Fault Avoidance Zone Mapping for Wairoa District, Napier City and surrounds

R. M. Langridge
A. Zajac
W. Ries

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CONTENTS

FIGURES

TABLES

APPENDIX

EXECUTIVE SUMMARY

Detailed active fault mapping has been undertaken for parts of Wairoa District, Napier City and surrounding areas, following the Ministry for the Environment's (MfE) Guidelines - "Planning for Development of Land on or Close to Active Faults". Fault traces and scarps have been mapped to produce Fault Avoidance Zones surrounding the active fault traces at a scale suitable for the purposes of cadastral zoning. For life safety purposes, the MfE Active Fault Guidelines focus on: (i) the location and complexity of faulting; (ii) the characterisation of recurrence interval of surface faulting; and (iii) the building importance category (BIC) with respect to land zonation for a site.

Five priority areas were selected for study on the basis of the presence of active faulting and/or good topographic data coverage. These were: (i) the Coastal portion of Wairoa District, where LiDAR coverage existed; (ii) Wairoa North, an area of similar geology, and to the north of (i); (iii) Mahia Peninsula; (iv) the Rangiora Fault in the western part of Wairoa District (and extending into Hastings District); and (v) Napier City, focusing on the buried trace of the Awanui Fault.

Mapping of active faults and construction of Fault Avoidance Zones was undertaken using a Geographic Information System (GIS). Most of the areas were mapped using rectified aerial photographs and a national-scale orthophotograph as base maps in the GIS, except where LiDAR imagery was available. Typically the data in this report has been mapped at a scale of c. 1:10,000. Linework on faults in the GNS Active Faults database[1] has been improved upon, and in some cases deleted from the database as a result of this study.

In general, the location of surface faulting is approximated by a line mapped in the GIS along each fault trace. Fault traces have been classified according to their form (scarp/ possible scarp/ inferred trace etc.) with the information stored in an Attribute Table in the GIS. Attached to each trace is a combined estimate of location uncertainty that includes: (i) the fault feature uncertainty; (ii) the location error, i.e. the exact location of the fault rupture with respect to the fault feature, and (iii) the uncertainty based on the underlying map data, e.g. the error associated with rectification of aerial photographs into a GIS. The total uncertainty varies between ± 40 and ± 80 m for each fault trace. Each "Fault Location Uncertainty" buffer has an additional ± 20 m "Factor of Safety" buffer placed around it to create the full Fault Avoidance Zone.

In the eastern half of Wairoa District, the number of fault traces previously shown in the GNS Active Faults database has been significantly reduced due to re-interpretation of the features and their origin. In Coastal Wairoa where LiDAR coverage exists, no active fault traces have been kept from previous mapping efforts. For the Wairoa North and Mahia priority areas, the mapped faults are typically normal faults, though some may be landslide-related lineaments. Due to the considerable uncertainty concerning their form and with some difficulty of geo-referencing aerial photographs, these faults have been given fault location uncertainties of ± 40-80 m. These yield full Fault Avoidance Zone widths, including the ± 20 m Factor of Safety buffer, of 120-200 m width. It is possible that these short, normal faults are not "seismic" (earthquake-generating) faults, i.e. they may rupture as secondary features. Nonetheless, they still pose a surface deformation hazard when they rupture. Many of the faults mapped in the eastern part of Wairoa District were not assigned to a Recurrence Interval Class due to a lack of basic geologic information to make such decisions. Several faults on the Mahia

[1] http://data.gns.cri.nz/af/

Peninsula were assigned to recurrence class IV (RI 5000-10,000 years), based on sparse information about their activity.

The Rangiora Fault is an active strike-slip fault in the western part of Wairoa and Hastings Districts. It has an assigned Recurrence Interval Class I (RI <2,000 years) based on preliminary slip rate and paleoearthquake studies. The Rangiora Fault was reviewed and mapped over a length of c. 20 km to the north and south of the Waikari River (Wairoa-Hastings District boundary). The fault trace was re-mapped over a distance of c. 8 km to the north of the Waikari River in Wairoa District. In this area the buffer widths range from ± 50-70 m (excluding Factor of Safety buffer). These yield full Fault Avoidance Zones of 140-180 m width. The Rangiora Fault was also re-mapped over a distance of c. 8 km to the south of the Waikari River within Hastings District. In this area the fault location uncertainty ranges from ± 40-70 m, excluding the Factor of Safety buffer. These yield full Fault Avoidance Zones of 120-180 m width.

There are no mapped active fault traces within the bounds of Napier City. As part of this study, we have reconsidered the role and effects of the 1931 M 7.8 Hawke's Bay earthquake, which destroyed Napier and Hastings. Significant effort was invested in trying to locate the Awanui Fault across the Heretaunga Plains. AD 1931 surface deformation related to the fault was broadly mapped across the plains between Bridge Pa and Awatoto. While the Awanui Fault should be considered as an active fault/fold of Recurrence Interval Class IV (>5000-≤10,000 yr), it has not been possible to accurately map a fault/fold trace or portray a relevant Fault Avoidance Zone.

Faults mapped in this study fall into RI Class I (≤2000 yr; Rangiora Fault), IV (>5000-≤10,000 yr; Mahia faults and Awanui Fault) or are of unknown recurrence interval. Tables that relate the Fault Recurrence Interval to the Fault Complexity and Building Importance Category are placed within Section 4 of this report. These form the basic guidelines that planners should use when assessing the risk attributed to resource and building consent applications.

†For example, according to the MfE Active Fault Guidelines, for Recurrence Interval Class IV faults like those across Mahia Peninsula BIC 2a and 2b (Normal) structures should be permitted activities. For BIC 3 (Important) structures, the resource consent activity is permitted in the case of developed or already subdivided, and typically Discretionary for Greenfield settings. BIC 4 (Critical) structures hold a Non-Complying Status in both the "Greenfield" and "previously subdivided" setting.

We recommend that this mapping and zonation be adopted by Hawke's Bay Regional Council and its Territorial Authorities. The GIS dataset on the accompanying CD, provides coverage at the appropriate scale and includes cadastral information, with respect to fault location[2]. In future, other parts of Hawke's Bay region, including the coastal ranges (Maraetotara Plateau) and inland parts of Central Hawke's Bay and Hastings Districts could receive further attention with regards to active fault mapping and fault avoidance zonation.

[2] Maps in the text of this report should not be used for planning purposes. They act as examples of what data resides on the GIS CD.

1.0 INTRODUCTION

1.1 Scope of the Study

This study was undertaken for Hawke's Bay Regional Council (HBRC) by the Institute of Geological and Nuclear Sciences Ltd (GNS Science). The purpose of the study is to help the Regional Council formulate and implement appropriate guidance for its Districts (and their plans) pertaining to development in areas on, or close to, active faults in the region. To facilitate this, the two principal aims of GNS' study were to: 1) more accurately define the location and activity of faults in parts of Wairoa District and the City of Napier (Figs. 1-3); and 2) produce Fault Avoidance Zones for active faults in a fashion that is wholly compatible with the MfE Active Fault Guidelines (Kerr et al. 2003). The main focus of this study was to continue on from similar fault mapping projects in Hastings and Central Hawke's Bay Districts which concentrated on areas that had been mapped using LiDAR[3] DEM coverage (Langridge and Villamor 2007; Langridge et al. 2006).

In this study, the main techniques for producing new fault and Fault Avoidance maps included:

- A literature review;
- An analysis of available large scale aerial photographs, orthophotographs, and LiDAR coverage;
- Accurate mapping of active fault traces within a GIS format;
- Limited reconnaissance field work to verify and more accurately define fault locations in specific areas; and
- Application of the MfE Guidelines.

Detailed fault mapping has been carried out in the Wairoa lowlands area where LiDAR coverage was made available by the HBRC (see Fig. 3). While many active faults in the inland parts of Wairoa District, e.g. the Mohaka and Waimana faults, have not been considered for this study, the Rangiora Fault has been re-mapped as it occurs on rural land within the district, and continues southward into Hastings District. In Napier City, the main focus of this study is in determining the location of the 1931 Hawke's Bay (Napier) earthquake source and better define the ground deformation style for this structure.

The results of this work are this report, and a GIS database of fault features (as lines and points with associated GIS attribute tables) and Fault Avoidance Zones (as sausage-shaped areas with associated GIS attributes). The Fault Avoidance Zones are linked to Resource Consent Categories via tables pertaining to Fault Recurrence Interval Class, and Building Importance Category. Maps derived from the GIS database are included in this report (e.g. Fig. 4). These maps are provided to illustrate the methodology used and level of detail obtained in some areas, but do not show all areas where similar detail is present.

[3] LiDAR (Light Detection and Ranging) is an optical remote sensing technology that measures properties of scattered light to find range and/or other information of a distant target. LiDAR survey data are used to create accurate digital topographic models.

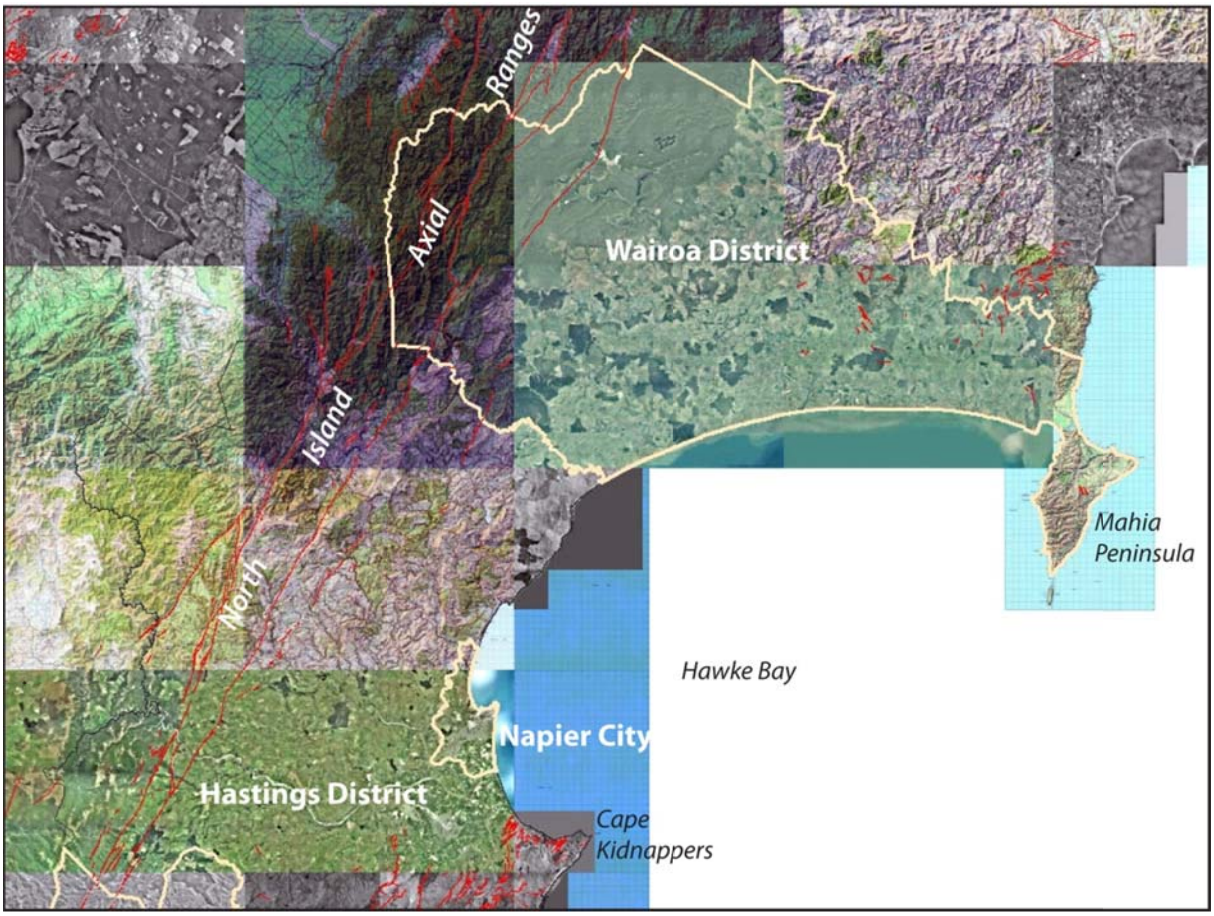

Figure 1 Map showing the northern part of Hawke's Bay region, with active faults in red (as at the time of this study) *Source*: GNS Science Active Faults database. This report is focused on active faulting within Napier City and Wairoa District.

In the report that follows, we first outline the background to this work, including the plate tectonic setting in Hawke's Bay region. We then discuss, in some detail, the methodology used to achieve the study's objectives. Following this, we present the results of the study, whereby we define Fault Avoidance Zones based on fault rupture location and complexity, and Recurrence Interval Class based on the fault's average recurrence of surface rupture. Combining these two fault rupture hazard parameters (Complexity and Recurrence), with information on Building Importance Category (i.e. building type) and development status (i.e. previously developed, or "Greenfield" site) an appropriate, risk-based Resource Consent Category can be defined for land on, or close to the active faults in the mapped areas. The report ends with a number of recommendations and conclusions.

The CD included with the report contains a copy of the report and tables (in PDF format) and figures (as tiff images) together with the data collated as part of this study in ESRI Shapefile format (i.e. the GIS information; see Appendix I for details). Potential users are referred to the GIS data on the enclosed CD for complete coverage of the study area.

1.2 Tectonic setting of Hawke's Bay region

New Zealand lies within the deforming boundary zone between the Australian and Pacific tectonic plates. The area administered by Hawke's Bay Regional Council (HBRC) lies within one of the more tectonically active parts of this boundary zone (Fig. 2). The region is underlain by the subducting Pacific plate along the Hikurangi subduction margin. Onland, the region is traversed by a number of active faults that are capable of rupturing the ground surface during large earthquakes. These include the Mohaka Fault, Patoka Fault, Poukawa Fault Zone and Tukituki Fault Zone (Fig. 2).

