Rotorua District Council
Hazard Studies: Active fault hazards

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BIBLIOGRAPHIC REFERENCE

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EXECUTIVE SUMMARY

The Rotorua District Council (RDC) has commissioned GNS Science to update information currently used to identify active faults and to provide recommendations for best practice management in high risk areas. GNS Science has produced an updated active fault map of the Rotorua District and compiled information that is relevant to active fault hazards. The two main hazards directly related to active faulting. In Rotorua District are strong ground shaking and surface deformation. The report presents information and data that is relevant to these two types of hazard.

The assessment of ground shaking hazard relies on the characterisation of the earthquake potential of active faults and the transfer of that information (together with seismicity and geodetic information) to probabilistic seismic hazard maps. In the Rotorua District, there are at least 45 major active faults that are capable of generating large earthquakes (M_w 5.5 to 6.9) that will produce strong ground shaking. Individually, these faults rupture with recurrence intervals between 500 and 10,000 years, so the likelihood of ground shaking in the area is high because of the large number of faults. In this report, while we provide mapping for all active or potentially fault traces, we can only provide earthquake data (maximum magnitude, slip rate and recurrence interval) relevant for seismic hazard assessment for at least half of the 45 major active faults, because there are no research studies undertaken for all faults to date.

Seismic hazard maps define the probability that a certain level of ground shaking will be exceeded in a certain time interval. These maps are used to evaluate requirements for seismic-resistant design of a site, a region or a country, and are essential for emergency response (combined with building vulnerability) and understanding of other hazards associated with ground shaking (e.g., landsides and liquefaction).

Information on probability of exceedance of high levels of ground shaking in the Rotorua area is currently contained in a nationwide seismic hazard map. In the Rotorua District, the level of ground shaking varies from 0.2 to 0.5 g (g or gravitational acceleration = 9.8 m/s^2) for 10% probability in the next 10 years, based on results from the 2002 National Seismic Hazard map. The resolution of nationwide maps is too coarse to be used for District level planning. It is recommended that region specific maps are produced to fully understand the level of ground shaking hazard in the area. In addition, the current national map (2002) and the new national map that is close to completion (2010) do not include all the active faults that have been recently (including this report) defined for the Rotorua District.

Ground deformation associated with surface fault rupture only occurs along active fault traces. However, Rotorua District has the largest density of active faults in New Zealand, and thus large areas of the district are likely to be affected by surface rupture (ground deformation) hazard. Although faults can often be located accurately (to within a few metres), there is currently no technology to prevent earthquake damage to buildings built across faults (Kerr et al., 2003). For this reason, we recommend the use of the Ministry for the Environment (MfE) guidelines to avoid building across hazardous faults (Kerr et al., 2003).

The main elements of the risk-based approach presented by the MfE guidelines are based on: a) fault characterisation relevant to planning for development across fault lines, which focuses on an accurate location of the fault, definition of a fault avoidance zone, and classification of the fault based on its recurrence interval; and b) the Building Importance Category, which indicates the acceptable level of risk of different types of buildings within a fault avoidance zone.

GNS Science has produced an updated active fault map and defined fault avoidance zones for all fault traces in the Rotorua district. The compilation of fault data shows that for most fault traces there is no information on the recurrence interval due to the large number of individual fault traces and the complicated fault pattern, which typically prevents correlations between traces with information and traces with no information. Paleoseismic studies in the area suggest a range in recurrence interval classes from I to V (from <2000 to 20,000 years). This means that the fault traces have different levels of activity and have to be assessed individually to be able to recommend the type of construction that should be permitted close to each fault. We recommend that if no further studies are undertaken on any of the fault lines provided here, that have no recurrence information, buildings of Building Importance Category (BIC) 2a to 4 be excluded from the fault avoidance zone given in this report. Paleoseismic investigations are recommended for site specific studies to reduce the width of the fault avoidance zone and/or characterise the fault recurrence interval and better define the type of building permitted close to the fault.

We recommend that RDC identify areas of fast development and undertake specific fault studies to improve the understanding of ground shaking and ground deformation (surface rupture) hazards for those specific areas.

1.0 INTRODUCTION

The Rotorua District Council (RDC) has commissioned GNS Science to undertake a study to update information currently used to map faults and to provide recommendations for best practice management in areas of high seismic risk. RDC has a GI data layer of fault lines that was prepared in 1995 and has not been updated since that time. Mapping technology has improved in the intervening 15 years, while a significant amount of research on the active faults has been completed in this time. GNS Science was commissioned to review the mapping of active faults and provide advice on the threat they represent in terms of probability and intensity of seismic shaking and ground rupture. This seismic information is important for managing land use in order to minimise the impact of future earthquakes.

