the Horohoro fault (<0.17 mm/yr) and a similarly long, or longer, RI (>7400 years), therefore it is an RI Class IV fault. Reasons to suggest the Peka fault has an equal or lower rate of fault activity to the Horohoro fault are based simply on the poor preservation and short surface traces of the Peka fault scarp. Two other short (<500 m) fault traces have been identified in the Peka site (Scarp 1 and Scarp 2, Figure 5.8). From such short traces it is difficult to assess the likelihood that these scarps are active faults, so we assign them “likely” and “possible” certainties. As with the Peka fault, we suggest these are treated as RI Class IV faults; these scarps may be part of the Horohoro fault zone.

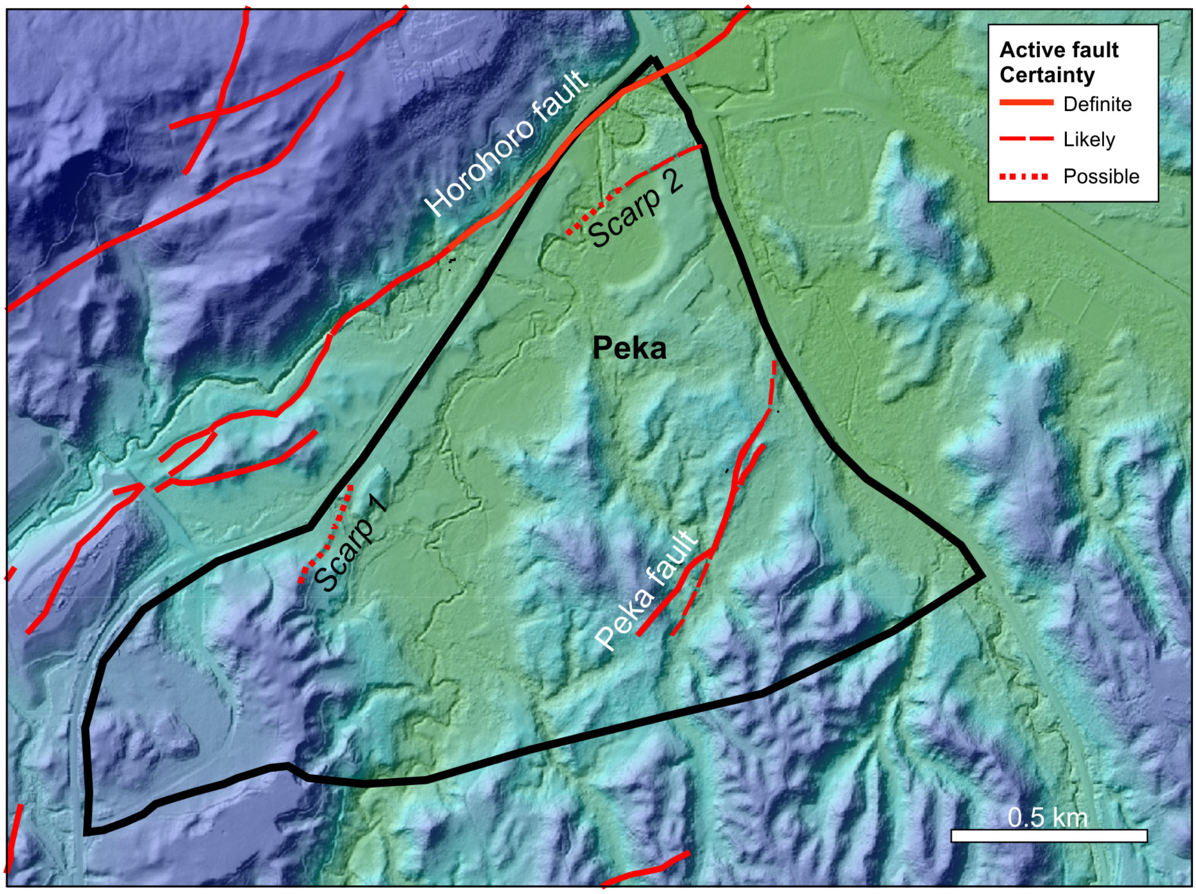

Figure 5.8 Active faults (red lines) around and within the Peka development site. Each fault trace has an assigned certainty which reflects the confidence we have that the feature is an active fault scarp.

5.5.1 Fault Avoidance Zones for the Peka Site

In accordance with the MfE Active Fault Guidelines, we place a fault rupture hazard zone around the definite, likely and possible fault traces identified at the Peka site (Figure 5.9), and we place an additional setback buffer of 20 m width in order to construct what is defined in the MfE Active Fault Guidelines as a Fault Avoidance Zone (FAZ). The fault rupture hazard zones (= deformation zones) for the Peka area fault traces are on the order of 40–60 m wide, and with the 20 m buffer the fault avoidance zones vary from 80 to 100 m wide (Figure 5.9). The faults of the Peka area should be treated as RI Class IV faults (RI >5000–<10,000 yr, Table A1.1). Should the Council decide to investigate whether the “likely” and “possible” fault scarps are indeed active faults, we recommend paleoseismic trenching and/or Ground Penetrating Radar (GPR) in order to assess the presence or absence of fault activity.

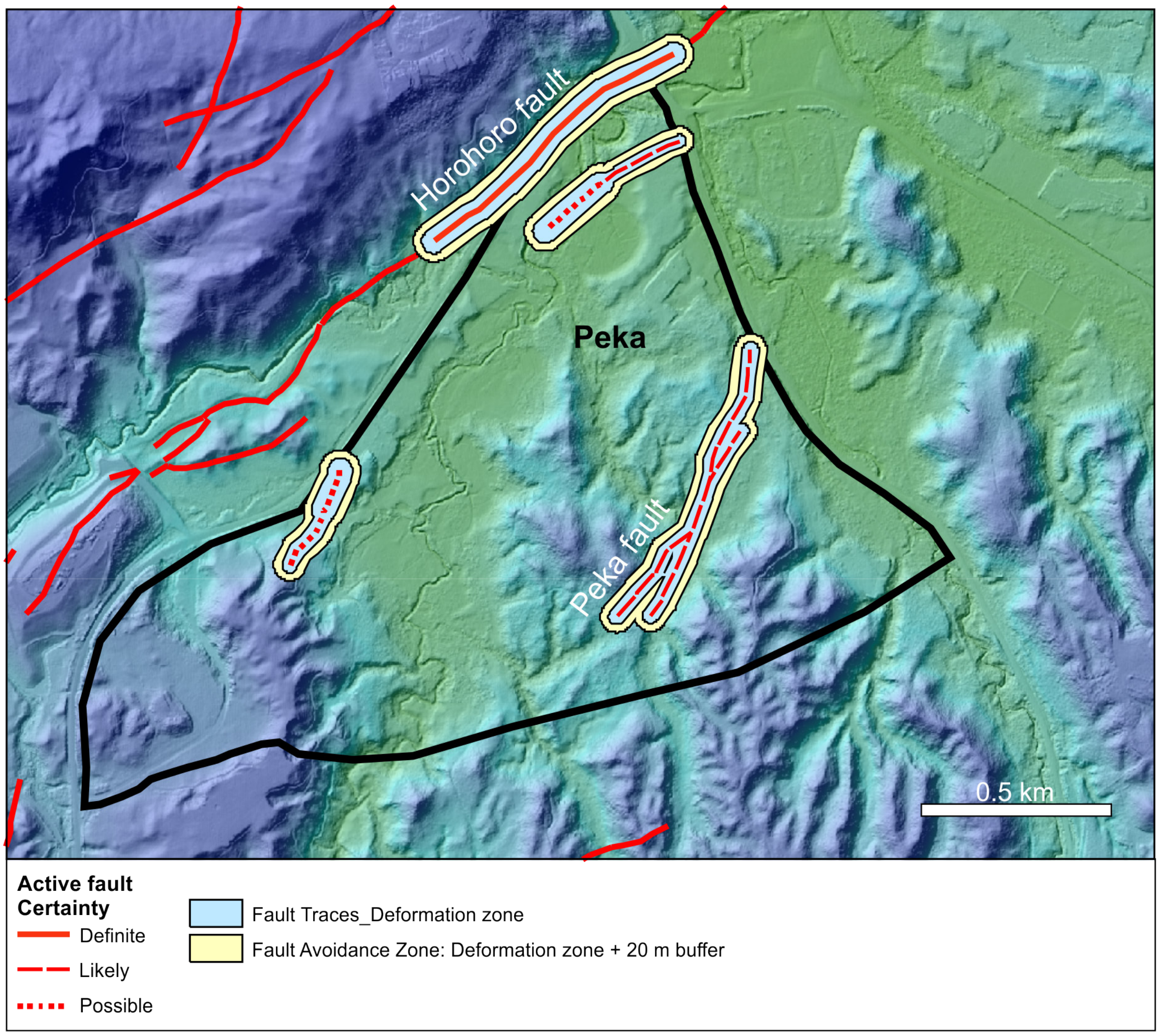

Figure 5.9 Fault avoidance zones for the Peka site active fault traces.

5.6 Ngongotaha

No active faults have been identified at the Ngongotaha site on the western side of Lake Rotorua. The Ngongotaha site is relatively distal from the zone of active faulting of the Taupo Rift (Figure 5.1) and the nearest active faults are located about 4 km north of the site. Recent fluvial and lake sediments underlie the Ngongotaha site, and although it is a quite youthful landscape, no active fault traces can be seen on the older, higher landforms immediately north and south of the Ngongotaha site (Figure 5.10). The absence of faults on the older surfaces shows there is an extremely low likelihood of any active faults concealed under the Ngongotaha site.