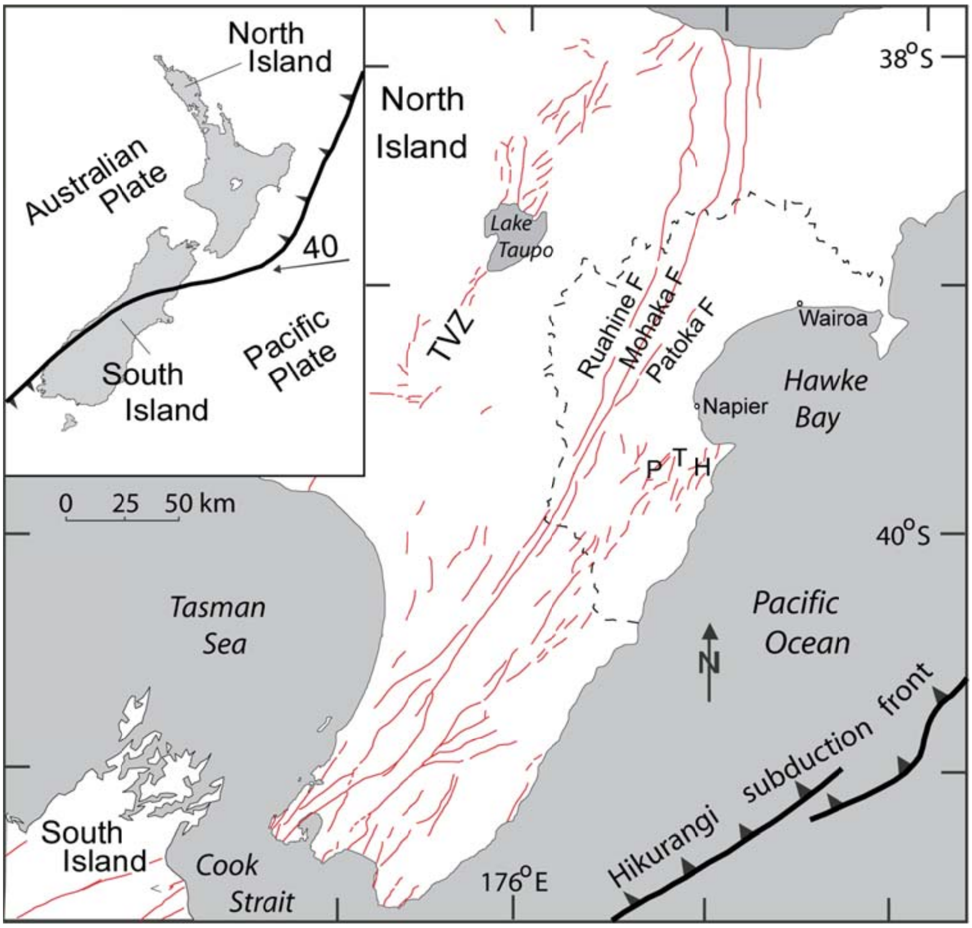

Figure 2 Simplified tectonic map of eastern North Island. Hawke's Bay region, shown within the dashed line, spans an area of active deformation between the Pacific and Australian plates. The region includes a number of major active fault zones, e.g. P, Poukawa Fault Zone; T, Tukituki Fault Zone; H, Hawke's Bay Extensional Domain; and to the west the Ruahine, Mohaka and Patoka faults.

Previously published data from these faults indicate that some have relatively high rates of activity (i.e. short recurrence intervals of earthquake fault rupture), and are capable of generating large earthquakes (M >6.5) associated with large (i.e. metre-scale) single event surface rupture displacements (Halliday 2003; Hull 1990; Cutten et al., 1988; Kelsey et al., 1998; Raub et al. 1987).

Surface rupture along these active faults 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. Such effects were witnessed as part of the September 4, 2010 Darfield earthquake (Quigley et al., 2010; Van Dissen et al., 2011).

Horizontal movements of up to 5 m (c. 2.5 m average) and typically 0.5 m vertical were measured across a 28 km surface break called the Greendale Fault.

Within Wairoa District, the main zones of active faulting occur within the Axial Ranges of the North Island. The Patoka, Mohaka and Ruahine faults and their northward equivalents (the Rangiora, Whakatane, and Waiohau faults are predominantly dextral strike-slip faults (Cutten et al. 1988; Mouslopoulou et al. 2007) These faults are involved in translating the eastern North Island southward, with respect to the rest of the island (Beanland 1995; Wallace et al. 2004). These faults fall into Recurrence Interval Classes I and II with estimated recurrence intervals of <2000 or 2000-3500 years (Van Dissen et al. 2003; Kerr et al. 2003). In the eastern half of Wairoa District a large number of short active fault strands have been shown in the Raukumara QMap sheet (Mazengarb and Speden 2001) and in the GNS Science Active Faults database (http://data.gns.cri.nz/af/). These fault traces are one of the focuses of this report as little is known about their activity, style or continuity.

Napier City is a small Territorial Authority that encompasses the area of Napier and its suburbs. While no active faults are currently shown through Napier City it is worth considering the location and role of the concealed Awanui (Napier) Fault during the 1931 Hawke's Bay earthquake (Hull 1990).

1.3 The Ministry for the Environment Guidelines

The Ministry for the Environment, has published Guidelines on "Planning for Development of Land on or Close to Active Faults[4,5] (Kerr at al. 2003, see also King et al. 2003; Van Dissen et al. 2003). The aim of the MfE Active Fault Guidelines is to assist resource management planners tasked with developing land use policy and making decisions about development of land on, or near, active faults. The MfE Active Fault Guidelines provide information about active faults, specifically fault rupture hazard, and promote a risk-based approach when dealing with development in areas subject to fault rupture hazard. In the MfE Active Fault Guidelines, the surface rupture hazard of an active fault at a specific site is characterised by two parameters: a) the average recurrence interval of surface rupture of the fault, and b) the complexity of surface rupture of the fault. In this report, these two fault rupture hazard parameters are defined for active fault zones that extend through the Hawke's Bay region.

The MfE Active Fault Guidelines also advance a hierarchical relationship between Recurrence Interval Class and Building Importance Class, such that the greater the importance of a built structure, with respect to life safety, the longer the avoidance recurrence interval (see Table 6, and Appendix I for more detail). For example, only low hazard structures, such as farm sheds and fences (e.g. Building Importance Category 1 structures), are permissible structures across active faults with average recurrence intervals of surface rupture less than 2000 years (RI Class I). In contrast, in a "Greenfield" (i.e. undeveloped) setting, more significant structures such as school halls, airport terminals, and large hotels (Building Importance Category 3 structures) should not be sited across faults with average recurrence intervals shorter than 10,000 years.

[4] The Ministry for the Environment's Guidelines "Planning for Development of Land on or Close to Active Faults: A guideline to assist resource management planners in New Zealand" is now available on both their main website and their Quality Planning website.

[5] Throughout the remainder of this report, the Ministry for the Environment's Guidelines will be referred to as the MfE Active Fault Guidelines.

1.4 Data sources and the priority mapping areas

The main data resources used in this study are the GNS Science Active Faults database (http://data.gns.cri.nz/af/) and QMap 1:250,000 scale geologic mapping (Mazengarb and Speden 2001; Lee et al. in review). Active fault mapping that was used in the former is typically undertaken from aerial photographs - that data being transferred to 1:50,000 scale maps and eventually digitised into a GIS database. Mapping resolution from these sources is not appropriate for cadastral purposes. Some of the effort undertaken in this study has been to review the location and quality of the active fault data from both the GNS Active Faults database and QMap sources, so that it can be implemented for planning purposes.

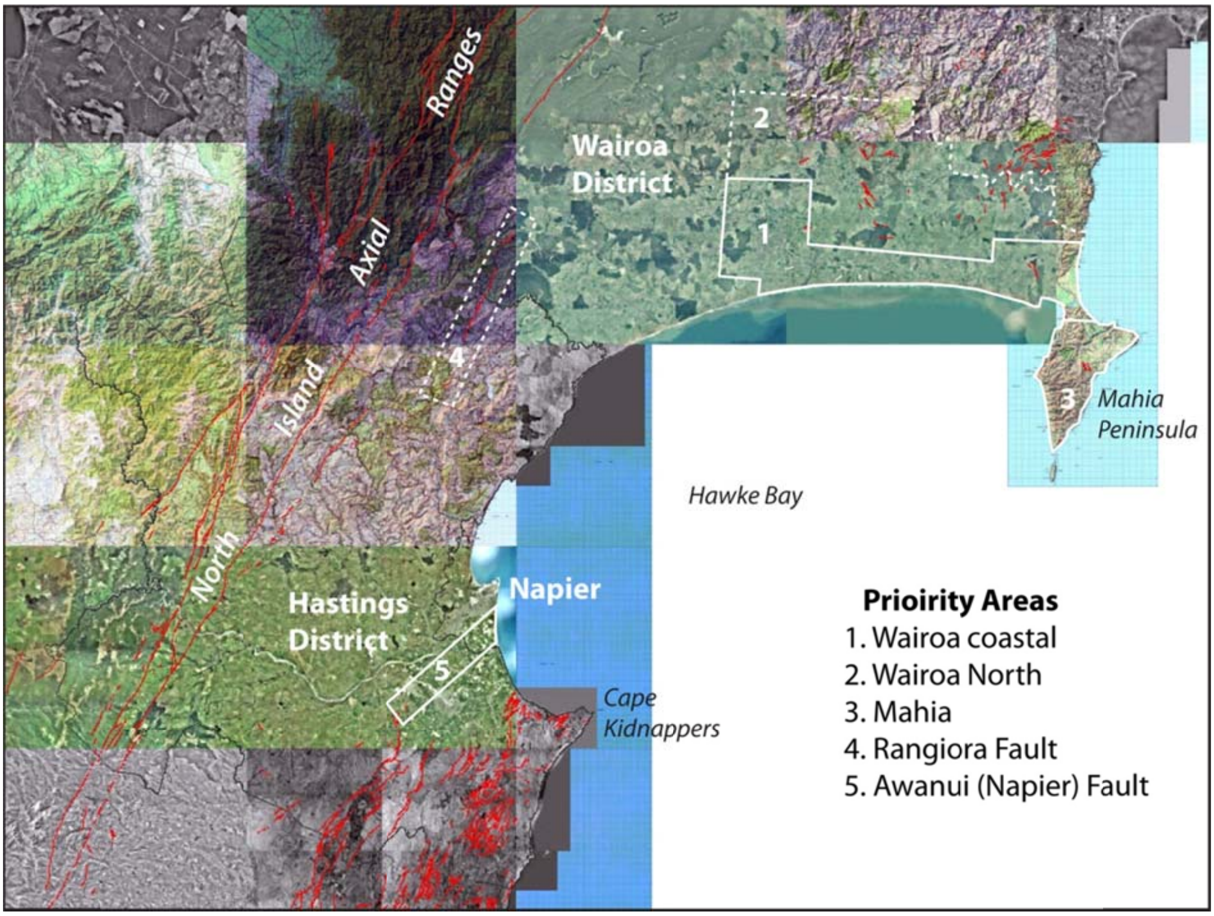

Figure 3 Orthophotograph coverage of northern Hawke's Bay. The priority mapping areas are shown by white polygons. Active faults from the GNS Science Active Faults database are shown in red. Area 1 is defined by a strip of LiDAR data flown in the coastal part of Wairoa District.

A brief summary of the priority areas follows (Fig. 3).These areas were chosen for study because they comprise areas of active faulting and/or they have good topographic data coverage, such as from LiDAR.

1. Wairoa Coastal: The Wairoa coastal area in this study is defined by the currently available LiDAR coverage, supplied by the HBRC (Fig. 3). This strip represents the area within Wairoa District that includes Wairoa township and the lower Wairoa River, so is by far the most densely populated zone in the district. A high quality 1-m Digital Elevation model of the Wairoa coastal area was developed from the LiDAR dataset to investigate the validity of mapped fault traces across low-lying sculpted hill country composed largely of Pliocene and Miocene mudstone rocks (Mazengarb and Speden 2001). The LiDAR data proved to be

invaluable for scrutinising previously mapped fault features, and acted as a guide for identifying faults in the Wairoa North area (e.g. Fig. 4).

2. Wairoa North: This priority area includes the area immediately north of the Wairoa coastal LiDAR DEM and as far as the District boundary to the north (Fig. 3). The area is almost entirely rural in its setting. At the time of this review, a significant number of active faults were shown on the GNS Active Faults database in this area (http://data.gns.cri.nz/af/). These faults typically have short traces and have been identified as normal faults occurring within Pliocene and Miocene sedimentary rocks. The area is also highly prone to erosion and landsliding as these deforested hillslopes tend to fail under heavy rainfall conditions. An important part of this study is to test the fault mapping that has been presented from previous studies. For example, some faults shown in the GNS Active Faults database are not shown on QMap Raukumara (Mazengarb and Speden 2001), and *vice versa*.

3. Mahia: This priority area covers the Mahia Peninsula from the eastern edge of the LiDAR DEM to the end of the peninsula. Prior to this study only a few active fault traces have been identified on the peninsula (Fig. 9). These faults are typically shown cutting across uplifted marine terraces that define the flat mesa-like topography of the peninsula. The most extensive marine terrace on Mahia Peninsula is identified as being of Q5 (i.e. Marine Isotope Stage 5) age, which refers to a global marine terrace of age c. 125,000 years (or less). This implies, by definition that these faults, if present, are active faults, i.e. they have moved in the last 125,000 years.

4. Rangiora Fault: The Rangiora Fault is an active dextral-slip fault that occurs at the eastern edge of the North Island Axial Ranges (Beanland 1995; Cutten et al. 1988). This fault is a high priority for surface rupture mapping as it occurs in rural land – compared to the similarly active Mohaka and Ruahine faults that typically occur in forest and National Park lands at the western edge of Wairoa District. The Rangiora Fault is a Class I fault based on Recurrence Interval (i.e. surface rupture recurs <2000 yr). The fault has an estimated late Holocene slip rate of c. 6.8 mm/yr and at least three late Holocene surface rupturing earthquakes, as evidenced by displaced tephra layers in outcrop and offset alluvial terraces that are capped by these tephra (Cutten et al. 1988).

5. Awanui (Napier) Fault: There are currently no active faults mapped within the confines of Napier City. However, it is clear that the February 3rd, 1931 M 7.8 Hawke's Bay earthquake caused ground deformation including surface rupture to the southwest of the Heretaunga Plains, in the area of Pakipaki and Poukawa (Hull 1990). While no surface rupture was recognised across the younger surfaces of the plains, ground deformation (warping or folding) was discerned from the re-levelling of the East Coast railway line following the earthquake. The ground deformation is related to the trace of a "blind" fault, i.e. one that does not rupture completely to the surface. This fault is now called the Awanui Fault. Alternatively, this feature can be considered as an active fold trace. In either case, this warrants some consideration in terms of future ground deformation from a repeat of the 1931 Hawke's Bay earthquake.