1.1 Scope of work

The scope of work included:

- Review of historical documents and other information related to active faults in the Rotorua region.
- Review of recent aerial photography for the district: old aerial photography owned by GNS Science and new orthophotos supplied by Council.
- Map fault lines to the maximum accuracy possible and attribute traces with relevant information for land use planning purposes.
- Produce GIS coverage maps with fault line information.
- Prepare a report describing the work carried out above. The information provided in the report will enable the RDC to formulate suitable policies and rules for identifying and mitigating this hazard in the context of the District Plan.

1.2 Active fault hazards

In the RDC area active fault studies indicate that numerous large earthquakes (M_w 5.5 to 6.9) have ruptured the ground surface in prehistoric times and are likely to happen in the future. A historic example was the M_w 6.6 1987 Edgecumbe Earthquake (Beanland et al., 1989) in the neighbouring Whakatane District, which occurred in an area that is geologically similar to the Rotorua District.

Strong ground shaking and surface deformation are the two main hazards directly related to active faults in Rotorua District. Strong ground shaking associated with a large earthquake can be devastating if structures and facilities within the area are not properly designed to resist earthquake loads. Strong ground shaking can also produce secondary geological effects such as landslides and soil liquefaction. Ground shaking will affect a larger area (e.g., 500 km^2) adjacent to the surface rupturing fault. An assessment of ground shaking hazard is dependent on the characterisation of the earthquake potential of active faults and the transfer of that information (together with seismicity and geodetic information) to probabilistic seismic hazard maps. A discussion of the earthquake size and recurrence expected for the Rotorua District, and current information on seismic hazard maps is presented in section “4.0 Large earthquakes and probability of strong ground shaking in the Rotorua District”.

Ground deformation associated with ground-surface fault rupture only occurs at the fault location. Although faults can often be located accurately (especially in RDC area where they have good surface expression), there is no technology to prevent earthquake damage to buildings built across faults (Kerr et al., 2003). For this reason, the Ministry for the Environment (MfE) established guidelines to avoid building across hazardous faults (Kerr et al., 2003). GNS Science recommends the MfE guidelines for “Planning for development of land on or close to active faults” and thus our fault map and fault attribute compilation is based on the requirements of those guidelines. We present next the main points of those guidelines.

1.3 MfE guidelines for planning for development of land on or close to active faults

The guidelines were developed because (Kerr et al., 2003):

> *“There is no technology to prevent earthquake damage to buildings built across faults.”*

The main elements of the risk-based approach presented by the guidelines are:

1) Fault characterisation relevant to planning for development across fault lines which focuses on: a) accurate location of faults (including its “fault complexity”, i.e., the distribution and deformation of land around a fault line) and; b) definition of fault avoidance zones; c) classification of faults based on their recurrence interval (time interval between large earthquakes on the same fault), which is an indicator of the likelihood of a fault rupturing in the near future.
2) The Building Importance Category, which indicates the acceptable level of risk of different types of buildings within a fault avoidance zone.

For these reasons our report will focus on aspects of accurate fault location (see section “Fault mapping”), fault recurrence interval (see section “Fault attributes”) and recommendations pertinent to the guidelines. For more details see section “5.0 Planning for development of land on or close to active faults in the Rotorua District”.

2.0 LITERATURE REVIEW OF ACTIVE FAULTING IN THE ROTORUA DISTRICT AREA

The Rotorua District is located in the Taupo Volcanic Zone (TVZ), a 1 to 2 million year old volcanic arc formed in association with the subduction of the Pacific Plate beneath the North Island of New Zealand (Wilson et al., 1995). The TVZ is characterised by high crustal heat flow (up to 700 mW/m^2), volcanism, numerous shallow focus earthquakes (< 8 km deep, at its central latitudes, Bryan et al., 1999), and active extensional faulting (Villamor and Berryman, 2001). Tectonic extension in the TVZ is partly accommodated by a dense system of NE-SW trending normal faults that dip both to the NW and SE (Figure 1). The fault traces represent the surface expression of accumulated fault displacement during prehistoric earthquakes. These active faults are capable of producing strong ground shaking (i.e., large earthquakes).