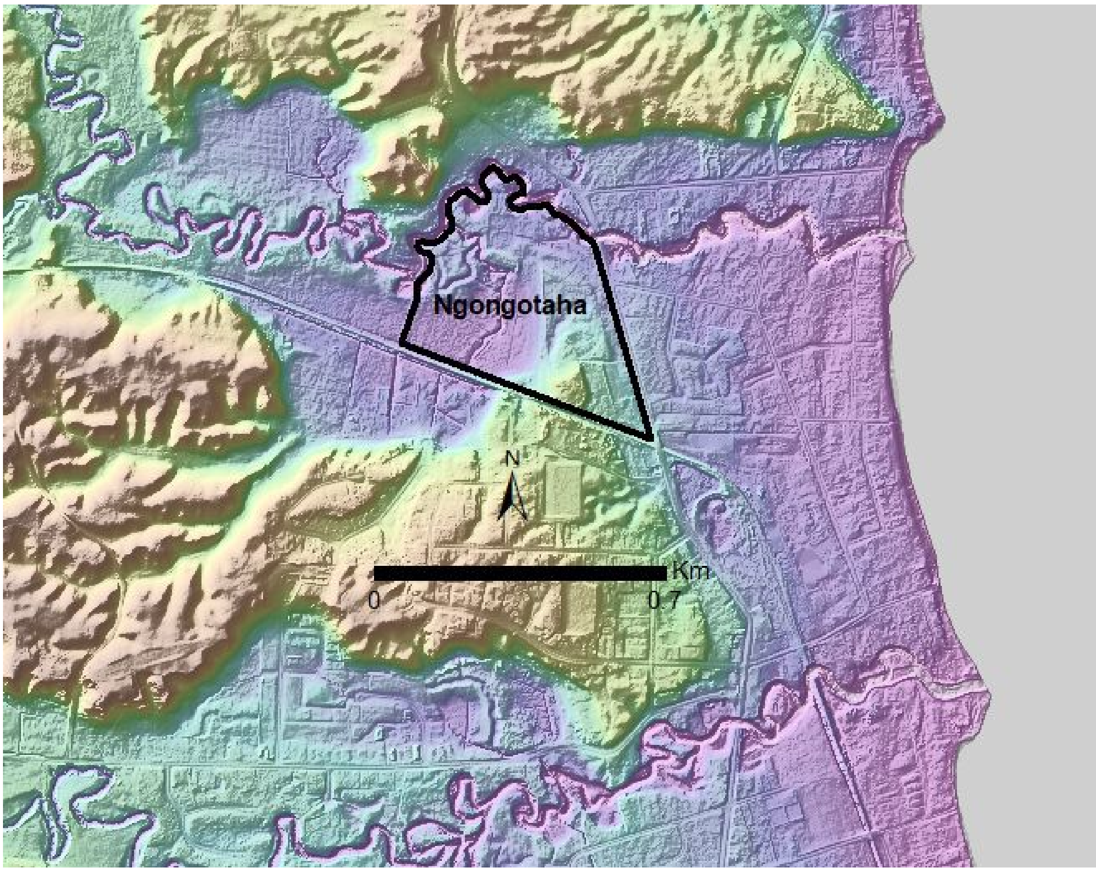

Figure 5.10 LiDAR DEM of the Ngongotaha site, where no active fault scarps have been identified.

5.7 Pukehangi Road

The active fault investigation of Pukehangi Road site was previously reported in a letter report (Villamor 2018) and in this section we only briefly summarise the results. The full letter report is provided in Appendix 4.

No active faults were identified at the Pukehangi Road site near Rotorua. There is also no evidence that the active faults mapped in the surrounding area (red lines in Figure 5.11) extend into the Pukehangi Rd site or nearby areas. To assess the potential presence, or absence, of active fault(s) at the Pukehangi Rd site, we analysed the Digital Elevation Model (DEM) derived from Light Detecting and Ranging (LIDAR) and 1940s aerial photographs (NZ Aerial Mapping run 710, photos 50 to 70), and assessed the ages of lake terrace surfaces. Due to the relatively youthful age of the landforms at Pukehangi Road, we cannot however, discount the possibility of a buried fault under the old lake sediments and surfaces. If such a fault existed, it would have not ruptured in at least the last 12,000 years, possibly the last 25,000 years, in the low elevation areas, and to the last 60,000 years in the high elevation areas. These age constraints on the time elapsed since the last possible surface fault rupture would place any potential buried faults in RI Class V (>10,000 to ≤ 20,000 yr) or RI Class VI (<20,000 - ≤125,000 yr) according to the MFE Guidelines.

Underlying the Pukehangi Rd site, faults in the basement rock have been identified or inferred by previous studies such as Milner (2001), Milner et al. (2002), and Ashwell et al. (2013). The maps in Appendix 5 show the location of the basement faults relative to the Pukehangi Road sites. The basement faults are largely interpreted from geophysical data (gravity) and relate to the formation and collapse of the Rotorua caldera at approximately 240,000 years BP. These faults are very unlikely to reactivate in the current tectonic regime. However, in case they do reactivate, the age of the unfaulted lake terrace surfaces overlying the basement faults shows us the recurrence intervals must be very long (>12,000 years). The position of the lake shorelines (in blue, Figure 5.11) is similar to the alignment of the inferred basement faults at depth, but this simply reflects deeper structural controls on the lake boundaries and does not necessarily indicate the faults reach the surface.

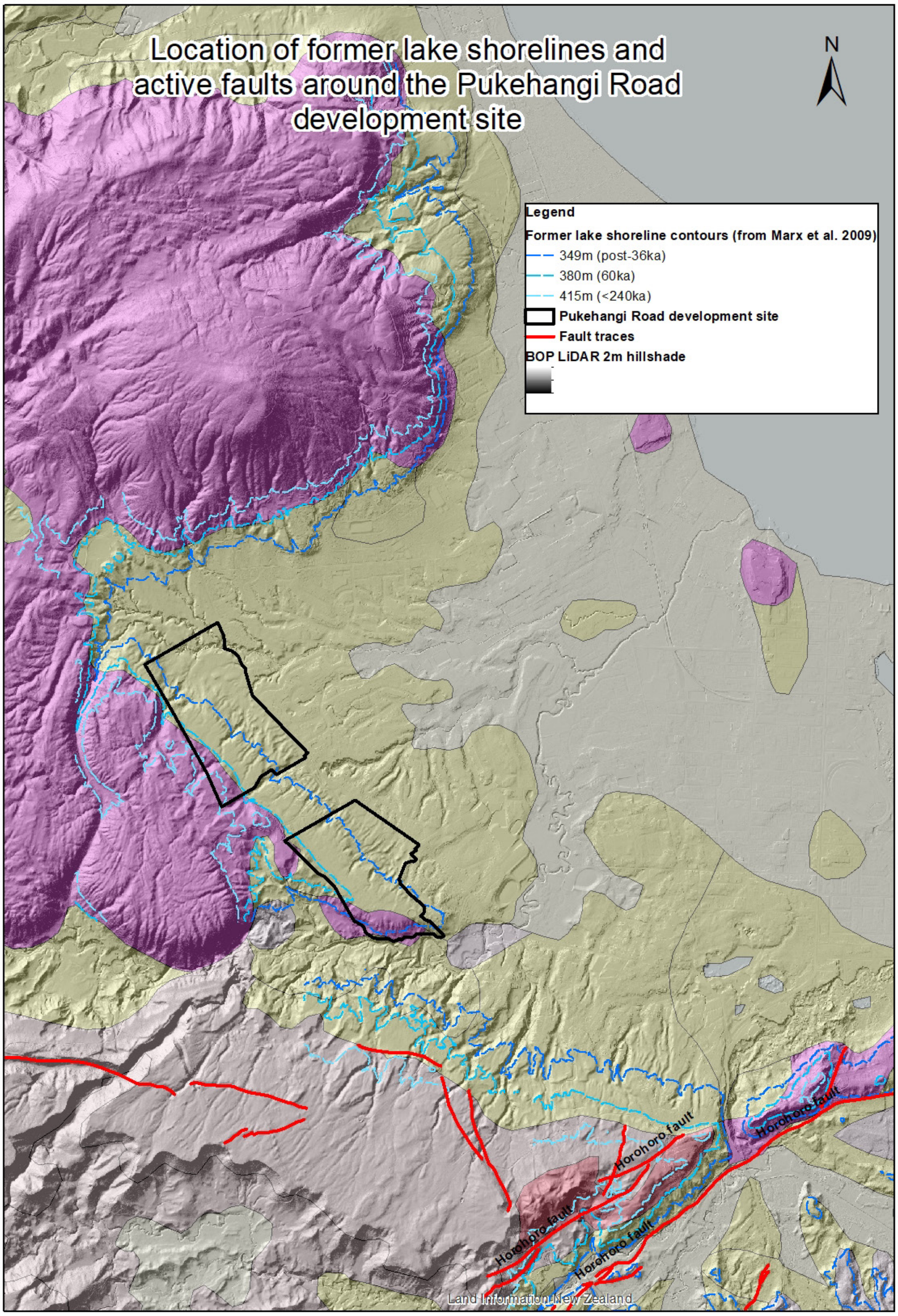

Figure 5.11 Location of the Pukehangi Rd development site (black solid lines) with respect to active faults (red solid lines: Leonard et al. 2010; Villamor et al. 2010; Langridge et al 2016; this study). Main coloured polygons are: purple= post -Mamaku eruption domes including Ngongotaha lavas (<240,000 years old); dark yellow= Late Pleistocene lake deposits (190,000–125,000 years old); and light yellow= Holocene river deposits (<12,000 years old).