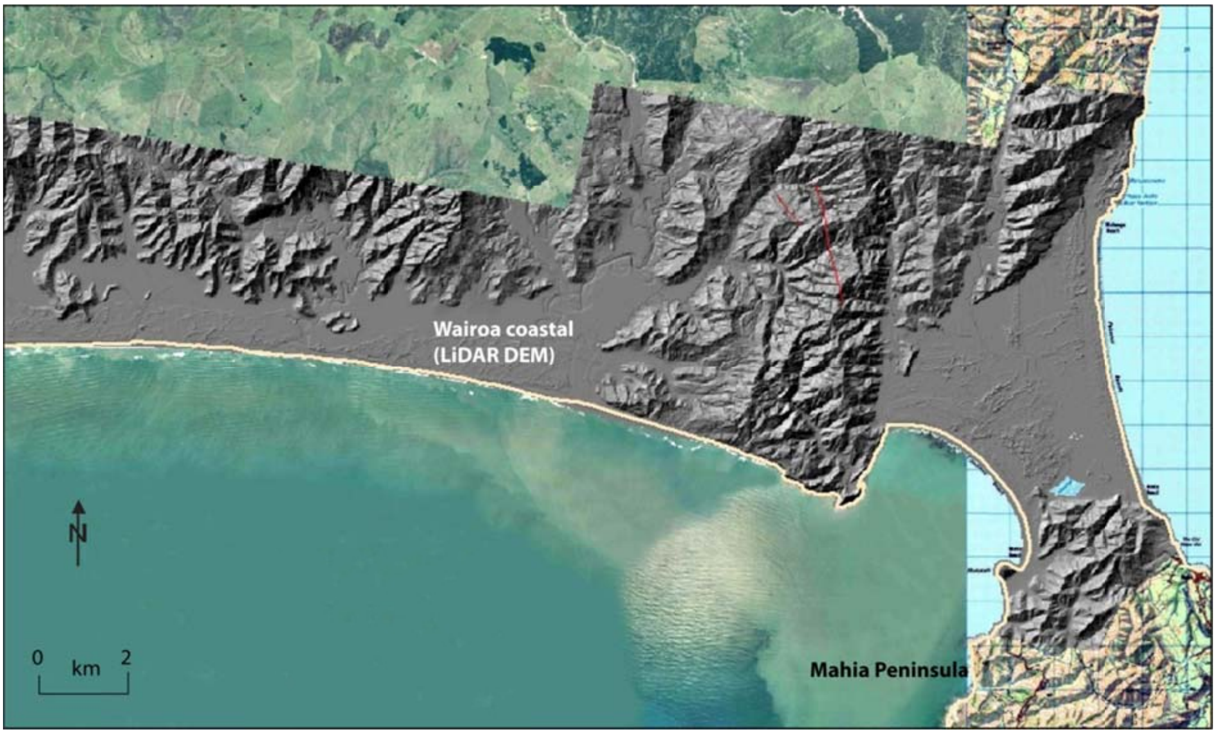

Figure 4 LiDAR shaded hillslope map of a portion of the Wairoa coastal area (grey DEM). Red lines represent active faults within the GNS Science Active Faults database prior to this study. The 1-m DEM has allowed us to revise this mapping, so that no active fault traces are now identified.

1.5 Field investigations of faults

Several research and reconnaissance field trips to 'ground truth' fault traces in Hawke's Bay have taken place between 2006-10 as part of the program of active fault mapping in the region (Langridge 2007; Langridge and Villamor 2007; Langridge et al., 2006). In addition, in 2002, a GNS field reconnaissance trip that included the lead author, visited the Rangiora Fault between Heays Access Road and the Waikari River. No other reconnaissance trips have been undertaken as part of this project.

2.0 METHODOLOGY OF FAULT MAPPING

The methodology for mapping faults and developing hazard zones (Fault Avoidance Zones) outlined in the MfE Active Fault Guidelines was used in this work. The main steps in the process were:

1) identifying active fault traces, and related features, in the priority areas through use of pre-existing knowledge of the region, aerial photographs (listed in Appendix), and LiDAR data;
2) mapping and defining the location of the fault traces and features of surface deformation in a Geographic Information System (GIS);
3) classifying all parts of a fault in terms of its Fault Complexity of surface rupture and uncertainty of its location (see Table 6 in Section 4.3);
4) defining Fault Avoidance Zones for each of these parts;
5) determining the average recurrence interval of surface rupture faulting (i.e. Recurrence Interval Class) for each of the major fault zones.

These data are then combined with standard tables for Building Importance Category (see Table 2 in Section 4.1) and Development Status (see Table 4) to determine appropriate Resource Consent Categories for proposed development of land on, or close to active faults identified in this study (see Tables 5, 6).

2.1 Identification of Active Fault Traces

The types of fault features and the techniques we used to identify fault features in the field and within the GIS (on aerial photographs etc.) are listed below:

Fault feature definition:
- Scarp = clear evidence of a fault scarp
- Broad scarp = smooth or broad shape of a scarp
- Rangefront scarp = scarp along a Tertiary bedrock hillslope
- Possible scarp = uncertain fault feature or identification
- Inferred trace = scarp/ fault not visible, but inferred

Feature Identification:
- Distinct on LiDAR
- Distinct on aerial photographs
- Estimated from aerial photographs
- Ground truthing (field mapping and/or trenching)

In some areas where fault features should be visible, they could not be observed or mapped. While in the subsurface a major active fault is typically a near-continuous geological structure, the surface expression of the last few surface ruptures of the fault is often intermittent. These ‘traces’ of faults are defined as “inferred traces”. For instance, on hillslopes or fault rangefronts, geological processes such as landslides and slope wash can quickly destroy or modify topographic fault features. Stream processes such as erosion and sediment deposition can destroy fault features on alluvial plains and terraces. Also, fault ruptures are seldom preserved on active floodplains where the young age and mobility of the fluvial sediments often erode or bury the evidence of faulting. It is along the stretches of an active fault where fault features are not preserved that uncertainty as to the fault’s precise location is greatest.

Previous studies of active faulting in Hawke's Bay, e.g. Kelsey et al. (1998); Begg et al. (1994; 1996), produced basic map data at differing scales on the location and type of fault-generated features present. These data are often produced at a regional scale (typically 1:50,000 scale), which is unsuitable for the purposes of the MfE Active Fault Guidelines. More recently, active fault mapping studies in Central Hawke's Bay and Hastings Districts have used a MfE Fault Avoidance Zone methodology (e.g. Langridge and Villamor 2007; Langridge et al., 2006).

2.2 Uncertainty of Fault Feature Location

The accuracy with which the location of a fault feature can be captured into a database is influenced by two types of uncertainty or error. The first is the error associated with how accurately the fault feature can be located on the ground. The second is the error associated with capturing that position into a map or database.

2.2.1 Uncertainty of locating a fault feature

Where fault features are preserved, the accuracy with which the fault can be located on the ground depends on the type and geometry of the feature. A fault scarp is one of the more definitive features that can be used to define the location of a fault. For example, in places, scarps of the Rangiora Fault are sharp and distinct (c. 5-10 m wide), and here it is possible to define the location of the fault quite accurately (to within several metres, e.g. well-defined fault complexity (see Fig. 5). However, in other places, scarps are broad topographic rises over a distance of 20 metres or more. Without trenching or other subsurface investigations at these sites, the ability to capture/ define the position of the fault plane that may rupture to the Earth's surface in an earthquake cannot be significantly more accurate than the distinctness/ sharpness of the topographic expression of the fault feature. So, even when topographic fault features are preserved, the ability to use these features to define the precise location of the fault plane, and therefore future surface rupture hazard, varies according to the distinctness of topographic expression of the feature.

Other parts of fault traces fall into the "distributed" category of fault complexity. These include broad scarps, and fault stepover zones. Where a scarp is broad it is difficult to determine the exact base and mid-point of the fault scarp. For broad scarps it is quite difficult to locate the exact point on the scarp where the deformation (rupture) is most pronounced, as it may be distributed over a broad zone.

At other locations, the fault trace is inferred. This occurs when the trace is not visible at all, but would be there if it were preserved. Inferred traces sometimes link together fault traces that traverse the landscape in a stepping or "en echelon" fashion. Inferred traces are also mapped across major rivers, e.g. Ngaruroro River. In these cases, the scarp has been eroded away by the river, or, there has been no surface faulting since the most recent period of river activity.

In limited instances, active faults and fault-related features can be located absolutely, for example, in trenches such as those that were excavated across the Poukawa Fault Zone (see Kelsey et al. 1998). GPS or traditional survey techniques can be used to locate and capture the positions of the fault features (or planes) to an accuracy of ± 0.1 m, and they are attributed as "surveyed" in the GIS database. However, in the case of this study, no new field work has been undertaken to ascertain the exact location of the fault plane within any fault features. LiDAR DEM's are also a means of yielding accurate topographic information that shows the geomorphology of active fault features. In this study a 1-m DEM could be produced from xyz-point data from the Wairoa coastal area.

2.2.2 Uncertainty of fault zone width due to the style of faulting

Mapped fault traces are used to construct fault rupture zones (zones within which future rupture is likely to cause ground deformation). In some areas, these zones are based on the position of a simple linear fault line, and the width of the zones reflects the accuracy of capture. In other places, the zone is based on complex features or inferred where no features are preserved. In these areas the width of the zone is large and reflects both the complexity and uncertainty of the fault location on the ground, and the accuracy of capture. In specific cases, detailed fault studies, such as trenching or ground surveying could, in the future, be used to reduce the uncertainty of fault location and thereby reduce the width of the fault rupture zone (Kerr et al., 2003).

An additional important source of mapping uncertainty is related to the style of faulting, e.g. strike-slip vs. dip-slip faulting. Faulting is usually confined to the width of the fault scarp shown on the ground surface. Strike-slip faults typically have a narrow fault scarp with little if any vertical height, unless there is an oblique (normal or reverse) component of movement associated with them (Fig. 5). Normal dip-slip faults occur where an area is under extension. Faults in the Wairoa area are believed to be normal in style, while faults located on Mahia Peninsula are likely to be normal or reverse in style. The Rangiora Fault is a right-lateral strike-slip fault, i.e. it is characterised by horizontal movement. In the case of normal and strike-slip faults a ± 20 metre buffer (a factor of safety buffer) is applied to the mapped zone of uncertainty or added to the mapped fault scarp.

In contrast, reverse, dip-slip faulting is characterised by low to moderately dipping faults (compared to steep dips for strike-slip faults). In Hawke's Bay most reverse faults dip to the west or northwest at angles of 20-60º. Because of their dip, reverse faults produce an asymmetric (skewed) distribution of surface deformation above them. For reverse fault earthquakes such as the 1999 Chi-Chi (Taiwan) event, the hangingwall block (upthrown block) is pushed up and over the footwall block (see Fig. 5 and examples in Kelson et al. 2001).

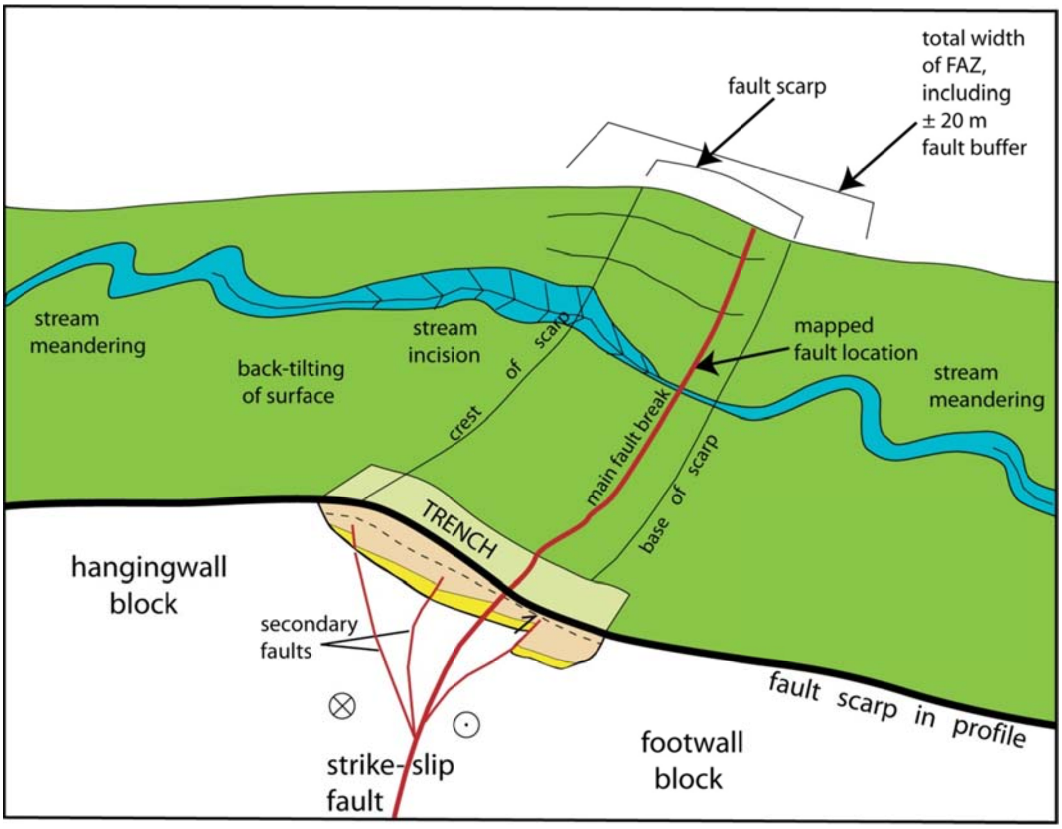

Figure 5 Schematic diagram of a typical fault scarp and active fault in plan view and cross-section. In this case the mapped fault trace (rupture surface; bold red line) is located near the base of the scarp. The scarp itself is well-defined, i.e. clear. The growth of such scarps affects the long–term morphology of streams that cross the structure. The trench shows the faulting events can be documented (e.g. faulted yellow layer). The concepts of fault location accuracy and setback are used to create a Fault Avoidance Zone (FAZ).

In the case of the reverse-sense Awanui (Napier) Fault, fault movement during the 1931 Hawke's Bay earthquake the up-dip tip of the fault plane did not rupture all the way to the ground surface across the Heretaunga Plains. Such a fault is often called a "blind" fault. Blind faulting may result in a broad scarp or warp, or an anticlinal ridge. Surface deformation is still present as folding, uplifting or tilting of the ground surface (similar to Fig. 5 but fault plane does not reach the surface). This type of surface deformation should also be considered as part of a Fault Avoidance Zone 'strategy', as it may also pose a Life Safety concern.

Due to the effect of more deformation focused in the hangingwall block of reverse faults, we believe that the Fault Avoidance Zone should be asymmetric[6] about the best estimate location of the fault rupture. As the amount of uncertainty varies from trace to trace, we consider it likely that the zone of deformation in the hangingwall could be twice as wide as that in footwall block (see Langridge and Villamor 2007).

2.2.3 Fault complexity and form of fault features

Fault Complexity refers to how clear/ distinct and/or how wide the zone of deformation is that is being mapped, i.e. how much uncertainty there is regarding the location of the fault and how it appears on the ground. Fault Complexity is an important parameter used in defining surface rupture hazard at a site. The MfE Active Fault Guidelines define Fault Complexity of

[6] The application of an asymmetric Fault Avoidance Zone has not been used for normal or strike-slip faults.

surface rupture using the following terms: *well-defined, distributed* or *uncertain* to describe fault location (Kerr et al. 2003; see also King et al. 2003, and Van Dissen & Heron 2003). When fault rupture deformation is distributed over a wide area, the amount of deformation at a specific locality within the distributed zone is less compared to where the deformation is concentrated on a single well-defined trace. Therefore, the relative fault rupture hazard/risk is less within a zone of distributed deformation than within a narrow well defined zone.