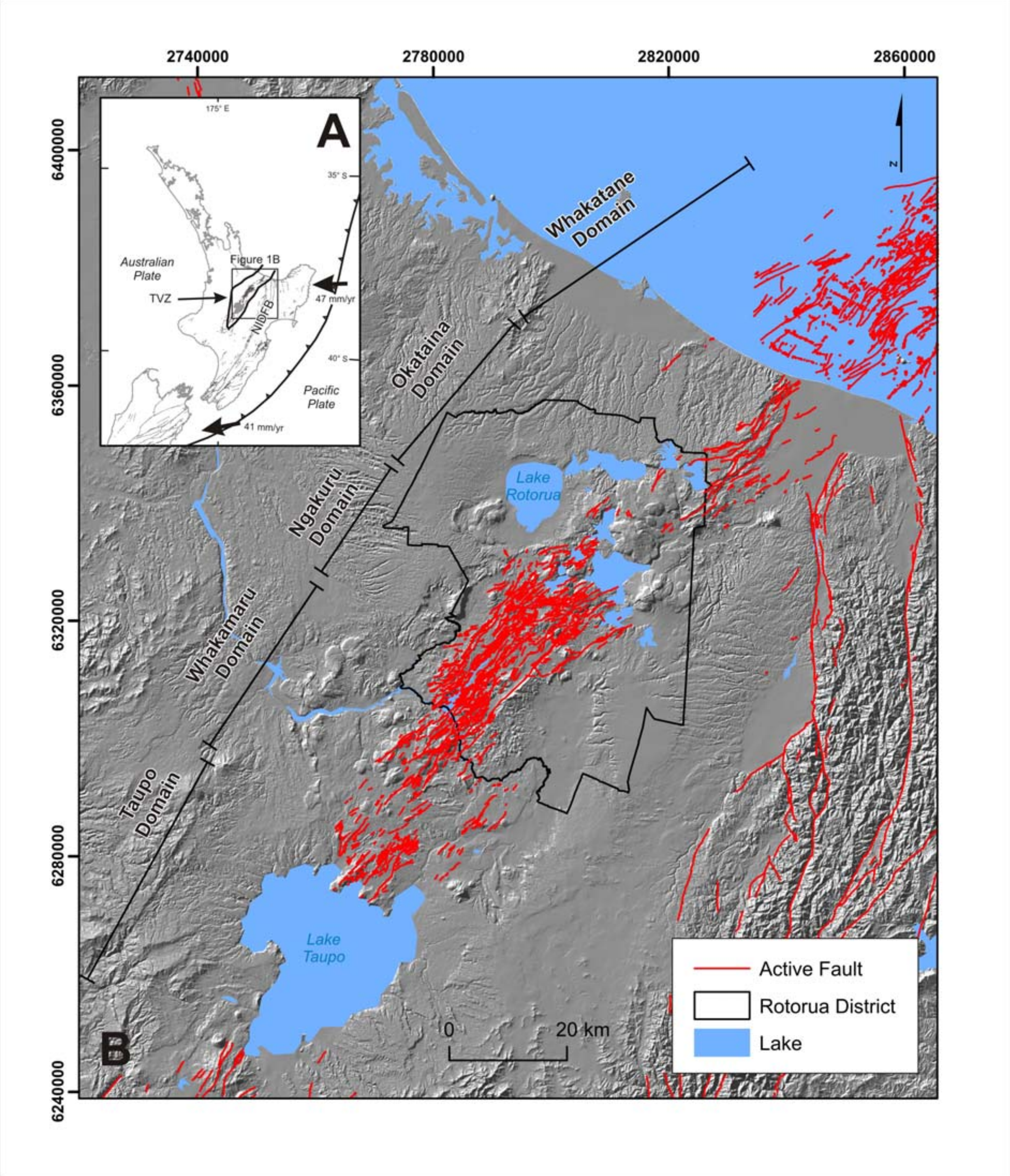

Figure 1 Active faults in the Rotorua District and neighbouring areas. Rift segments are from Rowland and Sibson. 2001. Inset, tectonic setting of the Taupo Rift.

Rowland and Sibson (2001) described the tectonic structure as a continental rift, here called the Taupo Rift (also known as the Taupo Fault Belt; Villamor and Berryman 2001), with near-symmetric distributions of opposite-facing normal faults about local axes. The rift is divided along its length into segments or domains (Fig. 1; Rowland and Sibson 2001). Each segment has a well defined set of NE trending faults which taper out at the end of the segment. The connection between two adjacent segments is called the “accommodation zone”, and it is the area where the tectonic deformation of one segment is transferred to the other.