6.0 WESTERN BAY OF PLENTY

The active fault investigations for the Katikati and Omokoroa (western Bay of Plenty) sites have been previously reported in a letter report (Lee and Villamor 2018) and in this section we only briefly summarise the results. The full letter report is provided in Appendix 6.

No active faults were identified at either the Katikati or Omokoroa sites (Figure 6.1). To assess the potential presence or absence of active faults at the Katikati and Omokoroa development sites, we: reviewed the existing published and unpublished literature and maps of the area; reviewed 1940s and 1960s aerial photographs (NZ Aerial Mapping, see references for list); and analysed the landforms from a digital elevation model derived from Light Detecting and Ranging (LiDAR) data (provided by Bay of Plenty Regional Council). We did not identify any geomorphic features in the landforms at either the Katikati or Omokoroa sites that could be classified as active faults. There may be old faults that are buried beneath the sediments and volcanic rock at these sites, but these would not likely have ruptured in at least the last 128,000 years, as the surfaces of that age do not seem to be displaced by any faults. Prior to this study, no active faults at those sites had been identified through geological mapping (Edbrooke 2001; Heron 2014) and active fault mapping (New Zealand Active Fault Database, Langridge et al., 2016). There are also no known offshore faults near the development sites (Lamarche & Barnes 2005).

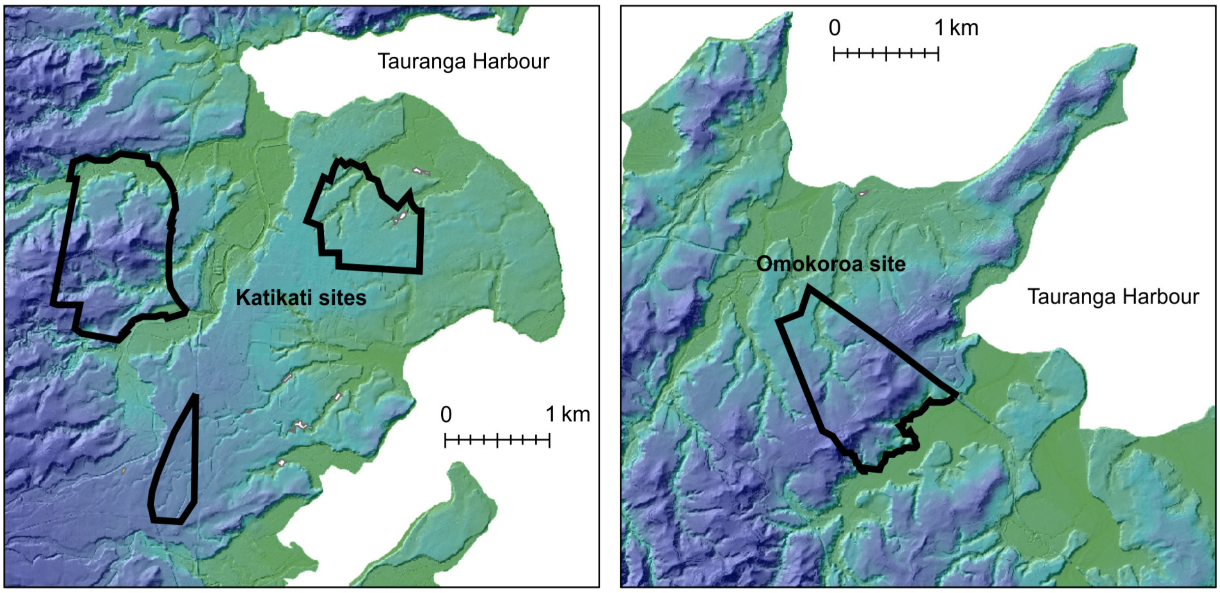

Figure 6.1 LiDAR DEM of the Katikati (left) and Omokoroa (right) sites. No active faults were identified at either site.

7.0 SUMMARY

We have assessed the absence or presence of active faults at 10 sites identified for proposed urban development in the Rotorua, Whakatāne-Opotiki and Western Bay of Plenty areas. This assessment has been undertaken so that urban development can take place in a manner that mitigates the fault rupture hazard. To identify active faults in the areas of this study, we examined high-resolution topography (LiDAR) and used existing knowledge of active fault locations and landform age information. The following summarises our assessment of active faults at the proposed urban development areas:

- No active faults were identified at the Katikati, Omokoroa, Ngongotaha, Pukehangi Road, Airport, Wharenui, and Opotiki sites.
- The Coastlands site (Whakatāne) is almost certainly underlain by the Whakatāne fault but its exact location remains highly uncertain due to the young geological landforms that underlie the Coastlands site. To more precisely locate the Whakatāne fault under the Coastlands site we recommend the use of near-surface geophysical methods to assess where the fault is located. The Whakatāne fault RI is also poorly constrained but we consider the Whakatāne fault should be treated as potentially having a RI of <2000 years and categorised as a RI Class I fault.
- At the Eastside site (Rotorua), two north-trending topographic lineations have been identified, the scarps may be active faults scarps or former shorelines of Lake Rotorua. Fault avoidance zones have been placed around the lineations, but it may be possible to undertake field investigations to resolve whether the lineations are active faults or not.
- The Peka site (Rotorua) has several active fault traces, particularly in parts of the site close to the Horohoro fault zone. We have placed fault avoidance zones around the fault traces in accordance with the MfE Active Fault Guidelines.

8.0 ACKNOWLEDGEMENTS

This report has been reviewed by Sally Dellow and Robert Langridge.

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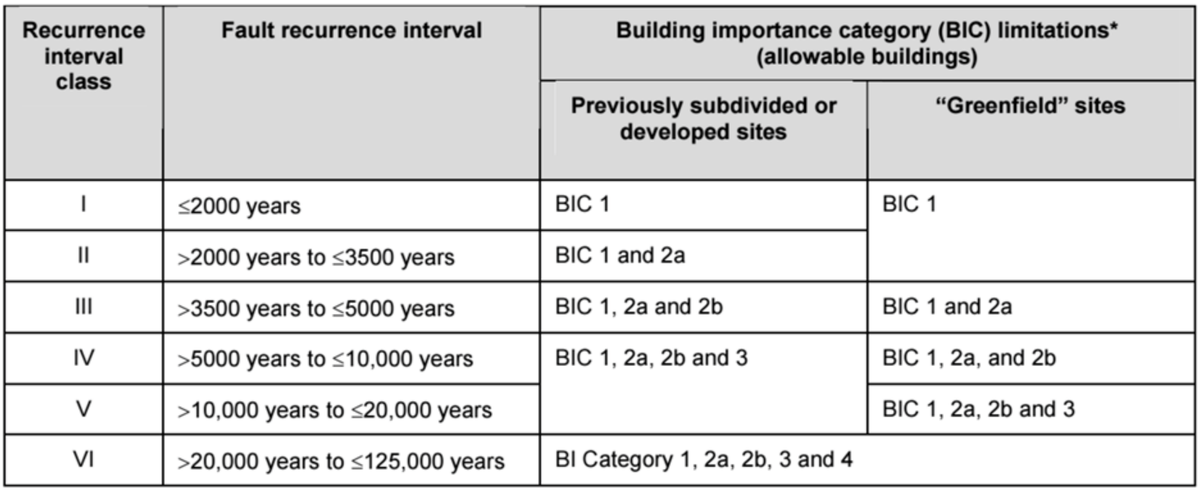
APPENDICES

APPENDIX 1 MFE GUIDELINES

Table A1.1 Relationship between fault recurrence interval (RI) and Building Importance Category (BIC) (source: Kerr et al., 2003). Note: Faults with average recurrence intervals >125,000 years are not considered active.



Recurrence interval class	Fault recurrence interval	Building importance category (BIC) limitations* (allowable buildings)	
		Previously subdivided or developed sites	"Greenfield" sites
I	≤2000 years	BIC 1	BIC 1
II	>2000 years to ≤3500 years	BIC 1 and 2a	
III	>3500 years to ≤5000 years	BIC 1, 2a and 2b	BIC 1 and 2a
IV	>5000 years to ≤10,000 years	BIC 1, 2a, 2b and 3	BIC 1, 2a, and 2b
V	>10,000 years to ≤20,000 years		BIC 1, 2a, 2b and 3
VI	>20,000 years to ≤125,000 years	BI Category 1, 2a, 2b, 3 and 4	

Table A1.2 Building Importance Categories and representative examples. For more detail see Kerr et al. (2003).