2.2.4 Uncertainty of capture method

The LiDAR shaded relief map has a capture uncertainty of c. ± 10 m. The fault traces are generally well-defined where a clear scarp is evident on the ground surface, on aerial photographs or on the LiDAR imagery. Clear scarps generally have a location uncertainty of ±10-20 metres (Table 1). This means that we have mapped a line that represents the fault location and there is an inaccuracy of that location to within c. ±10-20 metres. In most cases, this line has been placed at, or toward the base of the fault scarp or trace captured in the GIS. This is where we expect the fault to rupture and where the greatest amount of co-seismic deformation should be focused. This assertion comes from the experience of trenching many faults in Hawke's Bay and other similar tectonic environments (Beanland 1995; Kelsey et al., 1998), and by documentation of historic reverse fault earthquakes, such as the 1931 Hawke's Bay or 1999 Chi-Chi (Taiwan) earthquake ruptures (Hull 1990; Kelson et al. 2001).

We have developed a modified version of this hierarchy for recognising fault features in Hawke's Bay, locating them using mainly aerial photograph analysis and LiDAR, capturing the data (mapping them) into the GIS. This hierarchy establishes a "fault location accuracy" that reflects how distinct a fault feature appears on imagery (e.g. broad scarp vs. inferred trace), how we have identified them (e.g. ground truthing vs. LiDAR), and how we have captured the data in the GIS (e.g. via rectified aerial photograph vs. LiDAR). The variables that we have used to define fault feature, feature identification, and capture technique are listed in Table 1 below.

Table 1 Example of Attribute Table from the Geographic Information System, including the types of fault feature, and their complexity and combined uncertainty of mapping.

Fault Feature	Fault Complexity*	Combined Uncertainty
Scarp	Well defined	± 20-30 m
Broad scarp	Distributed	± 30-40 m
Rangefront scarp	Distributed	± 40-50 m
Possible trace	Distributed	± 50-70 m
Inferred trace	Uncertain, constrained	± 70-80 m

*These describe the fault features in terms of the fault complexity terminology in Van Dissen & Heron (2003) for strike-slip faults. We equate our terminology with their nomenclature. In practice, we never applied the term well-defined to any fault trace in a numerical fashion, i.e. the range of fault location uncertainty for faults in this study was typically 30-80 m (highlighted).

3.0 RESULTS

In this section, we present the main results of the study, beginning with priority areas within Wairoa District. The results include: (i) the re-mapping of fault traces within each priority area, (ii) the current best estimates of earthquake recurrence interval for faults within each area, and (iii) definition of Fault Avoidance Zones around these fault traces.

3.1 Wairoa District

Wairoa District can be divided into a western half, which is characterised by a number of continuous, throughgoing strike-slip faults that make up the western strand of the North Island Shear Belt (Beanland 1995); and an eastern half that is characterised by numerous short (0.3-3 km), mapped fault traces that do not appear to link together to form throughgoing fault systems. The eastern half of the study area is described in sections 3.1.1 through 3.1.3.

3.1.1 Wairoa Coastal area

A major tool for checking previously mapped features in this area was the LiDAR coverage of the Wairoa coastal area (Fig. 4). In addition to the LiDAR DEM, we compared an archived 1:50,000 scale fault trace map (Late Quaternary tectonic map; hereafter called LQT database map) with fault linework from QMap Raukumara. The GNS Active Faults database was originally constructed from scanned hard copy maps of the former. Line data on the 1:50,000 LQT database map showed a different number and density of active faults compared to QMap Raukumara.

In the area of the LiDAR DEM (Fig. 4) only 5 mapped fault traces existed in the GNS Active Fault database prior to this study. In contrast, the newer interpretation on the QMap Raukumara sheet of Mazengarb and Speden (2001) shows no active fault traces onshore. However, also shown on this map and based on NIWA sources (e.g. Barnes et al., 2002), are active fold and fault traces in northern Hawke Bay to the south of this area.

Following comparison between the LiDAR, aerial photographs and QMap Raukumara, all five onland fault traces from the Active Faults database were removed from the GIS of this study. Careful analysis of the LiDAR hillshade model showed that none of these traces could be confirmed as active fault traces. This was particularly evident in the LiDAR imagery, where the overwhelming geomorphic features of the hill country were of smoothly rounded hillocks of Miocene and Pliocene bedrock with no clear linear traces across them.

3.1.2 Wairoa North area

Prior to this study, approximately 30 short fault traces were shown in the GNS Active Faults database for the Wairoa North priority area (Fig. 6). In contrast, less than 10 active fault traces are shown for this area on QMap Raukumara (Mazengarb and Speden 2001). While there was no LiDAR hillshade model available for this area, analysis of the Wairoa North priority area benefited greatly from the experience of comparing the 1:50,000 LQT database map with QMap, aerial photographs and comparison to the LiDAR hillshade model to the south.

In the Wairoa North area, we relied on aerial photograph analysis as the means for confirming (or refuting) the presence of active faults (Fig. 6). Following a re-analysis of this area, a large number of traces were not considered to represent active fault traces. In many cases, traces on the 1:50,000 LQT database map were based on either: (i) linear bedrock related features (that may be considered as old inactive faults); (ii) straight reaches of streams and rivers, and/or (iii) features that were probably related to landsliding. Landsliding is a common process in Miocene to Pliocene hill country in this area, and thus several linear to arcuate traces were probably landslide-related. These traces often correlated with mapped landslides on QMap Raukumara (Mazengarb and Speden 2001). Our analysis highlights the difficulty in recognising active faults in Miocene to Pliocene mudstone country with or without detailed DEM's, or even in comparing onshore with offshore fault data (e.g. Barnes et al. 2002).

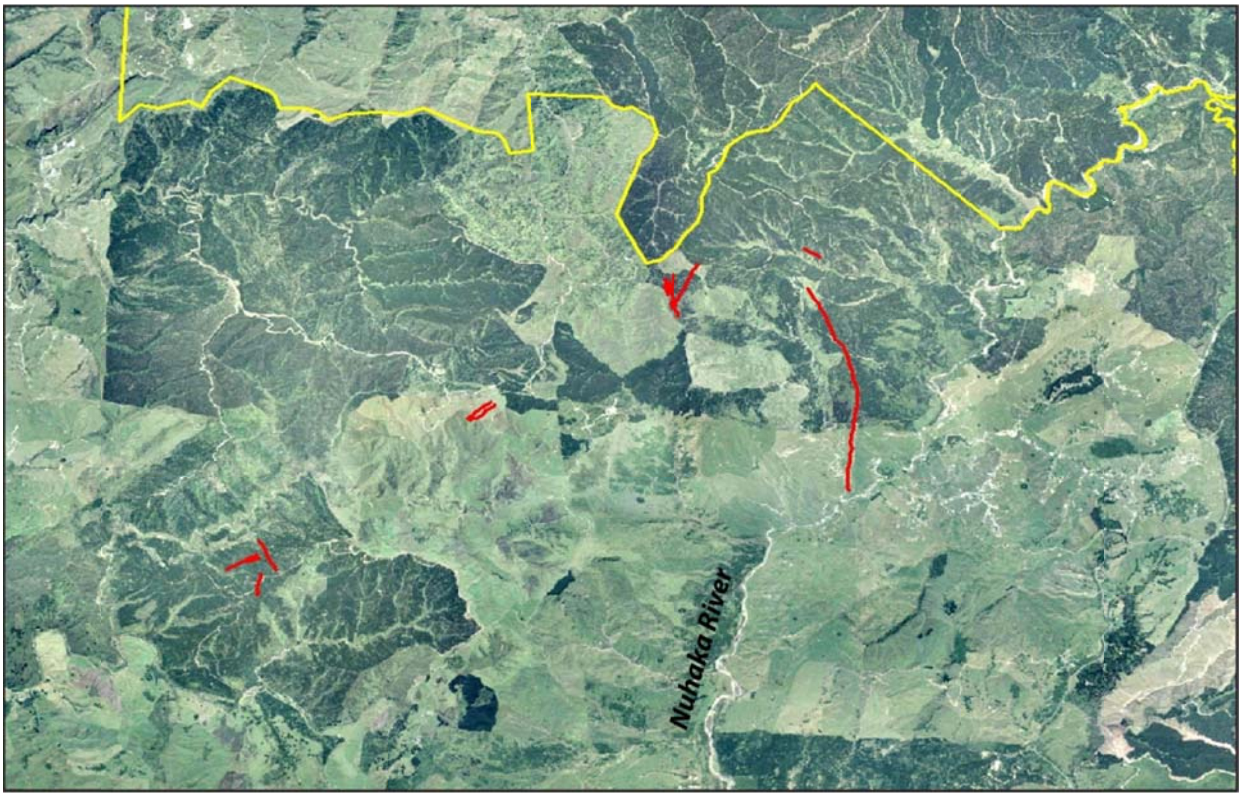

Figure 6 Orthophotograph of part of Wairoa District in the area of the upper Nuhaka River. The yellow line represents the northern boundary of Wairoa District. Red lines represent updated fault linework (possible active fault traces) for this area. The GIS data with Fault Avoidance Zones from the accompanying CD should be used to characterise this line data.

The revised map of active faults for the Wairoa North area has approximately 20 short (0.3-3 km) traces shown on it within the GIS. Fault traces have been mapped onto georeferenced aerial photographs within the GIS, and have an accuracy of typically ± 50 metres. Several of these are consistent with faults shown on the QMap Raukumara, while many of the faults shown on the LQT database map have been removed. In addition, some fault traces have had their locations revised by 10's of metres, reflecting poor control on the previous locations of features. Even so, there remains some uncertainty as to whether some of the features shown in this area are indeed faults, i.e. some mapped features could well be related to landsliding. Nevertheless, if they are landslide traces or scars then they still pose a hazard in terms of structural movement beneath a building foundation, and would be considered a hazard under the MfE Guidelines related to Active Landsliding and Building Consent (see Saunders and Glassey 2007).

The recurrence interval of fault movement on these mapped features (if faults) is unknown. To reflect this lack of knowledge, none of the fault traces shown in the GNS Active Faults database in the Wairoa Coastal and North areas has any recurrence interval information attached to it. No new recurrence interval data has been estimated as part of this study. Further work is required to ascertain the relevance and likely recurrence interval range of these faults.

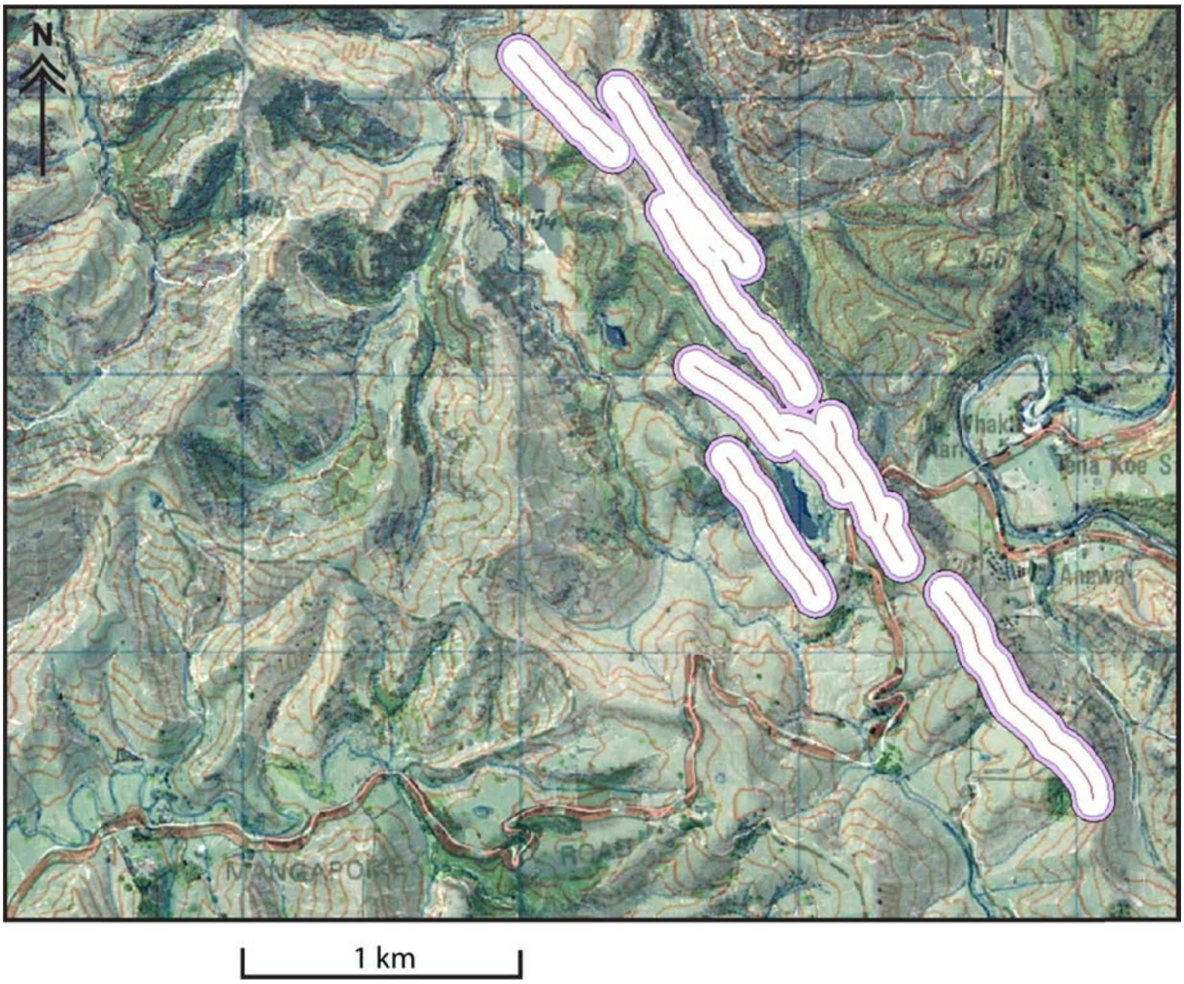

Figure 7 Example of a Fault Avoidance Zone created for fault traces in the North Wairoa area near Te Whaka Aari in Wairoa District. The red line represents the best estimate of the rupture trace of the fault. The white buffer represents the uncertainty of fault location, i.e. the uncertainty from mapping and GIS quality control (±60 m), while the purple buffer is an additional margin of safety equal to ±20 m. Therefore, an individual fault trace has a total FAZ width of 160 m in this area. The GIS data with Fault Avoidance Zones from the accompanying CD should be used to characterise this example.