The segments of the rift that are located within the Rotorua District are the Ngakuru and the Okataina segments (Fig. 1). The Ngakuru segment is located to the south of Rotorua township and has, by far, the highest density of active fault traces compared to any other district in New Zealand (Villamor and Berryman, 2001). The Okataina segment contains the currently active volcano complex known as the Okataina Volcanic Centre and has a lesser number of active fault traces. There are less fault traces in the Okataina segment because the tectonic extension is mainly accommodated by volcanism and only partially by tectonic faulting (i.e., earthquakes) (Seebeck and Nicol, 2010; Villamor et al., in press). To the north of the Okataina segment, in the Whakatane District, the Whakatane segment has numerous fault traces. These traces display a similar pattern (geometry complexity and density) to those of the Ngakuru graben, and they displace the Rangitaki Plains (Begg and Mouslopoulou, 2010) and extend offshore (Lamarche et al., 2006). To the south of the Ngakuru segment (south of Waikato River) is the Whakamaru segment.

Fault geometry is very complicated in the RDC area. There are numerous discontinuous short fault traces that we interpret to merge at depth into a few major faults. This geometric relationship is interpreted from surface mapping where single fault traces splay into several traces along the fault strike and merge back onto one or two traces (Villamor and Berryman 2001; Berryman et al., 2008). This relationship has also been imaged in subsurface seismic reflection profiles in the offshore part of the Taupo Rift (Lamarche et al., 2006). Major faults in the RDC area also merge with other major faults through “accommodation zones” that usually contain a complicated pattern of small fault traces with different orientations. It is often difficult to evaluate where one major fault ends and the next one starts. In Figure 2 we present our interpretation of the grouping of small surface traces into major fault lines in the Rotorua District. In Table 1 we associate major faults with the rift segment where they are located. Some faults straddle two segments, which is reflected in Table 1 as a transition between segments. The major faults listed in Table 1 extend in depth through the entire earth’s crust beneath the fault rift and are capable of producing large earthquakes $M_w > 5.5$.