Building Importance Category	Description	Examples
1	Temporary structures with low hazard to life and other property	• Structures with a floor area of <30m2 • Farm buildings, fences • Towers in rural situations
2a	Timber-framed residential construction	• Timber framed single-story dwellings
2b	Normal structures and structures not in other categories	• Timber framed houses with area >300 m2 • Houses outside the scope of NZS 3604 “Timber Framed Buildings” • Multi-occupancy residential, commercial, and industrial buildings accommodating <5000 people and <10,000 m2 • Public assembly buildings, theatres and cinemas <1000 m2 • Car parking buildings
3	Important structures that may contain people in crowds or contents of high value to the community or pose risks to people in crowds	• Emergency medical and other emergency facilities not designated as critical post disaster facilities • Airport terminals, principal railway stations, schools • Structures accommodating >5000 people • Public assembly buildings >1000 m2 • Covered malls >10,000 m2 • Museums and art galleries >1000 m2 • Municipal buildings • Grandstands >10,000 people • Service stations • Chemical storage facilities >500m2
4	Critical structures with special post disaster functions	• Major infrastructure facilities • Air traffic control installations • Designated civilian emergency centres, medical emergency facilities, emergency vehicle garages, fire and police stations

APPENDIX 2 FAULTS SOUTH OF EASTSIDE DEVELOPMENT SITE

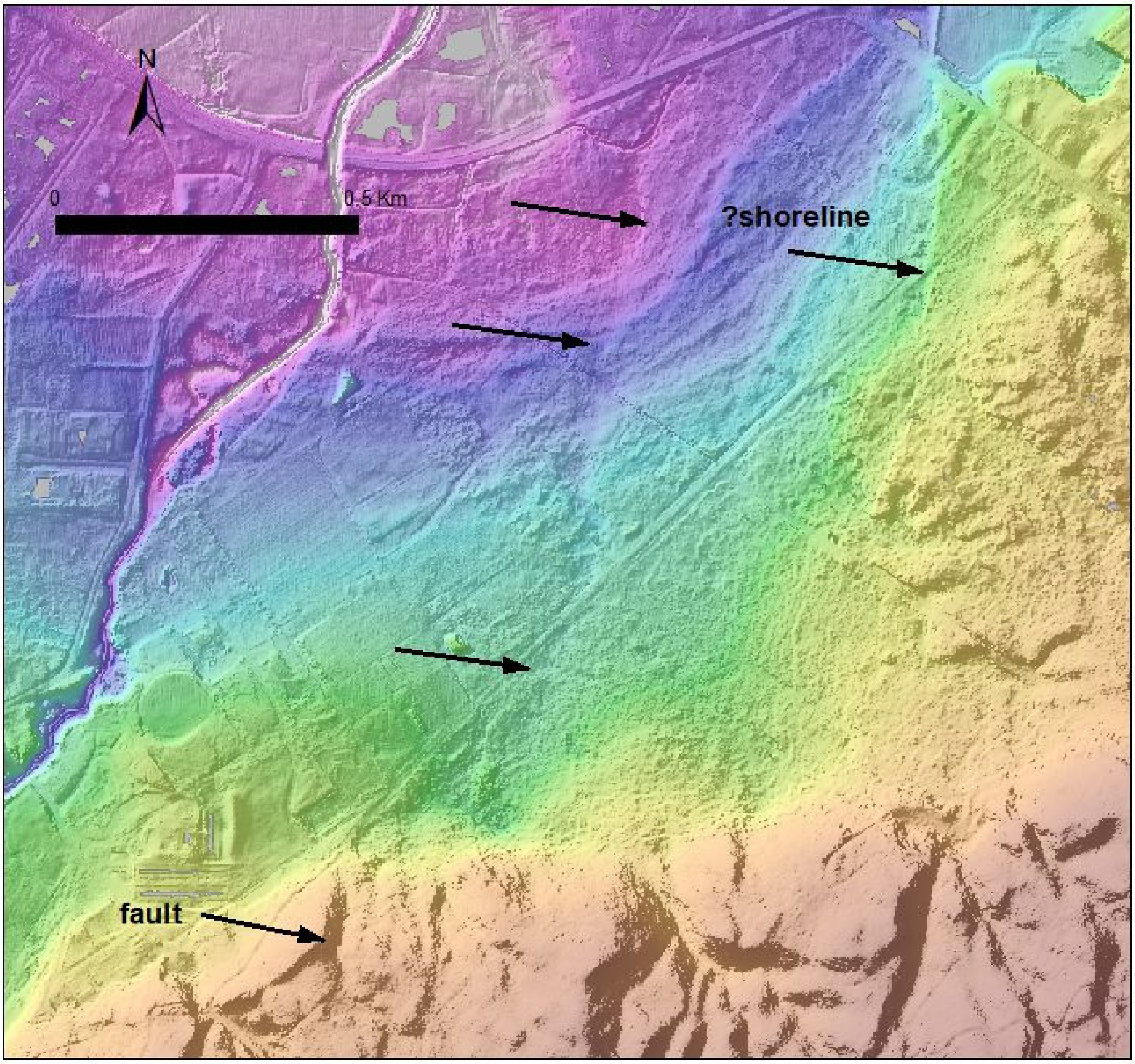


Figure A2.1 Lineations identified from LiDAR data (see Inset B in Figure 5.3) that trend northwards in the direction of the Eastside development site. The feature labelled “fault” is identified as a fault trace. The unlabelled arrows highlight a lineation that may possibly be a fault. The sharp lineation on the right may be a shoreline.

APPENDIX 3 LAKE ROTORUA SHORELINES

Several authors have defined where the highest water level (high-stand) of Lake Rotorua was at different times (Table A3.1). Kennedy et el (1978), Manville et al., (2007) and Marx et al. (2009) determined the reasons ("origin" in Table A3.1) for the different lake water levels. Infill and emptying of the lake is mainly related to: large eruptions and tectonic events (e.g., faulting, subsidence) that block and unblock the lake outlet; progressive lowering of water level through erosion of the outlet (generally Holocene fluvial incision in the landscape outside the lake which erodes the lake outlet); or unknown reasons. These authors could also determine the time of the high-stands using the ages of known local volcanic ash found in sediments exposed around the lake. Note that some literature references are old, and thus we have adopted the results from the newer ones. On occasions, we have combined shorelines from different authors that we thought may either be the same one, or that merging them may not make a difference to our interpretations of landscape ages.

We constrained the age of the area of land that is located between two lake high-stands with the ages of the high stands. Information relevant to all high-stand is compiled in Table A3.1 and their location shown with respect to the study sites in Figures A3.1 and A3.2.

Table A3.1 Shoreline elevations and ages around Lake Rotorua. Shorelines from: [1]Kennedy et al. (1978; Note that heights are corrected from current water level); [2]Manville et al. (2007); [3]Marx et al. (2009). Ages from: [A] Gravely et al. (2007), [B] Wilson et al. (2007); [C] Jurado-Chichay & Walker (2000); [D] Lowe et al. (2008).

Name	Height (m asl)	Age (ka)	Origin
Mamaku Ignimbrite	415[3]; 414–387[2]	c.240[A]	Mamaku Ignimbrite eruption formed the basin and a lake developed. Sometime later (undetermined) the water level dropped to heights similar to current level.
Rotoiti	380[3]; 380–370[2]; 370[3]	c. 60[B]	Water level rose after two coeval volcanic eruptions, the Rototiti and Earthquake Flat eruptions, through blockage of the outlet. The high-stand lasted at least ~20,000 year and then dropped to ~320m.
Hauparu	349[3]	c. 36[C]	The high-stand caused by blockage of the north-western lake outlet by volcanic sediments from Hauparu eruption. This high-stand was short lived.
Oruanui	293[1]	27 [D]	Rapid water level fall, post-Oruanui Tephra, possible breaching through the current outlet.
Te Rere/ Okareka	260[3]/278[1] (below current level)	25/21.8[D]	Progressive lowering of the water levels to levels below current level. With some high-stands: e.g. growth of Haroharo Complex Dome during Te Rere eruption[3] (equivalent Okareka Tephra level from [1]).
~9000	280[1] (same as present level)	c. 9[1]	Based on radiocarbon ages of drowned forest.
Rotoma[3]/Mamaku[1]	290[1]	c. 8[D]	Level rose immediately after the Mamaku eruption blocked the outlet.
Rotokawau	286[1]	c. 3.7	Progressive lowering of the water level (dated with Rotokawau Tephra).
Taupo	285[1]	1.7 [D]	Progressive lowering of the water level (dated with Taupo Tephra).

Name	Height (m asl)	Age (ka)	Origin
Kaharoa	283^1	0.64^D	Progressive lowering of the water level (dated with Kaharoa Tephra).
Current	280		