One significant historic seismic event, the 15 September, 1932 M 6.9 Wairoa earthquake occurred within the Wairoa area (Fig. 8). This event is often considered to be an ‘aftershock’ to the 1931 Hawke’s Bay earthquake (Downes 1995). There is some conjecture over whether this event caused any surface faulting. The epicentre of the earthquake was cited as being c. 16 km NNE of Wairoa amongst this hill country (Berryman et al. 1988), at a depth of c. 12 km. Some deformation was associated with a c. E-W striking feature in this area. This is in contrast to the regional, northeast strike of rocks and faults. Within the GIS our mapping shows a concentration of traces within 14-20 km to the NNE of Wairoa township, offering the possibility that some of the deformation observed is tectonic and also related to the 1932 Wairoa earthquake. It is equally possible that the epicentral location of the 1932 Wairoa earthquake occurs toward the downdip end of a reverse fault that daylights at the surface of the Earth to the east or southeast of the epicentral location. In this case the fault traces near the epicentre may have little to do with the Wairoa earthquake.

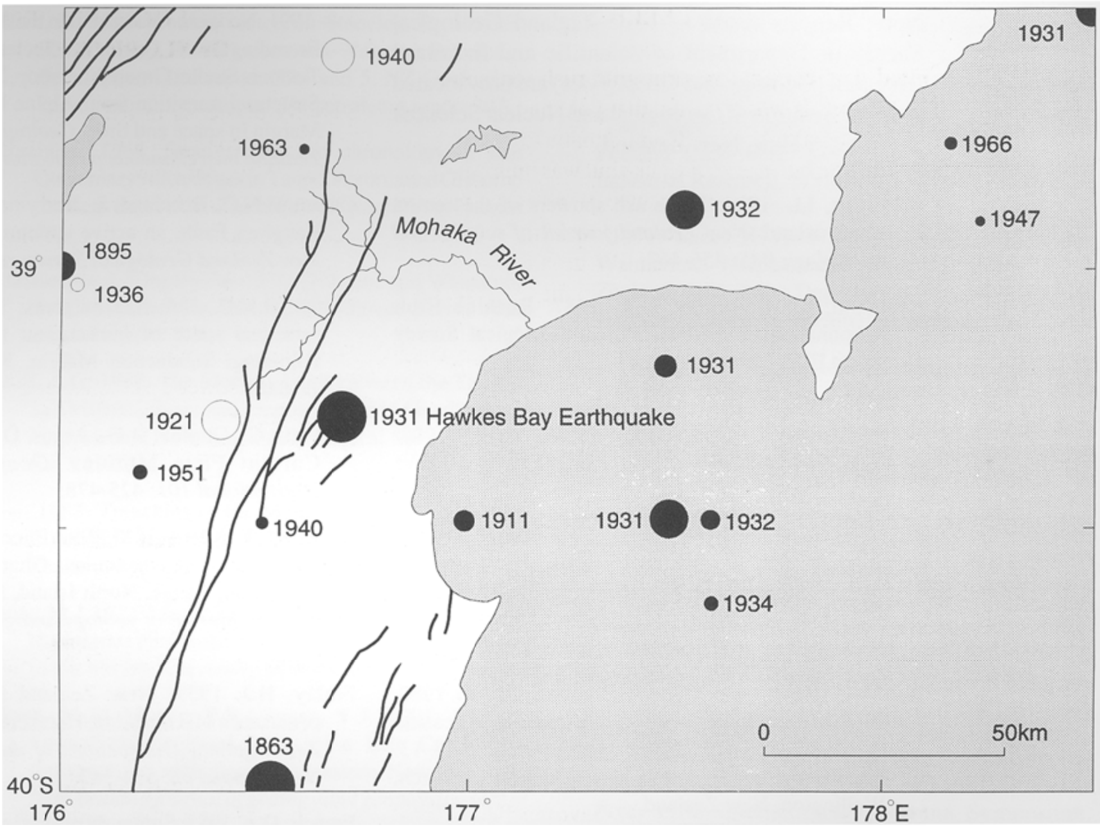

Figure 8 Map of the Hawke's Bay region showing large historic earthquakes. The epicentre of the 1932 M 6.9 Wairoa earthquake is shown near the top centre of the image (figure from Cutten 1994).

This lack of certainty is reflected in the GNS Active Faults database (http://data.gns.cri.nz/af/), which shows no historic rupture traces in the Wairoa area. Surface deformation features could have been related to landsliding from the strong ground motions.

3.1.3 Mahia area

The Mahia area covers the greater part of Mahia Peninsula to the south of where the LiDAR DEM was available for fault location checking (Fig. 9). Prior to this study, four short (0.6-1.5 km) fault traces were shown in the GNS Active Faults database on Mahia Peninsula. For this study, the greater part of the peninsula (including the four fault traces) was reviewed using aerial photographs. The four fault traces were confirmed as active fault traces. However, the locations and lengths of the traces were modified slightly from the Active Faults database.

Based on the geology of the peninsula and the kinematics of nearby active faults, the style of faulting for these fault traces is almost certainly dip-slip, and probably normal in sense. The geology of the peninsula is related to the uplift of Miocene to Quaternary marine rocks by the Lachlan Fault, a significant, offshore active fault (Mazengarb and Speden 2001; Barnes et al. 2002). The Lachlan Fault is a NNE-striking reverse fault that occurs as little as 3 km to the east of Mahia Peninsula. The southwest and northeast coasts of the peninsula are dominated by flights of late Quaternary to Holocene uplifted marine terraces and beach deposits. Their uplift is probably related to long term movement on the Lachlan Fault and/or the offshore subduction thrust (see also Berryman 2005). The most prominent of these marine terraces is labelled as Q5b on QMap Raukumara, which signifies that these terraces are c. 128,000 years in age or younger (Mazengarb and Speden 2001). In contrast to this study, QMap Raukumara does not show any active faults on Mahia Peninsula.

Aerial photograph analysis confirms that the four fault traces on the peninsula are active fault traces because they cut Q5 surfaces (Fig. 9). These traces have been mapped onto georeferenced aerial photographs within the GIS, and have a typical accuracy of ± 50 metres. The recurrence interval of movement of these faults is not known at this time, but is assumed to be quite long. As described above for the Wairoa Coastal and North areas, these short fault traces do not form major throughgoing structures that generate their own large seismic events. These fault traces are more likely to be secondary features related to the hangingwall (uplifting) block of the Lachlan Fault, which forms the tableland topography of Mahia Peninsula. Without better information on these fault traces, we tentatively assign these as faults in Recurrence Interval Class IV (recurrence 5000-10,000 years) for surface fault movement. Further work is required to ascertain the relevance and likely recurrence interval range of these faults.

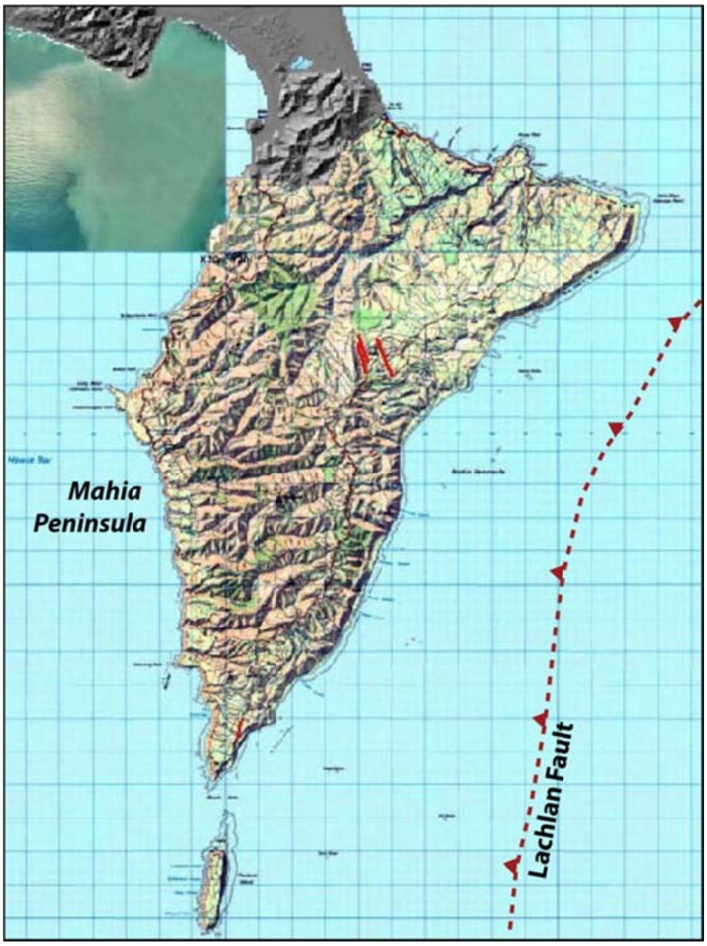

Figure 9 Map of Mahia Peninsula with the previous locations of active fault traces in red. No LiDAR or orthophotograph coverage exists over the majority of the peninsula. The approximate location of the Lachlan Fault, an important offshore reverse fault is shown to the east of the peninsula.

3.1.4 Rangiora Fault

As part of this study, active fault line data for the Rangiora Fault, a dextral-slip fault belonging to the North Island Shear Belt, has been reviewed and re-mapped over a distance of

c. 18 km (Fig. 10). The northern end of the mapped zone is the Mohaka River in Wairoa District, while the southern end of the mapped zone is near Pohokura Road in Hastings District. Within Wairoa District, traces of the Rangiora Fault can be followed clearly on aerial photographs from the Waikari River northward to Extension Road within pine forest. In some places, two clear fault traces are expressed. Fault traces have been mapped onto georeferenced aerial photographs within the GIS, and have a typical accuracy of ± 50 metres. Between Extension Road and the Mohaka River, the traces are somewhat less clear, less linear, and less connected. Therefore, there is less certainty that the mapped traces are active fault traces. In this area, the traces cross Miocene marine rocks, including the Titiokura Limestone (Lee et al. in prep). However, despite the NNE-striking structural grain, there is only a weak development of late Quaternary tectonic geomorphology including aligned drainages and late Quaternary deposits associated with this area. In this

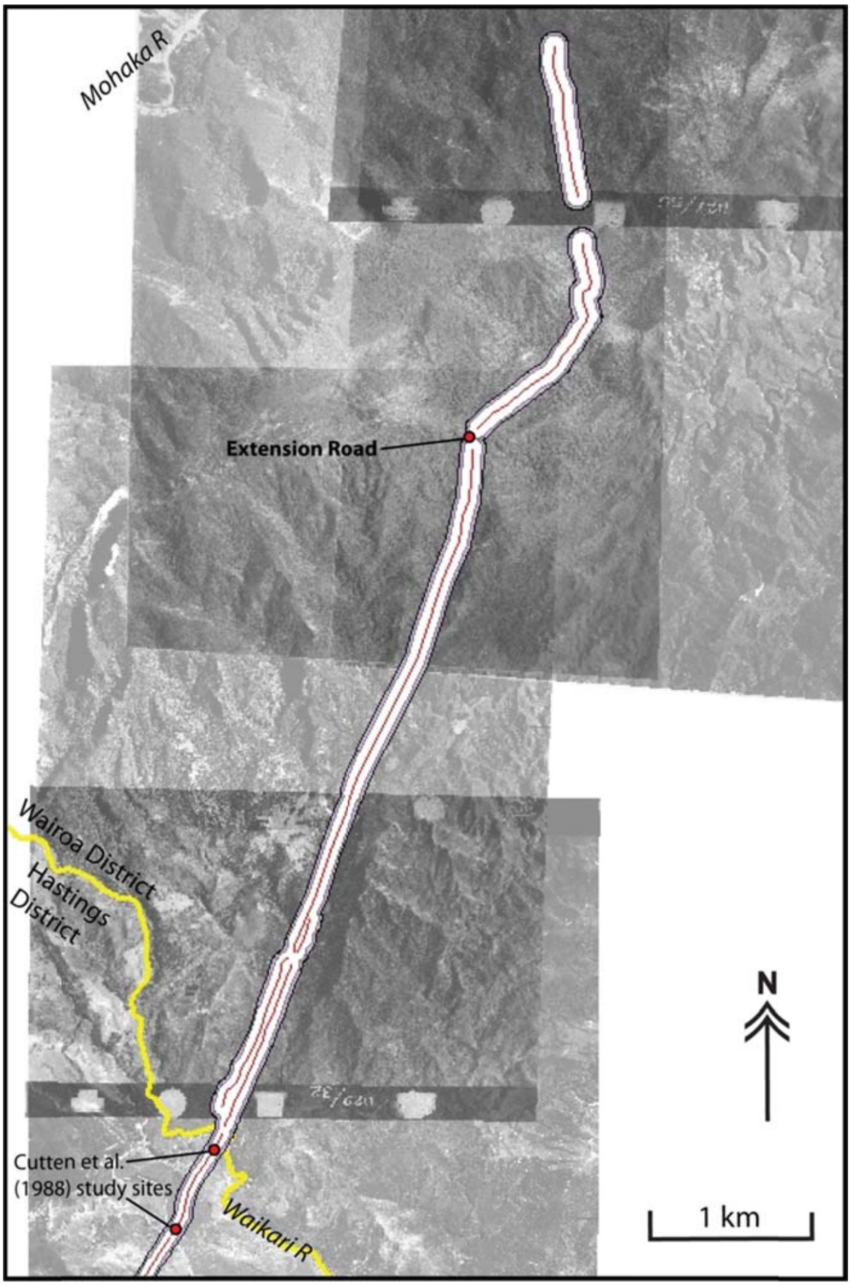

Figure 10 Fault mapping using georeferenced aerial photographs in a GIS. In this example, the northern end of the Rangiora Fault in Wairoa and Hastings Districts is shown with its Fault Avoidance Zone. The total width of the FAZ includes a margin of safety buffer of ±20 m (about the white buffer).

study, we have tentatively located two new fault traces between Extension Road and the Mohaka River (e.g. Cutten 1994; Berryman et al. 1988). These traces are typically not as straight, or connected as those faults traces to the south. This may reflect the diminishment of total fault movement at the northern end of the Rangiora Fault.

To the south, in Hastings District, the Rangiora Fault is well expressed across farmland near Rangiora Station (Cutten et al. 1988). A clear fault trace cuts terraces on the true right bank of the Waikari River and was exposed in a road cut on Heays Access Road. To the southwest, the fault can be traced clearly across country toward Lake Opouahi and Pohokura Road. Again, in places there are two distinct fault traces. Farther to the southwest, the Rangiora Fault is sometimes associated with the Patoka Fault, an active dextral-slip fault that branches off the Mohaka Fault in the Whanawhana-Otamauri area in Hastings District (Halliday 2003). However, the connection between these two faults is difficult to trace, as much of this country is dominated by landslide debris from the Maungaharuru Range (Lee et al. in prep).