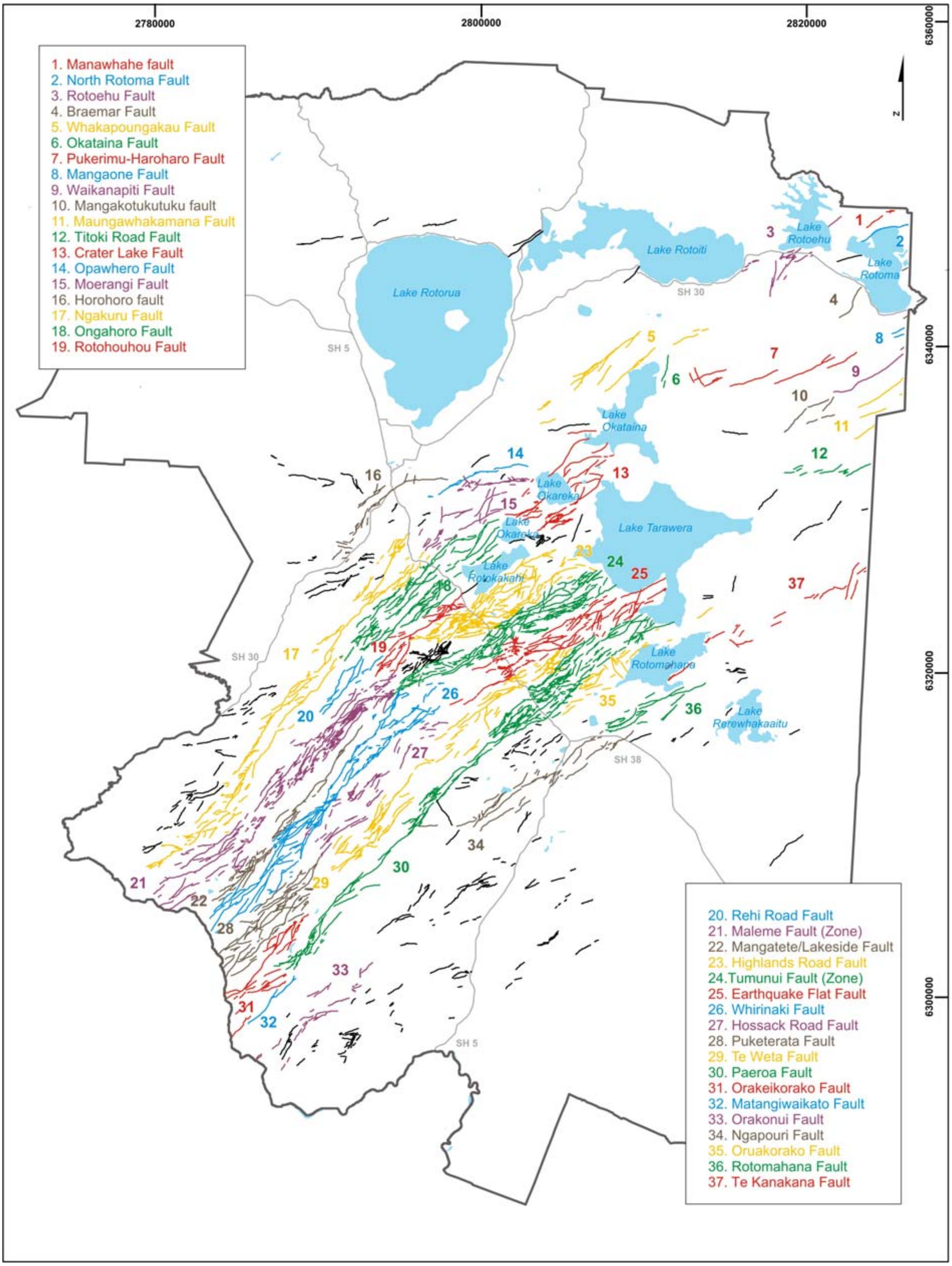

Figure 2 Major faults in the Rotorua District that are likely to produce earthquakes with M_w>6.0. Individual surface fault traces merged in depth into major faults.

Table 1 Earthquake characteristics of major faults within the Rotorua District.

Segment	Fault name	Surface length (km)	M_w	Slip rate** min/ave/max (mm/yr)	RI* (yrs)	Notes
Transition from Whakamaru to Ngakuru	Tuahu					
	Puketerata	17	6.4	1.3/1.8/2.3	600	Stirling et al. (in prep)
	Orakeikorako	17	6.4	1.3/1.8/2.3	600	Stirling et al. (in prep)
	Orakonui	19	6.5	0.2/0.6/1.0	2000	Stirling et al. (in prep)
Ngakuru	Ngakuru (SW)	9	6.0	0.4/0.5/0.6	950	Villamor and Berryman (2001); Stirling et al. (in prep)
	Ngakuru (NE)	18	6.5	0.4/0.5/0.6	2300	Villamor and Berryman (2001); Stirling et al. (in prep)
	Rehi Rd					
	Maleme	17	6.6	2.5/3.5/4.5	300	Villamor and Berryman (2001); Tronicke et al. (2006); McClymont et al. (2009);); Stirling et al. (in prep)
	Mangatete-Lakeside	7	5.9	0.05/0.1/0.2	4500	Villamor and Berryman (2001); Stirling et al. (in prep)
	Whirinaki All $^{\#}$	19.8	6.6	005/0.1/0.2	10700	Canora-Catalan et al. (2008); Stirling et al. (in prep)
	Whirinaki W $^{\#}$	10	6.1	0.1/0.2/0.3	2900	Canora-Catalan et al. (2008); Stirling et al. (in prep)
	Whirinaki E $^{\#}$	12	6.2	0.1/0.2/0.3	5100	Canora-Catalan et al. (2008); Stirling et al. (in prep)
	Hossack Road	4	5.5	0.05/0.1/0.2	1700	Villamor and Berryman (2001): Stirling et al. (in prep)
	Te Weta	14	6.3	0.3/0.4/0.5	2100	Villamor and Berryman (2001); Stirling et al. (in prep)
	Paeroa All$^{\#}$	27	6.7	0.7/0.8/0.9	2300	Berryman et al. (2008); Stirling et al. (in prep)
	Paeroa N$^{\#}$	9	6.1	0.7/0.8/0.9	800	Berryman et al. (2008); Stirling et al. (in prep)
	Paeroa C$^{\#}$	7	6.1	0.7/0.8/0.9	600	Berryman et al. (2008); Stirling et al. (in prep)
	Paeroa S$^{\#}$	10	6.2	0.7/0.8/0.9	900	Berryman et al. (2008); Stirling et al. (in prep)
	Ngapouri-Rotomahana	16	6.4	0.15/0.17/0.2	4400	Villamor and Berryman (2001); Berryman et al. (2002); Stirling et al. (in prep)
Transition from Ngakuru to Okataina	Horohoro	20	6.5	0.1/0.17/0.2	7400	Zachariasen and Van Dissen (2001); Stirling et al. (in prep)
	Ongahoro	≥13	6.3	1.4/1.7/2.0/	<3300	Nicol et al. in press
	Rotohouhou	9.5	6.0	0.5/0.6/0.7	2900	Nicol et al. in press
	Highlands	-	-	-	-	
	Tumunui	-	-	-	-	
	Earthquake Flat	-	-	-	-	
	Oruakorako	-	-	-	-	
	Opawhero	-	-	-	-	
Okataina	Moerangi	-	-	-	-	
	Crater Lake	-	-	-	-	
	Te Kanakana	-	-	-	-	
	Whakapoungakau	-	-	-	-	
	Okataina	-	-	-	-	
	Pukerimu-Haroharo	-	-	-	-	
	Mangakotukutuku	-	-	-	-	
	Waikanapiti	-	-	-	-	
	Maungawhakamana	-	-	-	-	