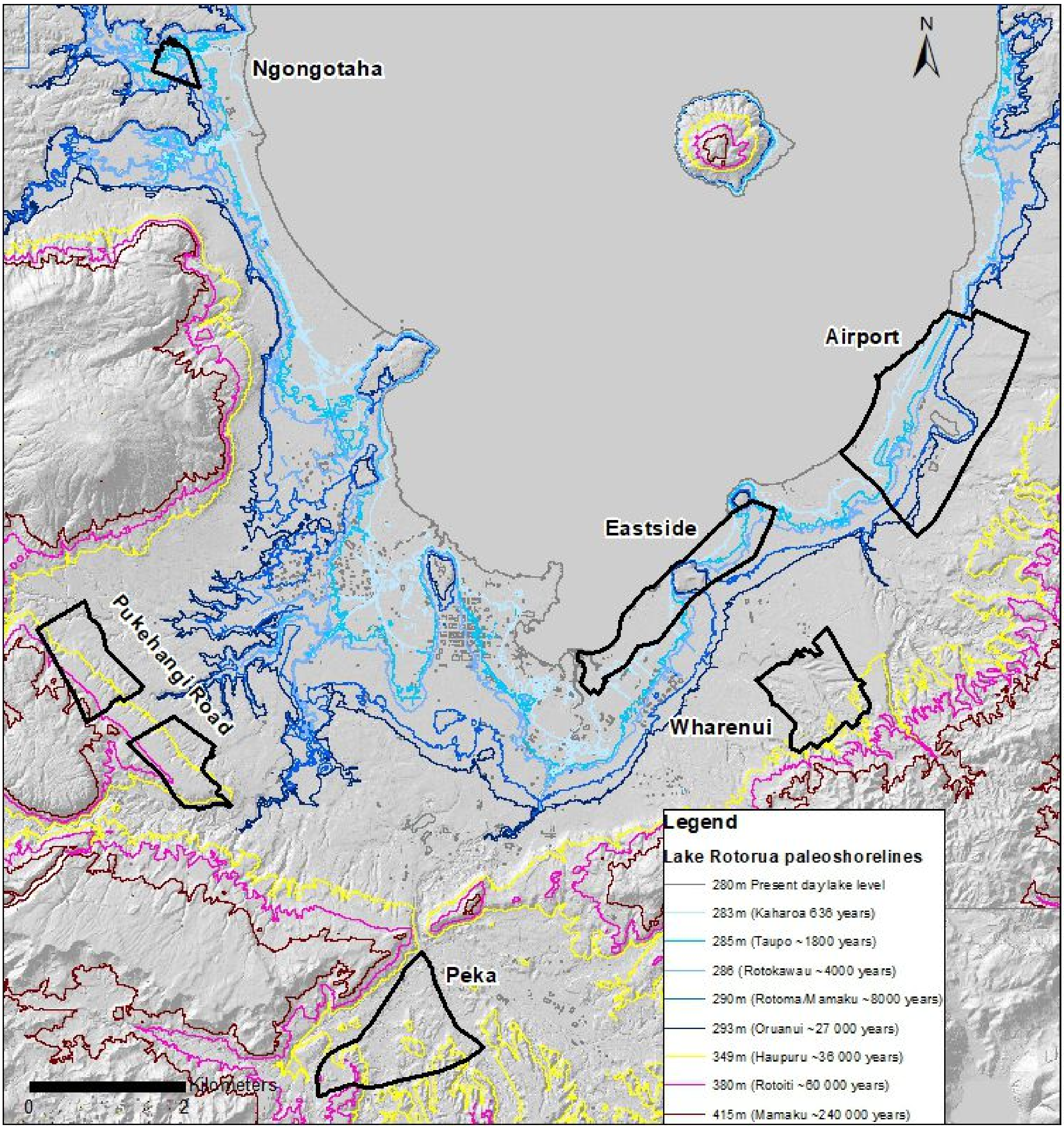


Figure A3.1 Paleoshorelines of Lake Rotorua (compiled from Kennedy et al. 1978, Manville et al. 2007, Marx et al. 2009) that correlate to changes in lake levels following volcanic activity dating back 240 000 years. The development sites at Ngongotaha, Wharenui, Pukehangi Road, Peka, Airport and Eastside lie predominantly on these old lake deposits. Buildings and other human-made structures distort the contours in built up areas.

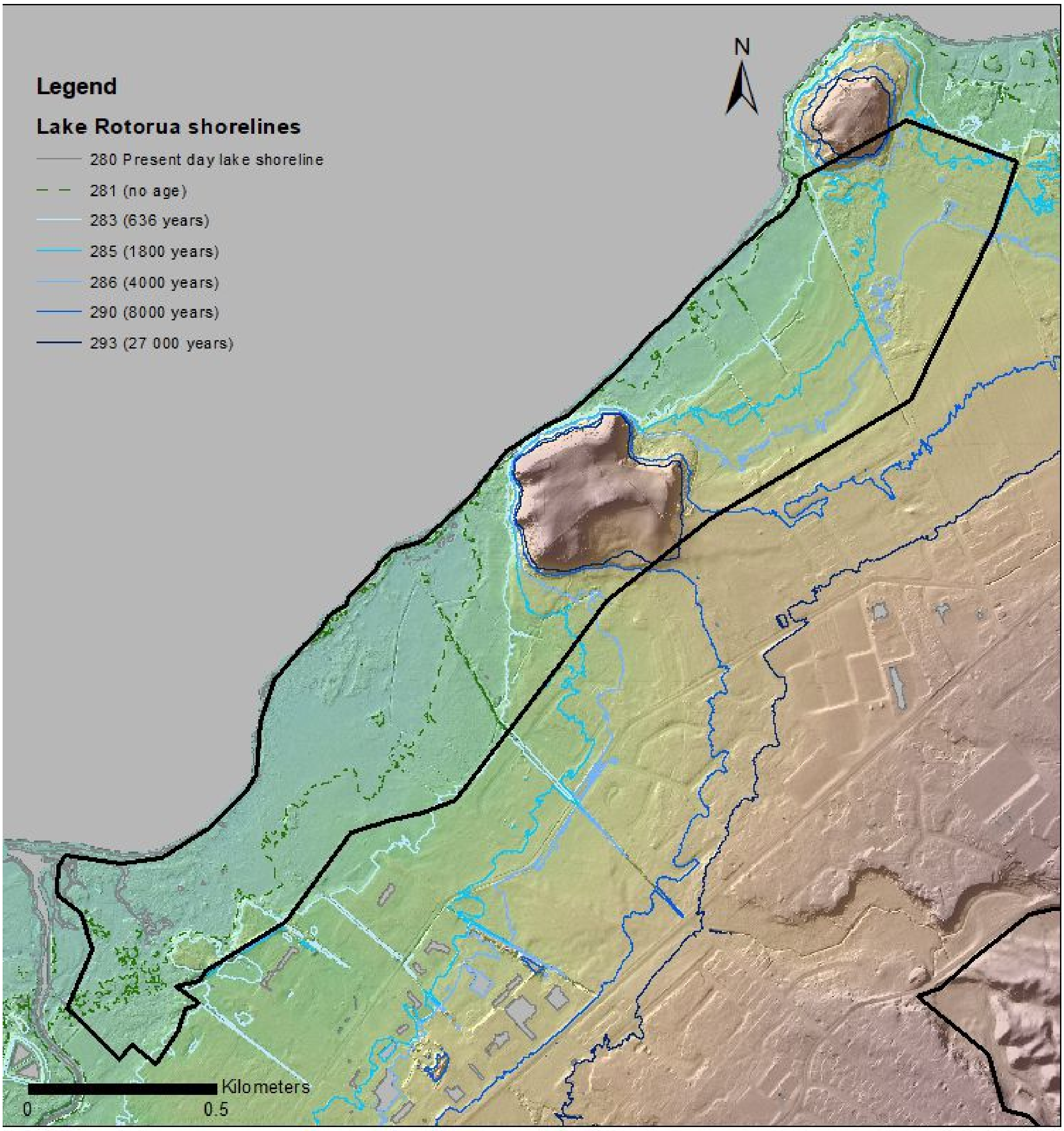


Figure A3.2 Shorelines on the Airport development site. The landscape at this site has been modified so the lake shorelines will not show their original positions. Contours 296 and 301 (light and dark green dashed lines) may approximately represent the lineation’s shown in Inset A.

APPENDIX 4 LETTER REPORT FOR PUKEHANGI ROAD SITE

Letter Report No: CR 2018/17 LR
Project No: 430W4198-00

9 February 2018

Natural Hazards Advisor
Bay of Plenty Regional Council Toi Moana
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Attention: Mark Ivamy

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Dear Mark Ivamy,

Interim results on active faults around the Pukehangi Road development site, Rotorua

1.0 ACTIVE FAULTS AROUND THE PUKEHANGI ROAD DEVELOPMENT SITE

To assess the potential presence, or absence, of active fault(s) at the Pukehangi Rd site, we have analysed the Digital Elevation Model (DEM) derived from Light Detecting and Ranging (LIDAR) and 1940s aerial photographs (NZ Aerial Mapping run 710, photos 50 to 70), and assessed the ages of lake terrace surfaces.

We cannot identify any geomorphic features (fault scarps) that can be classified as an active fault across the Pukehangi Rd site. There is also no evidence that the active faults mapped in the surrounding area (red lines in Figure 1) do extend into the Pukehangi Rd site or nearby areas.

We cannot however, discount the possibility of a buried fault under the old lake sediments and surfaces. If such a fault existed, it would have not ruptured in at least the last 12,000 years, possibly the last 25,000 years, in the low elevation areas, and to the last 60,000 years in the high elevation areas. Below we summarise the evidence for the ages of the surfaces that comprise the Pukehangi Rd site as these have relevance to how we have assessed the presence and rates of activity of active faults.

The Pukehangi Rd site is located within the Rotorua volcanic caldera. The caldera formed around 240,000 years ago by collapse of the ground the after the eruption of the voluminous Mamaku Formation (Milner et al. 2002; age of Mamaku Formation from Gravely et al. 2007). A large lake occupied this subsided area after the caldera formed (Marx et al. 2009). Since its formation, Lake Rotorua has reached different topographic levels as a consequence of blockage and establishment of lake outlets responding to the tectonic and volcanic activity around the lake. The modern lake shoreline is at 280 m above sea level (asl). Marx et al.