Cutten et al. (1988) present the most detailed information on the activity of the Rangiora Fault (Fig. 10). Based on the displaced terraces of the Waikari River, they provide evidence for c. 15 ± 3 m of dextral slip on the fault since deposition of the Waimihia Tephra (c. 3400 yr BP). This produces a (recalculated) slip rate of c. 4.4 ± 1 mm/yr. From the outcrop exposure on Heays Access Road, these authors suggest that up to 6 displacement events have occurred on the Rangiora Fault since deposition of the Waimihia Tephra (Cutten 1994). This yields an average recurrence interval of surface faulting of c. 570 yr. Two displacement events were recognised since the deposition of the Taupo Tephra (c. 1850 yr BP), which is consistent with a short recurrence interval. The Recurrence Interval Class for the Rangiora Fault is therefore Class I (i.e. <2000 yr). For such a short fault length (10-14 km), these represent high parameters (i.e. single-event displacement, slip rate, recurrence interval) of seismic hazard, suggesting further work is required to better characterise this fault. Nonetheless, current estimates suggest that the Rangiora Fault is a highly active, dextral-slip fault, in keeping with its location on the margins of the North Island Axial Ranges.

3.2 Napier City

Napier City is represents a small territorial authority of c. 106 km^2. Prior to this study, there were no known zones of active faulting mapped within the bounds of Napier City. No zones of active faulting have been identified as a consequence of this study. Nevertheless, it is well known that a large fault source caused the Hawke's Bay earthquake of February 3, 1931, which caused sever damage and uplift to Napier city and its environs. This largely buried or 'blind' fault source will be discussed in the following section.

3.3 The Awanui Fault and the 1931 Hawke's Bay earthquake

The Hawke's Bay earthquake caused surface rupture on fault traces at the northern end of the Poukawa Fault Zone in Hastings District (Fig. 11) (Hull 1990; Kelsey et al. 1998). Rupture traces in this area and north to Bridge Pa have traditionally been termed the Awanui Fault (Lee et al., in prep; http://data.gns.cri.nz/af/). In contrast, to the northeast of Bridge Pa across the Heretaunga Plains (including within Napier City), no surface rupture traces have been mapped (Hull 1990). Nevertheless, re-levelling of the railway system in Hawke's Bay following the earthquake revealed a significant amount of vertical deformation, aligned in a NE-SW direction parallel to the regional system of active faults (Hull 1990). Hull (1990) showed a c. 90 km long by 15 km wide asymmetric zone of deformation with uplift on the northwest side of, and subsidence to the southeast of, a line of approximately zero or neutral uplift (Fig. 11).

Uplift of up to 2.7 m was recorded near Oldmans Bluff, while subsidence of c. 1.1. m was recorded near Hastings on the southeast side of the deformation zone. The NE-SW trending line of neutral uplift runs from near Awatoto at the coast toward the rupture traces mapped near Bridge Pa. The implication of this is that the tip of the buried fault (that did not rupture the ground surface) is roughly coincident with the line of neutral uplift (Fig. 11).

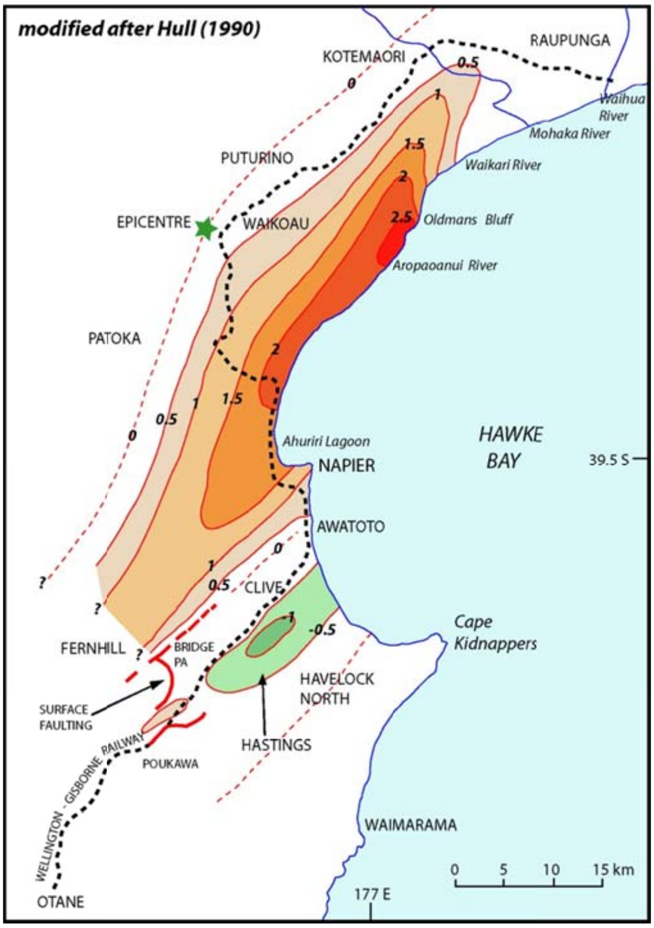

Figure 11 Map of vertical deformation and surface faulting (thick red lines) related to the 1931 Hawke's Bay earthquake as interpreted from the re-levelling of the local rail network (after Hull 1990). Uplift is shown in orange colours and subsidence in green.

While faulting across the Heretaunga Plains is essentially 'blind' i.e. with no surface rupture, it is reasonable to assume that the line of zero uplift is close to the upward tip of the fault associated with the Hawke's Bay earthquake. Future events on this fault source (Awanui Fault) may pose a surface rupture hazard. In an earlier report, Langridge and Villamor (2007) attempted to map the location of the 1931 earthquake rupture trace across the Heretaunga Plains from Bridge Pa toward Napier. Using some features of the LiDAR DEM within the ArcGIS software package, they were able to recognise very subtle changes that may relate to a rupture or deformation trace of the Awanui Fault. These techniques identified a long (c. 8 km) wavelength, broad pattern of warping with a NE-trending linear bulge of c. 1 m in height between Bridge Pa and Awatoto, and a parallel trough of c. -0.5 m depth trending NE through the Hastings area. These observations are consistent with deformation that was re-surveyed after the 1931 earthquake and analysed by Hull (1990).

In this study we attempted a similar profiling procedure using a LiDAR hillshade model of the Heretaunga Plains supplied by Hawke's Bay Regional Council. In this procedure, 3-6 km long profiles were arranged NW-SE perpendicular to the expected fault trace at intervals of c. 1 km across the Heretaunga Plains (Fig. 12). Each profile was exaggerated to highlight subtle changes in gradient in the expected area of the 1931 deformation. Each profile had at least one sharp to subtle change in gradient which corresponded well with the line of zero uplift, i.e. the profiles show a subtle bulge to the northwest and a subtle swale on the southeast side (see Fig. 12 inset).

Use of the LiDAR to construct profiles has been a useful exercise. However, it is difficult to precisely locate such a broad warp across the ground surface and also to expect that the zone of deformation could be mapped with great certainty. This means that even if we chose to designate a fault trace (i.e. use the green dashed line(s) in Figure 10), there would be a wide zone of uncertainty placed around its location. In addition, future events may not rupture the ground surface either. Therefore, use of the criteria for defining Fault Rupture Avoidance Zones in the MfE Guidelines (Kerr et al. 2003) is not appropriate for this fault feature.

This statement concerns that part of the plains in Hastings District, and is even more relevant for the projection of the fault trace into Napier City in the vicinity of Awatoto Lagoon (Figs. 11, 12). In our analysis, no clear warp could be traced across the lagoon near Awatoto.

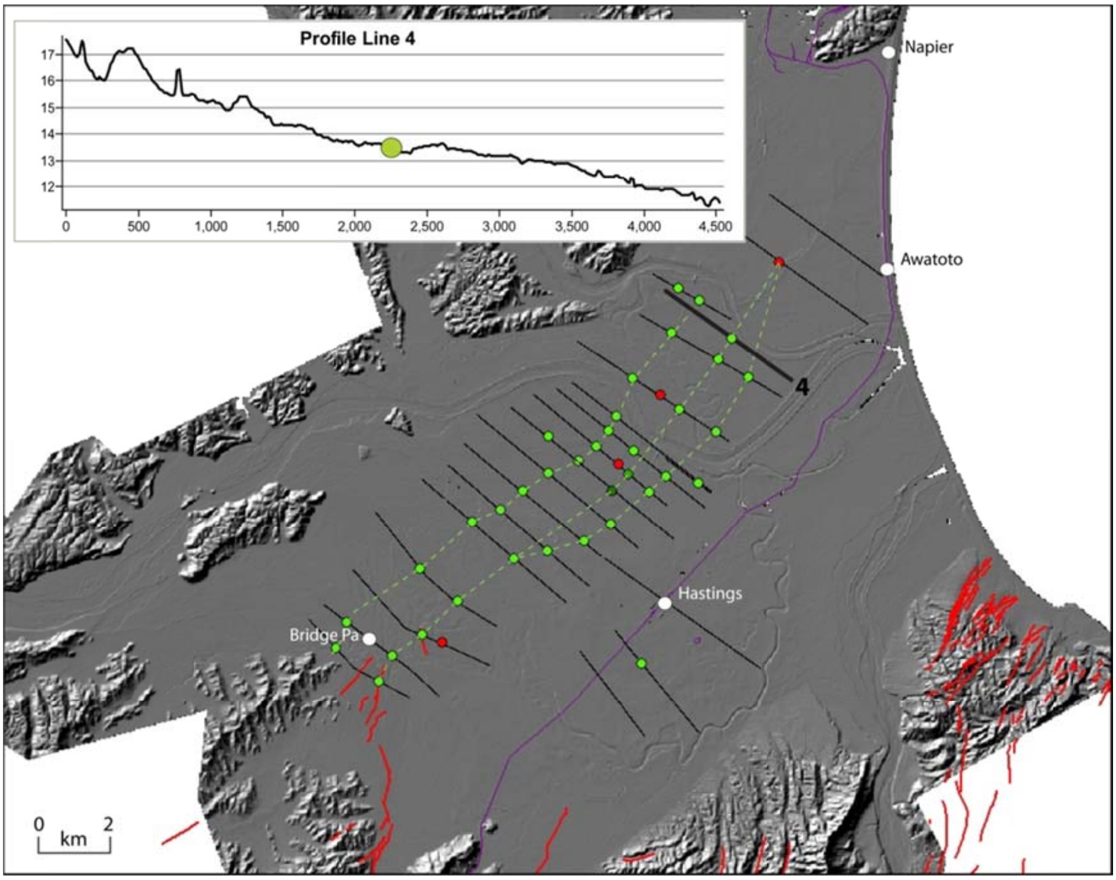

Figure 12 LiDAR DEM of the Heretaunga Plains and surrounding area. The locations of active fault traces are shown in red. Black lines represent profiles made on the hillshade model perpendicular to the NE-trending structural grain. Green and red dots represent inflection points in the profiles where there is a significant change in gradient or slope direction. The green dashed lines attempt to link these together. <u>Inset:</u> Profile 4 at the Northeastern end of the Heretaunga Plains.

This is probably because that land was completely saturated during the earthquake and either: i) suffered extensive liquefaction; and/or (ii) deformed in a somewhat ductile fashion.

Sedimentation (at least over the last 1800 yr) has outpaced tectonic activity so there is no evidence for Holocene fault scarps across the Heretaunga Plains. Large-scale sedimentation (flooding) occurs across the plains on a centennial to millennial timescale. A particularly large inundation of reworked Taupo ash has been deposited across the plains since that eruption c. 1800 years ago (Segschneider et al., 2000). While fault scarps are common south of Pakipaki, it is unsurprising, given the very active nature of the Heretaunga floodplain that there is no fault trace from previous 'Hawke's Bay-type' earthquakes anywhere across the plains.

Nearby at Ahuriri Lagoon, Hayward et al. (2006) have shown that there have been several sudden changes in the relative level of the lagoon since sea-level stabilised c. 7200 yr ago. These metre-scale sea-level changes are probably caused by sudden tectonic subsidence or uplift events. Interestingly, the only event that caused a relative uplift across the lagoon was the 1931 event. All other sudden vertical changes were subsidence events that have not been attributed to 'Hawke's Bay-type' earthquake events. Therefore, any movement prior to 1931 on the Awanui Fault, (i.e. that fault that causes uplift throughout Ahuriri Lagoon and plains) was at least 7200 years ago (Hayward et al., 2006). This is consistent with the results from trenching for the northern section of the Poukawa Fault Zone (RI Class IV; 5000-10,000 yr) (Kelsey et al., 1998).

In summary, it is clear that the 1931 Hawke's Bay earthquake caused a broad NE-trending pattern of warping across the Heretaunga Plains with an axis about the line of neutral (zero) uplift. However, there is no clear rupture trace across the plains and it would be very difficult to zone for a feature that we cannot clearly observe on the ground surface. Such a broad warp probably does not pose a life safety risk (from rupture) and accordingly should not require zonation. An alternative would be to create a 2-4 km wide, NE-trending buffer zone between Bridge Pa and Awatoto. Such a zone would have an "Uncertain – Poorly Constrained"location criteria placed on it, and be rather prohibitive in terms of urban development.

Therefore, while we recognise the presence of an earthquake source between Bridge Pa and Awatoto, we cannot map it with sufficient accuracy and certainty to be of use in terms of planning purposes. As will be discussed below, for faults of RI Class IV, planning and building consent restrictions are limited to BIC Category 4 buildings, i.e. Critical structures. If such buildings are likely to be sited along the axis of the deformation in future, then it would be prudent to consider fault deformation as a potential hazard to the life of such a building. Therefore, as stated above, there are no surface fault traces that can be currently mapped within the limits of Napier City.

However, within the low-lying parts of Napier City (such as Awatoto) it is critical to consider the ground conditions for buildings sited in areas that were uplifted above sea level as a result of the 1931 earthquake. Such land will be prone to increased levels of seismic shaking damage (including liquefaction) in strong earthquake events from nearby fault sources including the offshore subduction zone.

4.0 DEVELOPING FAULT AVOIDANCE ZONES

In this section, we combine the results of fault trace mapping and recurrence interval estimates with land use and the Building Code to define a series of Resource Consent activities from the MfE Active Fault Guidelines (Kerr et al. 2003). First we outline the nature of the Building Importance Categories and their relationship to the Fault Recurrence Interval Classes.