Segment	**Fault name**	**Surface length** (km)	**M_w**	**Slip rate**** **min/ave/max** (mm/yr)	**RI*** (yrs)	**Notes**
	Rotoehu	-	-	-	-	
Transition from Okataina to Whakatane	Manawahe	-	-	-	-	
	North Rotoma	-	-	-	-	
	Braemar	32	6.8	1.0/2.0/3.0	900	
	Mangaone	-	-	-	-	
	Rotoitipakau	15	6.4	0.5/1.5/1.7	550	
	Onepu	-	-	-	-	

* Slip rate is a measure of the total amount of displacement per time (e.g., accumulated displacement from several fault ruptures during the time interval when those ruptures occurred). It is a measure of relative fault activity.

**note that the Recurrence interval (RI) is an average value for the whole fault that in cases consists of several parallel strands. This is an appropriate value for seismic hazard assessment. For planning purposes it would be more relevant to assess the recurrence interval for the individual fault trace.

The Whirinaki, Paeroa faults can rupture with smaller or larger earthquakes (shorter or longer rupture length) and this is described separately in this table. For details se, e.g., Canora et al., 2008

\- There are several faults that lack paleoseismic studies as thus there is no information on fault parameters.

The activity of the fault lines in the Rotorua District is presented in several papers (see Table 1). Villamor and Berryman 2001, present a review of the major fault traces in the Ngakuru segment and conclude that the total extension of the rift in the area is up to ~ 7 mm/year and is distributed into major faults with fault slip rates ranging from 0.1 mm/year to 2-3 mm/year (e.g., Maleme and Paeroa faults). Fault slip rate is the cumulative surface displacement (associated with several large earthquakes) that occurred during a certain time interval, and is a measure of fault activity. Individual faults in the Rotorua District have low to moderate slip rates compared with the fastest fault in New Zealand, the Alpine fault, that has a 25 mm/year slip rate.

The digital maps of active faults in the study area compiled prior to this study have been done in the context of the research programmes within GNS Science and thus fault locations are not accurate enough to be used for land use planning (Kerr et al., 2003). The RDC coverage, which dates from 1995 (based on RDC accounts), is likely to be the same as the active fault database prior to this study. The line work for that digital map was manually compiled on 1:50,000 scale maps and was digitised from those maps into digital coverages for GIS. The uncertainly on the location of those fault traces was up to several hundred meters. In addition, current common practice for active fault mapping for planning purposes has advanced greatly from 1995 (see next section).

3.0 FAULT MAPPING

Prior to this study, GNS Science was in the process of updating the mapping of the Taupo Rift faults. Part of the fault traces within the Rotorua District had been mapped with great accuracy. For this study, we have focussed on mapping the remainder of the Rotorua District faults and bringing fault lines within the district to the same level of accuracy. We have also attributed all of the faults in a consistent fashion, including information on the accuracy/resolution of the fault mapping for all traces, and definition of fault avoidance zones suitable for land-use planning purposes. For those fault traces that we have extra information from paleoseismic trenches, we have been able to provide Recurrence Interval Class characterisations as defined in the MfE guidelines for “Planning for Development of Land on or Close to Active Faults" (Kerr et al., 2003).

3.1 What is an active fault in the Taupo Rift?

In the Active Faults Database of New Zealand, an "active fault" is defined as a fault that shows evidence of rupture in the last 120,000 years (Jongens and Dellow, 2003). This definition is well suited for New Zealand use because Quaternary deposits and surfaces of this age are widespread. This definition has been used on many published maps of New Zealand geology.

In the Taupo Rift, we use an alternative definition because of the rapid evolution of active faulting in the rift. Active faulting at the margins of the older Taupo Rift, outside the active faults of Figure 1, has recently ceased (less than 125,000 years) and active faulting has since concentrated on the modern Taupo Rift (Fig. 1) (Villamor and Berryman, 2006). Faults outside the currently active fault belt have not moved at least in the last ~20,000 year. This is based on numerous geomorphic and geologic formations of that age that have not being affected by faulting. Geodetic measurements also show that most of the current tectonic deformation is confined to the region of the modern Taupo Rift (Beavan, et al. 2007).