(2009) determined the age of the geomorphic surfaces and sediments exposed around the current lake; they identified and dated three main lake shore levels:

- **Highest terrace at ~415 m asl** was the highstand (i.e. highest water level) associated with the lake that formed **<240,000 years ago.**
- **Shoreline and littoral terraces at up to ~380 m asl** correspond to the lake that formed after two coeval volcanic eruptions, the Rototiti and Earthquake Flat eruptions, around **60,000 years** ago (age from Wilson et al. 2007). The products from these eruptions blocked both the north and south outlets of the lake.
- **Shoreline terrace at 349 m asl** was the highstand caused by blockage of the northwestern lake outlet by volcanic sediments from Hauparu eruption (**~36,000 years ago;** age from Jurado-Chichay and Walker, 2000). The highstand was short lived and the lake dropped to near current levels. It is possible that other short duration high stands occurred in the period between 36 and 25,000 years ago.
- After 25,000 years ago, some highstands occurred (e.g. with the 25,000 year old Te Rere eruption the lake rose to 260 m asl and with the 9500-year-old Rotoma eruption the lake rose to 277 m asl). However, those were formed below the current 280 m asl level (formed as a consequence of the Mamaku eruption at 8000 years ago).

In Figure 1 we have display a hill-shaded DEM from the LiDAR data (provided by BoP Regional Council) overlain with the:

- previously mapped active faults in the surrounding area in red solid lines (Leonard et al. 2010, Villamor et al. 2010; Langridge et al 2016; this study);
- three topographic contour lines defining the highstand of the three lakes mentioned above; and
- location of the Pukehangi site in black solid lines.

We have used the geomorphic surfaces established by Marx et al. (2009), together with the ages they assigned to these surfaces, and geological mapping (Leonard et al., 2010), to assess the age of the surfaces at the Pukehangi Rd site. The site partially occupies a sub-horizontal (slightly sloping towards the lake) surface (380—367 m asl) that corresponds to the 60,000-year-old lake shoreline. The rest of the Pukehangi site east of the sub-horizontal area is a steeper sloping surface. This sloping surface corresponds to the erosional surface left behind as the 60,000 years-old lake drew down, as well as the erosional surface left by the ~36,000-year-old lake draw down (for elevations <349 m asl). The shoreline and littoral surfaces associated with ~36,000 years old lake are not represented at the site; they are likely to have been eroded. Therefore, for the sections of the Pukehangi site above 367 m asl we assigned a ~60,000 years surface age, and for those between 367 and 349 m asl we assign an age of 60,000 to 36,000 years. Areas located below 349 m asl are assigned a surface age of < 36,000 years (from Marx et al. 2009) and >12,000 years (from geological mapping Leonard et al. 2010). The lower age bound is likely to be at least > 25,000 years as none of the younger highstands seem to have reached the lowest elevations of the Pukehangi site.

Therefore, we conclude that no active faults have been identified at the Pukehangi Rd development site. We cannot however, discount the possibility of a buried fault at the site. If such fault existed, it would have not ruptured in at least the last 12,000 years, possibly the last 25,000 years in the low elevation areas and to the last 60,000 years in the high elevation areas.

Please let me now if you need further clarification.

Yours sincerely

Pilar Villamor

Pilar Villamor
Senior Scientist

This report was undertaken by Pilar Villamor, Julie Lee and Kate Clark. It was internally reviewed by Nicola Litchfield.

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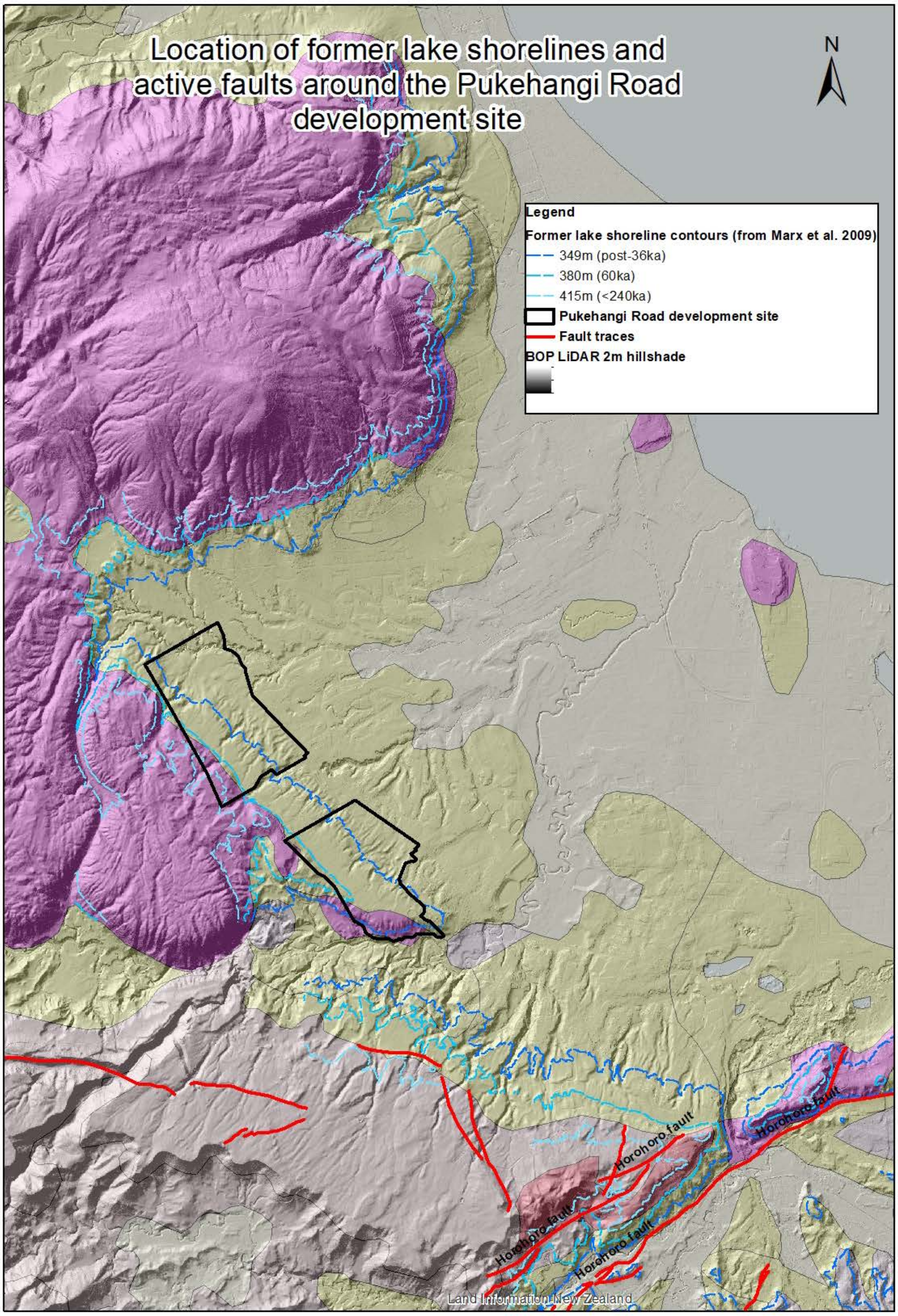

Figure 1 Location of the Pukehangi Rd development site (black solid lines) with respect to active faults (red solid lines: Leonard et al. 2010, Villamor et al. 2010; Langridge et al 2016; this study). Main coloured polygons are: purple= post -Mamaku eruption domes including Ngongotaha lavas (<240,000 years old); dark yellow= Late Pleistocene lake deposits (190,000-125,000 years old); and light yellow= Holocene river deposits (< 12,000 years old).