4.1 Building Importance Category

In the event of fault rupture, buildings constructed on a fault line will suffer significant stress and can suffer extensive damage. This was highlighted during the 2010 Darfield earthquake in Canterbury, which ruptured the Greendale Fault (Quigley et al., 2010; Van Dissen et al., 2011). Buildings adjacent to the fault and within the Fault Avoidance Zone may also be damaged by fault deformation. The MfE Active Fault Guidelines define five Building Importance Categories (Table 2) based on accepted risk levels for building collapse considering building type, use and occupancy. This categorisation is weighted towards life-safety, but also allows for the importance of critical structures, e.g. schools or post-disaster

Table 2 Building Importance Categories and representative examples. For more detail see Kerr et al. (2003), and King 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 <30m^2 • 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 m^2 • Houses outside the scope of NZS 3604 “Timber Framed Buildings” • Multi-occupancy residential, commercial, and industrial buildings accommodating <5000 people and <10,000 m^2 • Public assembly buildings, theatres and cinemas <1000 m^2 • 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 m^2 • Covered malls >10,000 m^2 • Museums and art galleries >1000 m^2 • Municipal buildings • Grandstands >10,000 people • Service stations • Chemical storage facilities >500m^2
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

facilities, and the need to locate these wisely. Table 2 shows the Building Importance categories used in New Zealand and applied in the MfE Active Fault Guidelines (Kerr et al., 2003).

4.2 Relationship between Recurrence Interval and Building Importance Class

The hazard posed by fault rupture is quantified using two parameters: a) Fault Complexity and its incorporation into the mapping of Fault Avoidance Zones, and b) the average recurrence interval of surface rupture on a given fault. The average recurrence interval of surface rupture is the average number of years between successive surface rupture earthquakes along a specific section of fault. Typically, the longer the average recurrence interval of surface rupture of a fault, the less likely the fault is to rupture in the near future. In the MfE Active Fault Guidelines, faults are grouped according to Recurrence Interval Class (Table 4; Kerr et al. 2003, see also Van Dissen et al. 2003), such that the most hazardous faults, i.e. those with the shortest recurrence intervals, are grouped within Recurrence Interval Class I.

Table 3 Recurrence Interval Classes of active faults within parts of Wairoa District and Napier City. For more detail see Kerr et al. (2003) and Van Dissen et al. (2003).

Priority area / Fault Name	Recurrence Interval Class	Recurrence Interval Range of Respective Recurrence Interval Class	Confidence of Recurrence Interval Classification*
Wairoa North	No data	No data	n/a
Mahia	Class IV	>5000 years to ≤10,000 years	Low
Rangiora Fault	Class I	≤2000 years	High
Awanui Fault	Class IV	>5000 years to ≤10,000 years	Medium

Note:
* As defined in the MfE Active Fault Guidelines, a Low confidence of recurrence interval classification is assigned to an active fault when the range of uncertainty of the fault's recurrence interval embraces a significant portion of three or more Recurrence Interval Classes, or when there are no fault-specific data available for the fault to enable an estimation of its fault-specific recurrence interval (i.e. Recurrence Interval Class is assigned based only on subjective comparisons with other better studied faults).

The MfE Active Fault Guidelines advocate a risk-based approach to dealing with development of land on, or close to active faults. The risk at a site, of fault rupture is a function not only of the location and activity of a fault, but also the type of structure/building that may be impacted by rupture of the fault. For a site on, or immediately adjacent to an active fault, risk increases both as fault activity increases (i.e. fault recurrence interval and Recurrence Interval Class decrease) and Building Importance Category increases. In order to maintain a relatively constant/ consistent level of risk throughout the district, it is reasonable to impose more restrictions on the development of sites located on, or immediately adjacent to highly active faults, compared to sites located on, or immediately adjacent to low activity faults. This hierarchical relation between fault activity (Recurrence Interval Class) and building type (Building Importance Category) is presented in Table 4.

With regards to this project, the most active fault with the shortest recurrence interval is the Rangiora Fault, which is a Recurrence Interval (RI) Class I active fault. Faults on Mahia Peninsula have been assigned to RI Class IV, while all other faults in the eastern half of Wairoa District have no recurrence interval information with which to make any decision regarding RI Class. No active faults have been mapped within Napier City. The Awanui Fault is assigned to RI Class IV (Table 4). Surface rupture traces from the 1931 Hawke's Bay earthquake have been zoned within Hastings District (Langridge & Villamor 2007), however, no traces of the Awanui Fault can be mapped near the coast within Napier City.

The MfE Active Fault Guidelines also make a pragmatic distinction between previously subdivided and/or developed sites, and undeveloped "Greenfield" sites, and allows for different conditions to apply to these two types of sites of differing development status (Tables 5, 6). The rationale for this is that in the subdivision/development of a Greenfield area, a change of land usage is usually being sought, and it is much easier, for example, to require a building setback distance from an active fault, or to plan subdivision of land around the location of an active fault. However, in built-up areas, buildings may have been established without knowledge of the existence or location of an active fault, and the community may have an expectation to continue to live there, despite the potential danger. Also, existing use rights under the Resource Management Act mean that where an existing building over a fault is damaged, it can be rebuilt, even after the hazard/risk has been identified. The distinction between previous or new developments is incorporated into Tables 5 & 6.

Table 4 Relationships between Recurrence Interval Class, Average Recurrence Interval of Surface Rupture, and Building Importance Category for Previously Subdivided and Greenfield Sites. For more detail see Kerr et al. (2003), and King et al. (2003).

<table>
<tr><th rowspan="2">Recurrence Interval Class</th><th rowspan="2">Average Recurrence Interval of Surface Rupture</th><th colspan="2">Building Importance (BI) Category Limitations
(allowable buildings)</th></tr>
<tr><th>Previously subdivided or developed sites</th><th>"Greenfield" sites</th></tr>
<tr><td>I</td><td>≤2000 years</td><td>BI Category 1
temporary buildings only</td><td rowspan="2">BI Category 1
temporary buildings only</td></tr>
<tr><td>II</td><td>>2000 years to ≤3500 years</td><td>BI Category 1& 2a
temporary & residential timber-framed buildings only</td></tr>
<tr><td>III</td><td>>3500 years to ≤5000 years</td><td>BI Category 1, 2a, & 2b
temporary, residential timber-framed & normal structures</td><td>BI Category 1& 2a
temporary & residential timber-framed buildings only</td></tr>
<tr><td>IV</td><td>>5000 years to ≤10,000 years</td><td rowspan="2">BI Category 1, 2a, 2b & 3
temporary, residential timber-framed, normal & important structures
(but not critical post-disaster facilities)</td><td>BI Category 1, 2a, & 2b
temporary, residential timber-framed & normal structures</td></tr>
<tr><td>V</td><td>>10,000 years to ≤20,000 years</td><td>BI Category 1, 2a, 2b & 3
temporary, residential timber-framed, normal & important structures
(but not critical post-disaster facilities)</td></tr>
<tr><td>VI</td><td>>20,000 years to ≤125,000 years</td><td colspan="2">BI Category 1, 2a, 2b, 3 & 4
critical post-disaster facilities cannot be built across an active fault with a recurrence interval ≤20,000 years</td></tr>
<tr><td colspan="4">Note: Faults with average recurrence intervals >125,000 years are not considered active</td></tr>
</table>

4.3 Resource Consent Categories

Fault Recurrence Interval Class, Fault Complexity, and Building Importance Category are the three key elements, that when brought together, enable a risk-based approach to be taken when making planning decisions about development of land on, or close to active faults. Understanding the interrelationships between these key parameters is critical to the development of consistent, risk-based objectives, policies and methods to guide development of land that may be impacted by surface rupture faulting. The critical relationships between Recurrence Interval Class, and Building Importance Category have already been summarised in Table 4. These interrelationships are expanded in Tables 5 and 6 to incorporate Fault Complexity. These tables are extracted directly from the MfE Active Fault Guidelines (see Kerr et al. 2003) to provide specific examples of Resource Consent Category suggestions for various combinations of Recurrence Interval Class, Fault Complexity, and Building Importance Category for the faults discussed in this report.

Determining the appropriate Resource Consent Category for different scenarios/ combinations of Recurrence Interval Class, Fault Complexity, and Building Importance Category is a complex task, especially when trying to anticipate the level of risk that a community may or may not be willing to accept. Certainly, as the risk increases, the Resource Consent Category should become more restrictive, and the range of matters that Council needs to consider increases. Ultimately, the Council needs to be able to impose consent conditions to avoid or mitigate the adverse effects of fault rupture, by requiring allotments to be subject to requirements such as to the use, bulk, location and foundations of any structure.

The Council will wish to apply Resource Consent Categories depending upon their own requirements/ circumstances. The principal issue is to ensure that the Council has the ability to address fault rupture hazard/risk when assessing a resource consent application. When dealing with Controlled and Discretionary activities, the matters over which the Council reserves control or restricts its discretion are important. For these categories, the matters the Council may need to consider include: the proposed use of the building; the site layout including building setback and separation distance; building height and design; construction type (note only for resource management purposes); and financial contributions such as reserve contributions.

It is important to remember that surface fault rupture is a seismic hazard of relatively limited geographic extent, compared to strong ground shaking, and can, in many cases, be avoided. If avoidance of surface rupture fault hazard at a site is not practical, then planning/ design measures need to be prescribed/ incorporated to mitigate/ accommodate the co-seismic surface rupture displacements anticipated at the site. The planning and design measures also need to be consistent with the appropriate combination of Fault Complexity, Recurrence Interval Class, and Building Importance Category relevant to that site.

Also worth commenting on is that specific fault studies at or near the site may provide more certainty as to the fault's location, and thus allow the Fault Avoidance Zone to be reduced in width. This is shown below in Figure 13, taken directly from Kerr et al. (2003). Where detailed geologic studies are undertaken, e.g. trenching or surveying, it may be possible to narrow the zone of uncertainty about the zone of faulting and deformation associated with a fault.

A good example of the usefulness of this concept was the work undertaken at Parkhill near Havelock North (Langridge 2007). After viewing the faults and fault zones in a total of 6 trenches it was possible to determine at what point of the fault scarp these faults had ruptured repeatedly to the ground surface, and to determine the width of the surface deformation around the fault zone. This led to the Fault Avoidance Zones being narrowed for the purposes of planning and the layout of house lots for a subdivision there.

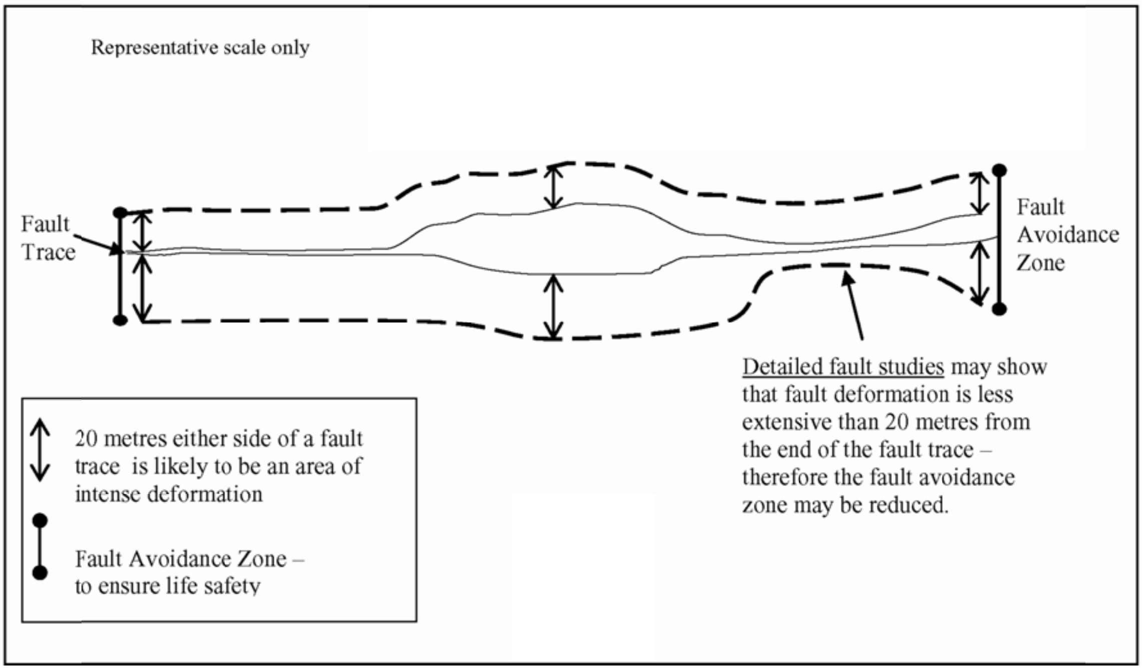

Figure 13 A fault avoidance zone on a district planning map (from Kerr et al. 2003). Note that following specific targeted geological or surveying work, the Fault Avoidance Zone width can be decreased to allow buildings closer to the fault trace.

Table 5 The relationship between Resource Consent Category, Building Importance Category, Fault Recurrence Interval Class, and Fault Complexity for developed and/or already subdivided sites for the Rangiora Fault, based on the MfE Active Fault Guidelines (for detail see Kerr et al 2003). Note: In this example the Permitted activities have been highlighted.

RANGIORA FAULT **Fault Recurrence Interval Class I #** (average recurrence interval ≤2000 years)					
Developed and/or Already Subdivided Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Non-Complying
Distributed, & *Uncertain - constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
*Uncertain - poorly constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
Greenfield Sites					
Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	*Non-Complying*	*Non-Complying*	*Non-Complying*	Prohibited
Distributed, & *Uncertain - constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying
*Uncertain - poorly constrained	Permitted	*Discretionary*	*Non-Complying*	*Non-Complying*	Non-Complying

Notes:
* - Where the fault trace is uncertain, specific fault studies may provide more certainty on the location of the fault.
Italics: The use of italics indicates that the Resource Consent Category of these categories is more flexible. For example, where *discretionary* is indicated, *controlled* may be considered more suitable by Council, or vice versa.

Table 6 Examples, based on the MfE Active Fault Guidelines, of Resource Consent Category for both developed and/or already subdivided sites, and Greenfield sites for the Mahia Peninsula area, accounting for various combinations of Building Importance Category, and Fault Complexity. Note: In this example the Non-Complying activities have been highlighted.

Mahia Peninsula area
(based on Fault Recurrence Interval Class IV, >5000 to ≤10,000 years)

Developed and/or Already Subdivided Sites

Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	Permitted*	Non-Complying
Distributed	Permitted	Permitted	Permitted	Permitted	Non-Complying
Uncertain - constrained	Permitted	Permitted	Permitted	Permitted	Non-Complying

Greenfield Sites

Building Importance Category	**1**	**2a**	**2b**	**3**	**4**
Fault Complexity	**Resource Consent Category**				
Well Defined	Permitted	Permitted*	Permitted*	*Non-Complying*	Non-Complying
Distributed	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying
Uncertain - constrained	Permitted	Permitted	Permitted	*Discretionary*	Non-Complying

Notes:
* Indicates that the Resource Consent Category is permitted, but could be Controlled or Discretionary given that the fault location is well defined.
Italics: The use of italics indicates that the Resource Consent Category – activity status of these categories is more flexible. For example, where *Discretionary* is indicated, *Controlled* may be considered more suitable by Council, or vice versa.