For the reasons mentioned above, we define an "active fault" in the Taupo Rift as a fault that shows evidence of rupture in the last 20,000 years. This definition does not affect the application of the MfE guidelines (see discussion on section "Planning for development of land on or close to active faults in the Rotorua District").

3.2 Fault Mapping Methodology

In order to produce an updated active fault map for an area of the Rotorua District, the following work has been undertaken:

- For the area that has not been updated prior to this study, we have reviewed c. 1500, 1:16:000 scale, aerial photos from the 1940's and 1960's at from the GNS Science collection together with RDC LiDAR data and other detailed topographic maps to map fault lines. Fault lines were mapped onto trace paper on the aerial photos.
- Key aerial photos, where faults were mapped, were scanned and geo-referenced. The base maps for geo-referencing were the ortho-photos and LiDAR provided by the Client and/or LINZ ortho-photos.
- Digitised new mapped fault traces into shape files, from the scanned fault lines or from fault scarps identified on the RDC LiDAR.

Figure 3 shows the different layers that were incorporated in to the GIS to enable fault traces to be accurately digitised in the Rotorua District.

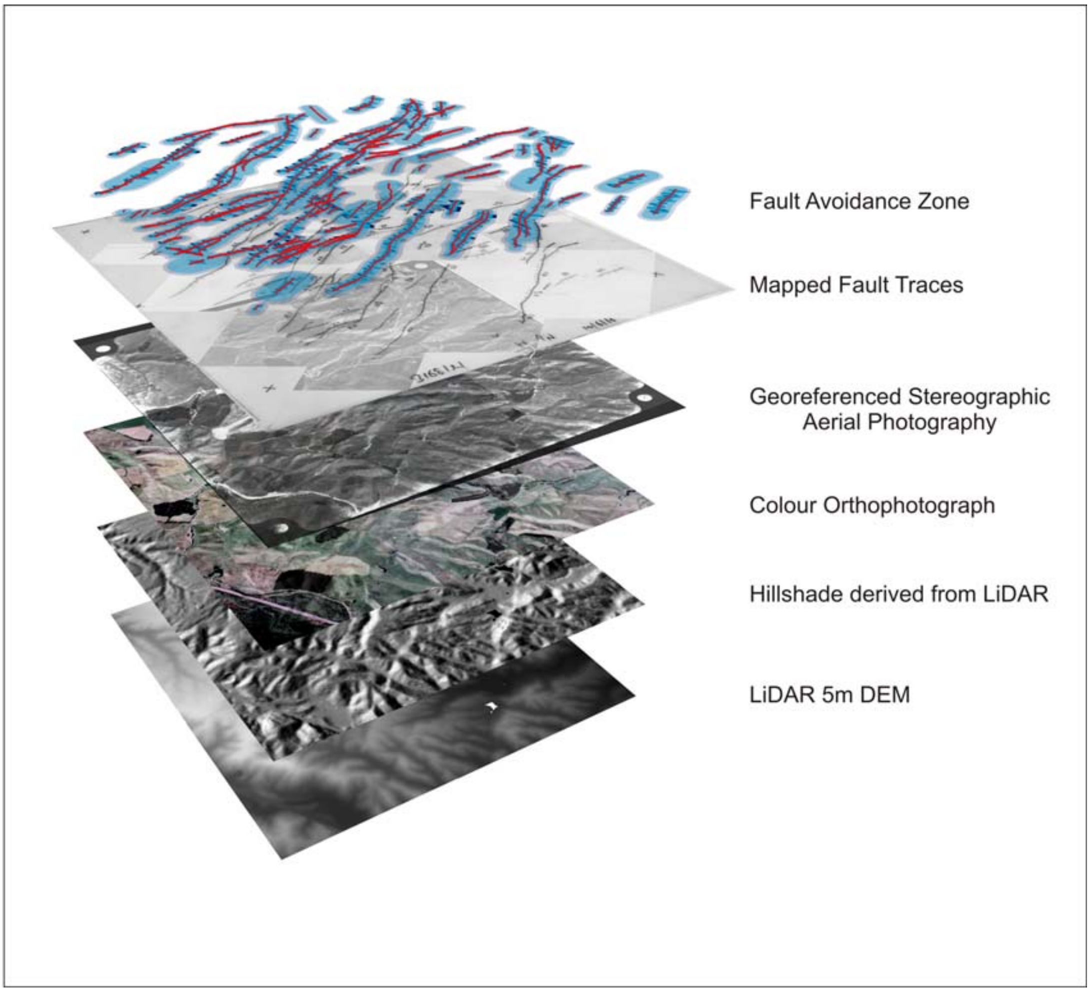

Figure 3 Sequence of GIS Layers that have been produced to digitise active fault with great accuracy.