APPENDIX 5 BASEMENT FAULTS OF THE PUKEHANGI AREA

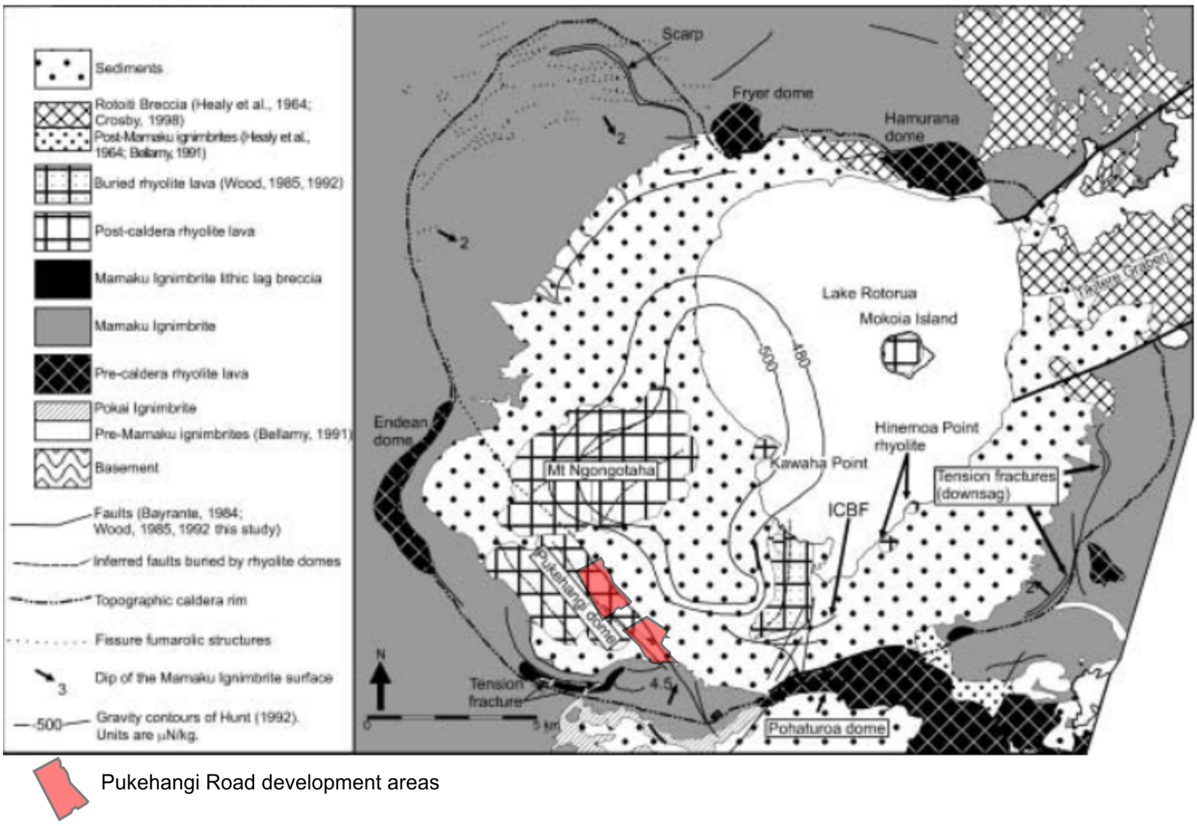

Figure A5.1 Pukehangi Road site overlain on the basement fault map of Milner et al. (2002). Summarised caption from Milner et al. (2002): Geological map of Rotorua Caldera. The area of the lowest gravity anomaly is in the southwest of the caldera. Fissure fumarolic structures are present towards the northwest edge of the caldera. Faults have been inferred beneath rhyolite domes surrounding the gravity low.

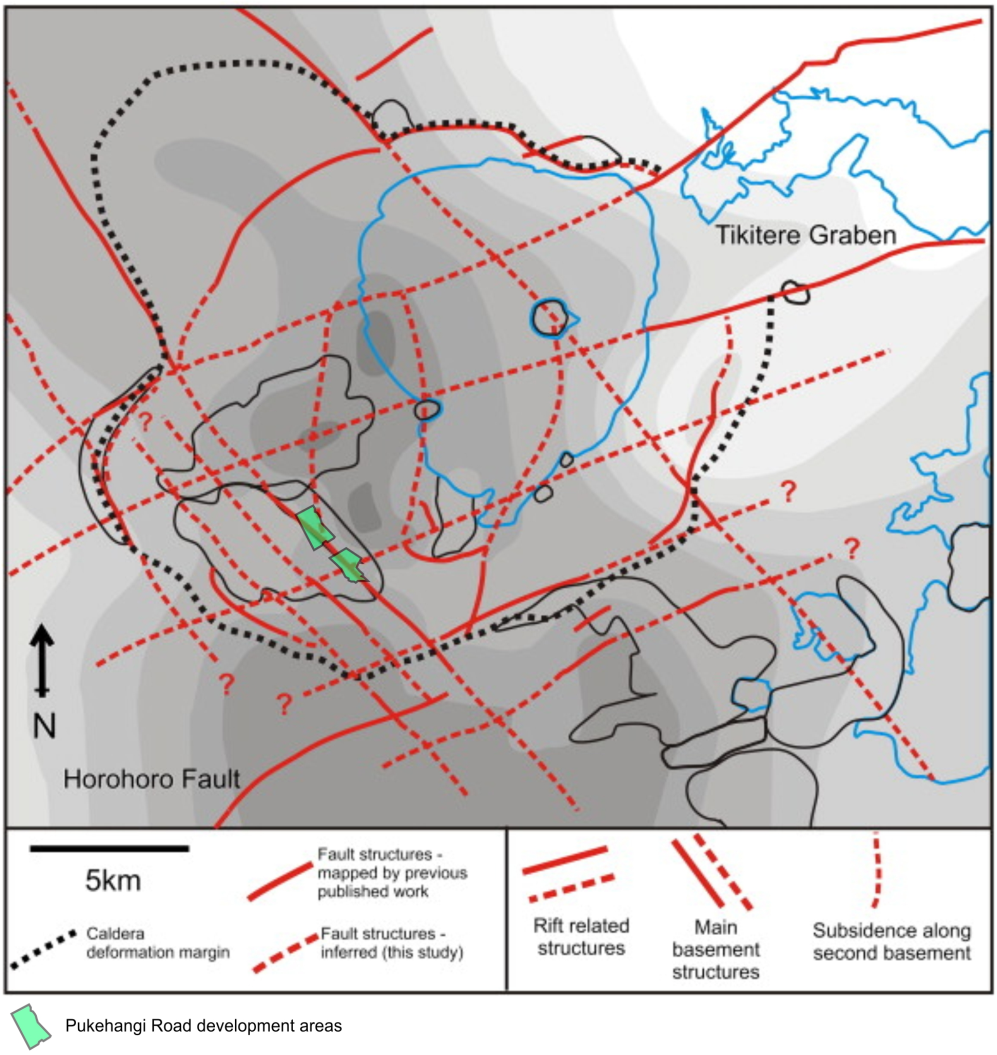

Figure A5.2 Pukehangi Road site overlain on the basement fault map of Ashwell et al. (2013). Summarised figure caption from Ashwell et al. (2013): Regional (trending NE–SW), caldera collapse (N–S) and basement related (trending NW–SE) structures grouped by strike and based upon dome elongations and internal structures. Domes are outlined in black, see Figure 1.2 for names, while lakes are outlined in blue. Known fault structures are taken from Milner (2001). Inferred faults are based on gravity gradients, dome locations, continuation of regional scale faults across the caldera, and field measurements of flow bands and fractures sets in lava domes.

APPENDIX 6 LETTER REPORT FOR THE OMOKOROA-KATIKATI SITES

Letter Report No: CR 2018/52 LR
Project No: 430W4198-00

6 April 2018

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Attention: Mark Ivamy

Dear Mark Ivamy,

Interim results on active faults around the Omokoroa-Katikati development sites, Tauranga

1.0 SUMMARY

To assess the potential presence or absence of active faults at the Katikati and Omokoroa development sites, we: reviewed the existing published and unpublished literature and maps of the area; reviewed 1940s and 1960s aerial photographs (NZ Aerial Mapping, see references for list); and analysed the landforms from a digital elevation model derived from Light Detecting and Ranging (LiDAR) data (provided by Bay of Plenty Regional Council).

The Katikati site overlies mostly old river deposits (Tauranga Group; 128,000 years to 2 million years old), with parts of the sites overlying low terraces containing younger river sediments (Holocene; 0 to ~12,000 years) (Figures 1 and 2). The Omokoroa site overlies both Tauranga Group sediments and volcanic rock (aged around 2 million years) (Figures 1 and 2). Prior to this study, no active faults at those sites had been identified through geological mapping (Edbrooke, 2001; Heron, 2014) and active fault mapping (New Zealand Active Fault Database, Langridge et al., 2016).

We cannot identify any geomorphic features in the landforms at either the Katikati or Omokoroa sites that can be classified as active faults. There may be old faults (such as the Tuapiro Fault; Figure 1) that are buried beneath the sediments and volcanic rock at these sites, but these would not likely have ruptured in at least the last 128, 000 years, as the surfaces of that age does not seem to be displaced by any faults.

There are also no known offshore faults near the development sites (Lamarche and Barnes, 2005).

1.1 GEOLOGY

The Omokoroa and Katikati development sites lie within the Tauranga basin, a depression which has been infilled with river and estuarine sediment, ignimbrite and volcanic-derived sediment since around 2 million years (Brathwaite & Christie 1996, Briggs et al. 1996).

The development sites at Omokoroa and Katikati are flanked to the west by the Kaimai Range, which comprises volcanic rocks that erupted nearby around 2-5 million years ago (Coromandel Group). The sites themselves overlie fluvial sediments of gravel, sand, silt and loess (Tauranga Group) that were deposited between 2 million years and around 128,000 years ago (see Figure 1). The Omokoroa development site overlies both Tauranga and Coromandel group rocks.

1.2 KATIKATI SITES

The western-most site at Katikati is located on higher hill terrain of alluvial fan sand and silt that is composed mostly of older Tauranga Group sediment aged between around 500,000 and 128,000 years old, with a smaller section of the site located on a Holocene valley (~12,000 years old or younger). The eastern sites overlie topographically lower hill terrain that is composed of younger Tauranga Group alluvial sediments of sand and silt; although the absolute maximum age of these sediments are 2 million years it is likely to be younger than those of the western-most Katikati development site but not younger than 128,000 years.

The closest known mapped faults to the Katikati development site is the Tuapiro Fault, which lies about 600 m west to the west of the sites (Figure 1); it is a concealed fault the location of which is inferred from the presence of warm springs, a steep gradient in Bouguer gravity data and absence of sediments in drillholes to the west of the fault (Brathwaite & Christie 1996). We do not see the surface expression of this fault on the digital elevation model generated from LiDAR data and the aerial photos; this implies that the Tuapiro fault and any other potentially buried fault in the area have not ruptured the ground surface in the last 128,000 years.

1.3 OMOKOROA SITE

The development site at Omokoroa overlies Coromandel Group ignimbrite (2-5 million years) and Tauranga Group (2 million years to 128,000 years) alluvial gravel, sand and silt. The nearest faults to this site are the Tuapiro and Hauraki faults that are 14 km and 16 km to the north and west respectively (Figure 1). Neither of those faults has been described as active in the literature and they do not show recent signs of movement based on our geomorphic study.

We cannot see visible evidence of geomorphic features that can be classified as an active fault at the Omokoroa site or in the surrounding area.