5.0 SUMMARY AND RECOMMENDATIONS

- We have mapped parts of Wairoa District, Napier City and surrounds at a scale of c. 1:10,000 following the Ministry for the Environment's Guidelines of "Planning for Development of Land on or Close to Active Faults". We have defined Fault Avoidance Zones around a number of active fault traces that encompass the area of possible ground deformation associated with these faults.
- Mapping of the fault zones has been undertaken using a Geographic Information System (GIS) in conjunction with LiDAR imagery and rectified aerial photographs. Each of these data media carry a level of mapping uncertainty.
- Five priority areas were defined for the purposes of mapping active faults and developing Fault Avoidance Zones. These are: Coastal Wairoa, North Wairoa, Mahia Peninsula, the Rangiora Fault, and the Awanui Fault. The latter is the fault that ruptured during the 1931 Hawke's Bay earthquake.
- For Land Use and Life Safety purposes, the "MfE Active Fault Guidelines" focus on: (i) the location and characterisation of surface deformation related to faulting; (ii) the characterisation of the recurrence interval of faulting, and (iii) the building importance category (BIC) of the proposed structures.
- The faults have been classified according to their expression at the ground surface, e.g., clear scarp/ broad scarp/ inferred trace, with the information stored in an Attribute Table in the GIS. In general, a line which approximates the location of surface faulting has been mapped along each fault trace. Attached to that trace is a location error based on the uncertainty of the exact location of the fault plane with respect to the fault scarp, and the media used, e.g. LiDAR, to capture the line on a map. In addition to this a ±20 metre setback is added to create the full Fault Avoidance Zone.
- No active fault traces were identified in the Wairoa Coastal area. In this area, the 1-metre LiDAR DEM produced particularly accurate micro-topography of the mapping areas and was therefore the most useful mapping tool, allowing us to eliminate several fault traces that could not be confirmed as active faults.
- Several faults in the Wairoa North priority area are considered to be possible active normal (dip-slip) faults. Fault Avoidance Zones (FAZ's) have widths of 120-200 m for individual fault traces. However, at this time, there is no recurrence interval information available for these faults, therefore, no RI Class can be established for faults in this area.
- Faults in the Mahia priority area are also considered to be normal dip-slip faults. We interpret the recurrence interval class for these faults area to be RI Class IV, i.e. >5000-≤10,000 years. Fault Avoidance Zones (FAZ's) in the Mahia priority areas have widths of 120-200 m for individual fault traces. This implies that the fault traces are not strictly "well defined".
- The MfE Active Fault Guidelines suggest that for Recurrence Interval Class IV faults, such as those mapped across Mahia Peninsula, that BIC 2a and 2b structures should be permitted activities. For BIC 3 structures, the resource consent activity is permitted in the case of developed or already subdivided, and typically Discretionary for Greenfield settings. BIC 4 structures hold a Non-Complying Status in both the "Greenfield" and "previously subdivided" setting.

- Paleoseismic data indicates that the strike-slip Rangiora Fault is a RI Class I fault with surface rupture repeating every 2000 years or less. The FAZ for the Rangiora Fault is 140-160 m wide for individual fault traces. The MfE Active Fault Guidelines suggest that for Recurrence Interval Class I faults, such as the Rangiora Fault only BIC 1 structures should be permitted activities within the FAZ, in both the “Greenfield” and “previously subdivided” setting.
- No clear fault trace of the reverse, dip-slip Awanui Fault could be mapped across the Heretaunga Plains and more significantly no trace was observed across the Awatoto lagoon area in Napier City. It is our conclusion that the surface trace of this fault cannot currently be mapped in a means that is useful in terms of the MfE guidelines.
- No surface traces of active faults have been mapped in the Napier City area. Given the expected recurrence interval of faulting (RI Class IV; 5000-10,000 yr) for the Awanui Fault, surface faulting should only be considered if BIC 4 structures are to be sited within c. 1 km of the zone of neutral uplift mapped out by Hull (1990).
- Fault Avoidance Zones defined in this study may be reduced in width following additional surveying or paleoseismic (trenching) studies that locate and define the nature of surface deformation. This may be particularly useful for the placement of future developments. In general, if it is possible to avoid building within a Fault Avoidance Zone, then this is a preferable action.
- The figures displayed in this report are not to be used for planning purposes. They are meant as examples of how faults were mapped and FAZ’s were developed. The GIS in the enclosed CD contains the relevant fault location information at the scale we undertook the mapping for cadastral purposes, i.e. c. 1: 10,000, and also contains the Fault Avoidance Zones.

Further to this summary, we recommend that:

- Our new mapped fault locations and Fault Avoidance Zones be adopted by the District Councils in the area for planning purposes. They are of an appropriate scale for cadastral use (1: 10,000) and are in keeping with the recommendations of the Ministry for the Environment’s Active Fault Guidelines. Using the CD provided enables uploading of Shapefiles for the fault traces and FAZ’s into a council GIS.
- The recommendations of the MfE’s Active Fault Guidelines (Planning for Development of Land on or Close to Active Faults; Kerr et al. 2003) be adopted by all District Councils in the Hawke’s Bay region.
- Where possible, fault location work such as ground truthing should be undertaken to assess whether many of the traces mapped in the eastern Wairoa area re active faults, and if so, some effort should go into considering their activity (recurrence interval).
- In future, other parts of Hawke’s Bay region, including the coastal ranges (Maraetotara Plateau) and inland parts of Central Hawke’s Bay and Hastings Districts could receive further attention with regards to active fault mapping and fault avoidance zonation.

6.0 ACKNOWLEDGEMENTS

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7.0 REFERENCES

Barnes, P.M., Nicol A., Harrison T. 2002: Late Cenozoic evolution and earthquake potential of an active listric thrust complex above the Hikurangi subduction zone, New Zealand. Geological Society of America Bulletin 114: 1379-1405.

Beanland S 1995. The North Island Dextral Fault Belt, Hikurangi Subduction Margin, New Zealand, Ph.D. thesis, Victoria University of Wellington, New Zealand.

Begg JG, Hull AG, Downes GL 1994. Earthquake hazards in Hawke's Bay: initial assessment. GNS Client Report 333901.10.

Begg JG, Hull AG, Robinson RJ 1996. Earthquake hazard analysis – Stage 1. Recurrence of large earthquakes determined from geological and seismological studies, Hawke's Bay area. GNS Client Report 1995/33491D.30.

Berryman K (compiler) 2005. Review of tsunami hazard and risk in New Zealand. GNS Science Consultancy Report 2005/104.

Berryman KR, Beanland S, Cutten HNC, Darby DJ, Hancox GT, Hull AG, Read SAL, 1988. Seismotectonic hazard evaluation for the Mohaka River power development. NZ Geological Survey Contract Report 090/03.

Cutten HNC 1994. Geology of the middle reaches of the Mohaka River. Scale 1:50,000. Institute of Geological and Nuclear Sciences geological map 6. 1 sheet and 38 p. Institute of Geological and Nuclear Sciences Ltd., Lower Hutt, New Zealand.

Cutten HNC, Beanland S, Berryman KR 1988. The Rangiora fault, an active structure in Hawkes Bay. N. Z. Geological Survey Record 35: 65-72.

Downes GL 1995. Atlas of isoseismal maps of New Zealand earthquakes. *Institute of Geological & Nuclear Sciences monograph 11,* 304 p., Lower Hutt, New Zealand. Institute of Geological & Nuclear Sciences Limited.

Halliday S 2003: The tectonic geomorphology and paleoseismology of the Patoka Fault, North Island Dextral Fault Belt, New Zealand. Unpublished B.Sc. (Hons.) thesis, School of Earth Sciences, Victoria University of Wellington, Wellington.

Hayward BW, Grenfell HR, Sabaa AT, Carter R, Cochran U, Lipps JH, Shane PR, Morley MS 2006. Micropaleontological evidence of large earthquakes in the pat 7200 years in southern Hawke's Bay, New Zealand. Quaternary Science Reviews 25: 1186-1207.

Hull AG 1990. Tectonics of the 1931 Hawke's Bay earthquake. New Zealand Journal of Geology and Geophysics 33: 309-320.

Kelson KI, Kang K-H, Page WD, Lee, C-T, Cluff LS 2001. Representative styles of deformation along the Chelengpu Fault from the 1999 Chi-Chi (Taiwan) earthquake: Geomorphic characteristics and responses of man-made structures. Bulletin of the Seismological Society of America 91: 930-952.

Kelsey HM, Erdman, CF, Cashman SM 1993. Geology of southern Hawkes Bay from the Maraetotara Plateau and Waipawa westward to the Wakarara Range and Ohara Depression. IGNS Client Report 93/2, 17p. + maps. Institute of Geological & Nuclear Sciences, Lower Hutt.

Kelsey HM, Hull AG, Cashman SM, Berryman KR, Cashman PH, Trexler JH Jr, Begg JG 1998. Paleoseismology of an active reverse fault in a forearc setting: The Poukawa Fault Zone, Hikurangi forearc, New Zealand. Tectonics 110: 1123-1148.

Kerr J, Nathan, S, Van Dissen, R, Webb, P, Brunsdon, D, King, A, 2003. Planning for Development of Land on or Close to Active Faults: A guideline to assist resource management planners in New Zealand GNS Client Report 2002.124, prepared for the Ministry for the Environment (ME Report 483).

King AB, Brunsdon DR, Shephard RB, Kerr JE, Van Dissen RJ 2003. Building adjacent to active faults: a risk-based approach. In proceedings, Pacific Conference on Earthquake Engineering, Christchurch, New Zealand, February, 2003, Paper No.158.

Langridge RM 2007. Fault rupture avoidance issues at Parkhill Farmpark, Hawke's Bay. GNS Science Consultancy Report 2007/333.

Langridge R, Villamor P 2007. Hastings District LiDAR Fault Trace Survey. GNS Science Client Report 2007/145.

Langridge RM, Villamor P, Basili R 2006: Earthquake Fault Trace Survey – Central Hawke's Bay District. GNS Science Report 2006/98.

Lee J, Bland K, Kamp PJJ (compilers), in press. Geology of the Hawkes Bay area. Institute of Geological & Nuclear Sciences 1:250,000 geological map 8. 1 sheet + 71 p. Lower Hutt, New Zealand. GNS Science.

Mazengarb C, Speden IG (compilers) 2001. Geology of the Raukumara area. Institute of Geological & Nuclear Sciences 1:250,000 geological map 6. 1 sheet + 60 p. Lower Hutt, New Zealand: Institute of Geological & Nuclear Sciences Ltd.

Mouslopoulou V, Nicol A, Little TA, Walsh JJ 2007: Terminations of large strike-slip faults: an alternative model from New Zealand. In: Cunningham WD, Mann P (eds.) Tectonics of strike-slip restraining and releasing bends. Geological Society of London Special Publication 290, 387-415.

Quigley M, Van Dissen R, Villamor, P, Litchfield N, Barrell D, Furlong K, Stahl T, Duffy B, Bilderback, E, Noble D, Townsend D, Begg J, Jongens R, Ries W, Claridge, A, Klahn A, Mackenzie H, Smith A, Hornblow S, Nicol R, Cox, S, Langridge R, Pedley K, 2010. Surface rupture of the Greendale fault during the Darfield (Canterbury) earthquake, New Zealand: Preliminary Findings. Bulletin of the New Zealand Society for Earthquake Engineering 43: 236-242.

Raub ML, Cutten HNC, Hull AG 1987: Seismotectonic hazard analysis of the Mohaka Fault, North Island, New Zealand. In: Proceedings, Pacific Conference on Earthquake Engineering. The New Zealand National Society for Earthquake Engineering, Wellington. Volume 3: 219-230.

Saunders W, Glassey P (compilers) (2007). Guidelines for assessing planning policy and consent requirements for landslide-prone land. GNS Science Miscellaneous Series 7.

Segschneider B, Landis CA, Manville V, White JDL, Wilson CJN 2002. Environmental response to a large, explosive rhyolitic eruption: sedimentology of post-1.8 ka pumice-rich Taupo volcaniclastics in the Hawke's Bay region, New Zealand. Sedimentary Geology 150: 275-299.

Van Dissen R, Heron D 2003. Earthquake Fault Trace Survey – Kapiti Coast District. GNS Client Report 2003/77.

Van Dissen R, Barrell D, Litchfield N, Villamor P, Quigley M, King A, Furlong K, Begg J, Townsend D, Mackenzie H, Stahl T, Noble D, Duffy B, Bilderback E, Claridge J, Klahn A, Jongens R, Cox S, Langridge R, Ries W, Dhakal R, Smith A, Hornblow S, Nicol R, Pedley K, Henham H, Hunter R, Zajac A, Mote T 2011. Surface rupture displacement on the Greendale Fault during the Mw 7.1 Darfield (Canterbury) earthquake, New Zealand, and its impact on man-made structures. Proceedings of the 9th Pacific Conference on Earthquake Engineering, Auckland, New Zealand.

Van Dissen RJ, Berryman K, Webb T, Stirling M, Villamor P, Wood PR, Nathan S, Nicol A, Begg J, Barrell D, McVerry G, Langridge R, Litchfield N, Pace, B, 2003, An interim classification of New Zealand's active faults for the mitigation of surface rupture hazards. In proceedings, Pacific Conference on Earthquake Engineering, Christchurch, New Zealand, February, 2003, Paper No.155.

Wallace LM, Beavan J.; McCaffrey R, Darby D 2004. Subduction zone coupling and tectonic block rotations in the North Island, New Zealand. Journal of Geophysical Research, 109, B12406, doi:10.1029/2004JB003241.

APPENDIX 1 – AERIAL PHOTOGRAPH RUNS

Rangiora Fault:

Runs - 1109 (1, 2); 1127 (34-36); 1128 (32, 33); 1129 (31-33); 1130 (30-32); 1131 (26-28); 1132 (27-30); 1133 (25-27)

Coastal and northern Wairoa District:

Runs – 1105 (32-41); 446 (42-44); 445 (43-70); 444 (37-40; 51-55); 443 (33-60); 442 (14-25; 44-47); 3361 (2-15); 3362 (31-35)

Mahia:

Runs – 453 (6-9); 454 (7-10); 458 (2-4)

APPENDIX 2 – CD CONTENTS

1: *Report*:

- Fault Avoidance Zone Mapping for Wairoa District and Napier City. PDF Format.

2: *GIS Data*:

- Line Fault Features – line.shp. Shapefile format. These are line features representing observed line fault features such as scarps, degraded scarps, guided drainage, and ridge rents. Details are provided on the fault name, the landscape feature involved, the fault feature observed, a statement concerning the accuracy of location, and an estimate of the accuracy in metres.

- Fault Avoidance Zone – zone.shp. Shapefile format. These are polygon features representing the Fault Avoidance Zones developed for this study. Details are provided on the fault name, the fault complexity, the recurrence interval class, and suggested Resource Consent Category.

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