2.0 CONCLUSIONS

We conclude that no active faults have been identified in the present-day geomorphology at both the Katikati and Omokoroa development sites. The buried Tuapiro Fault that lies west of the Katikati site and other potentially buried faults that may lay in close proximity to the sites last moved before 128,000 years ago, and thus are not considered active under the current definition of active faults in the New Zealand Active fault database (Langridge et al, 2016).

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New Zealand Aerial Mapping photos 1940s: Run and photo numbers - 3000 (19-25), 3001 (18-25), 3002 (18-27), 3006 (15-22)

New Zealand Aerial Mapping photos 1960s: Run and photo numbers - 499 (33-40), 495 (33-43), 493 (84-91), 498 (28-36)

Yours sincerely

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This report was undertaken by Julie Lee and Pilar Villamor. It was internally reviewed by Rob Langridge.

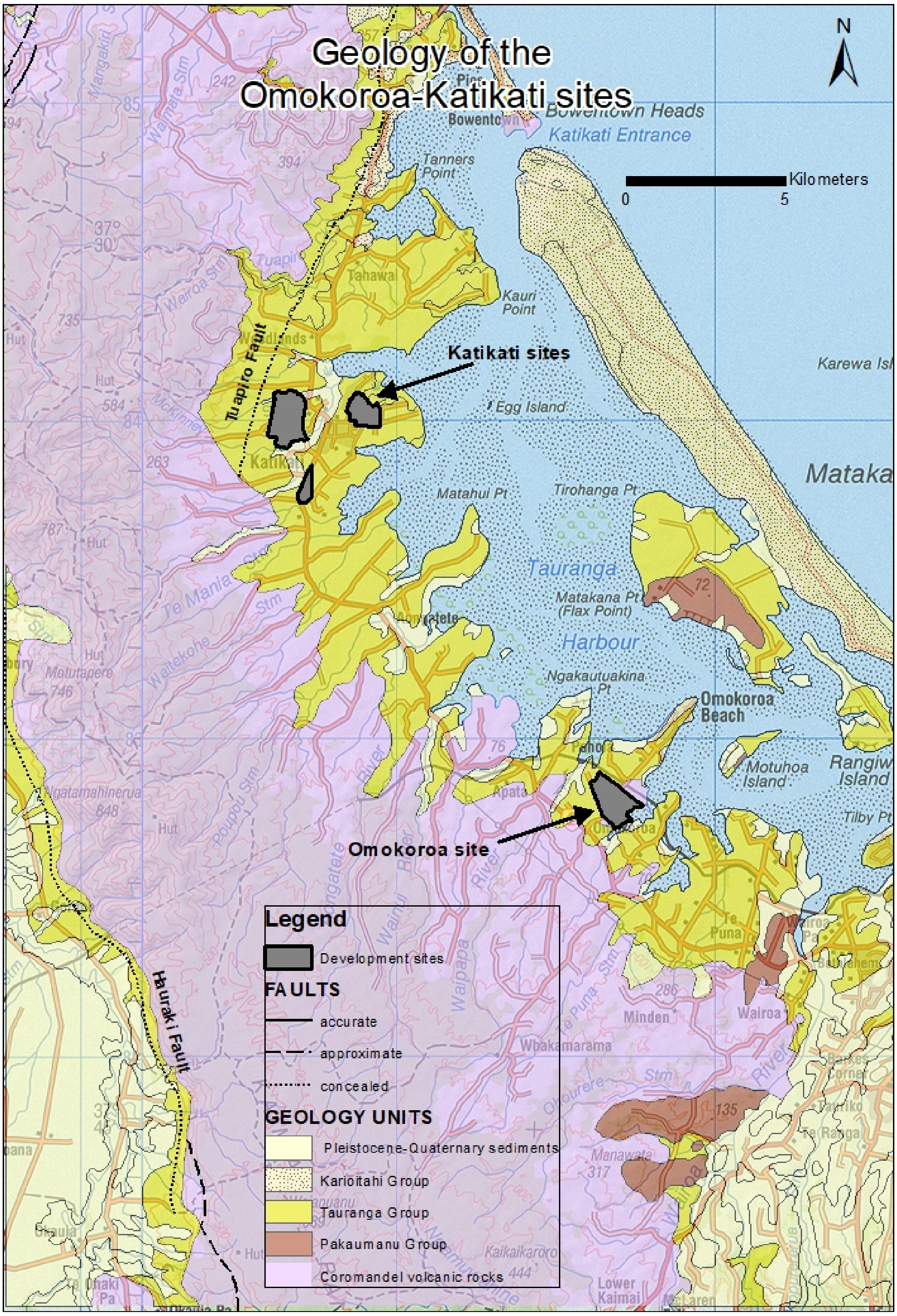

Figure 1 A generalised geological map of the area surrounding the Katikati and Omokoroa development sites (grey polygons). Volcanic rock of ignimbrite, lava flows, domes and other volcaniclastic sediment (2-5 Million years) form the Kaimai Range, which is bound to the west by the Hauraki Fault. Most of the volcanic rock was sourced from the Coromandel area although there are some outcrops of Pakaumanu Group ignimbrite that originated from Taupo area. The Tauranga Basin refers to the area east of the Kaimai Range where younger 2 Million years to 128,000 year old alluvial sediment infilled the depression. The geology and ages of the geological units are from Heron (2014).

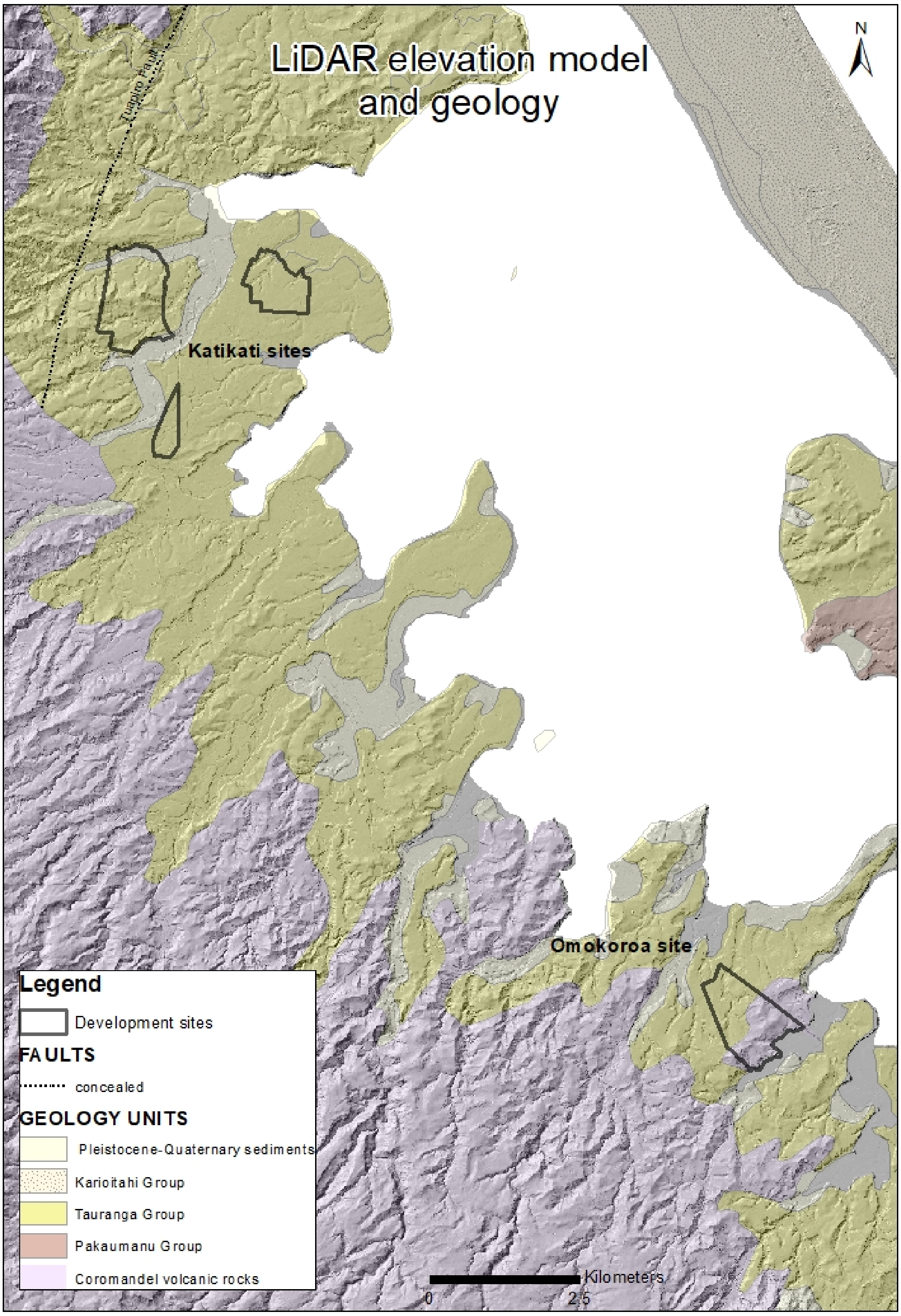

Figure 2 A 2 m LiDAR elevation model with geology for the Omokoroa and Katikati development sites. The landforms show the Coromandel volcanic rocks (purple) dip down towards the coast. Younger fan and river sediments (dark and light yellow) are deposited where streams and rivers carry their bedload downstream. There is no evidence of active faulting (recent displacement of the ground surface by faults) at the study sites. The geology is from Heron (2014).