3.3 Fault Location Uncertainty Criteria

Active faults are more appropriately defined as zones rather than lines. This is because of the lack of knowledge on the exact location of the fault plane (unless the faults plane is exposed in an excavation), and because the surface area that will be deformed by faulting is likely to be somewhat wider than the main fault plane (fault complexity in Kerr et al., 2003). The accuracy with which the location of a fault feature (fault zone) can be captured into a map is influenced by two types of uncertainty or error:

I. The first is the error associated with how accurately the feature can be located on the ground (feature error), i.e., does the fault have a clear geomorphic expression. Highest resolution is obtained when the actual fault plane is exposed (natural outcrop or exploratory trench) and identified. Reasonable resolution can be obtained when a clear fault scarp is identified on aerial photos and/or on the ground. Poor resolution is obtained when the fault scarp can not be located on the ground surface (i.e. it has been eroded away or is covered by vegetation and/or buried by young sediments).This type of error is recorded by the attributes called “EXPRESSION”, “ACCURACY” and “UN_loc” in the GIS files.

With respect to the “EXPRESSION” attribute, highest resolution (EXPRESSION = “surface trace”) is obtained when the actual fault plane is exposed (natural outcrop or exploratory/paleoseismic trench) and identified. Relatively high resolution can also be obtained when a clear fault scarp, that has not undergone much erosion, is identified on aerial photos and/or on the ground. The location of a trace classified as a fault “surface trace” is where the fault is more likely to rupture through the ground in a future event. Moderate resolution is obtained when the fault scarp is eroded (EXPRESSION= “eroded scarp”). For an eroded scarp, it is not possible to locate precisely where the fault will rupture, and thus the location of the fault is better expressed as a zone that covers the width of the scarp. Poor resolution is obtained when the fault scarp cannot be located on the ground surface (i.e., it has been eroded away or is covered by vegetation and/or buried by young sediments) (EXPRESSION = “no trace”). Also, poor resolution is obtained when it is not known whether a geomorphic feature is a fault or not (EXPRESSION = “unknown”). The “EXPRESSION” attribute also records the epistemic uncertainty of the trace. For example, if any of the three first options (“surface trace”, “eroded scarp” and “no trace”) are assigned to a fault line, it implies that the scientist is attributing the fault is sure that the trace is a fault. Conversely, the option “unknown” means that the scientist suspects that the feature is a fault but he/she is not sure. We also define as “unknown” those lines that are clearly identified as faults but that we do not know if they are active or inactive.

The “EXPRESSION” attribute is directly related to the “ACCURACY” attribute (“ACCURACY” = “accurate”, “approximate”, “concealed” or “inferred”; see Jongens and Dellow, 2003, for definitions). Usually a “surface trace” will be “accurately” located, and “eroded scarps” will be “approximate”. For the other two options there are some combinations. For example, a topographic feature that looks like an eroded fault scarp but it is not clear whether it is a fault could be defined as “unknown” (is it a fault?) “approximate” (e.g., feature is identifiable in the aerial photo as a subtle scarp). If an “approximate unknown” fault scarp terminates abruptly we infer that there could be some extension of the trace that is not visible (eroded or buried). This type of fault line is defined as “inferred unknown”. Another example is when a part of a fault has been eroded by the river and young sediments cover the fault but the surface trace on both sides of the river can be easily identified. The line connecting these clear fault can be classified as “no trace” (there is a fault trace in continuation with traces that can be easily identified in the field) and “concealed” (is eroded and /or buried by sediments).

The different combinations of “EXPRESSION” and “ACCURACY” attributes give a qualitative measure of location uncertainty (Table 2). However, traces with similar attributes can have wider or narrower uncertainty zones based on the dimensions of the surface expression of the fault, i.e., the fault scarp height and width. If the fault plane is not exposed (e.g., by exploratory trenches) the initial line that we have identified as a fault trace on the aerial photos gives only an indication of the fault plane location. For faults, with normal sense of movement (such as those within the Taupo Rift), a fault plane is likely to be located anywhere within the width of the fault scarp (Figure 4). Where secondary faulting is associated with the main plane, it also tends to be located within the fault scarp width. This secondary faulting is defined as the “fault complexity” (Kerr et al., 2003), which refers to the width and distribution of the deformed land around the fault trace. For this reason and because our study aims to get the highest resolution possible, we have quantitatively assessed the location uncertainty (expressed as the half width of the fault scarp in metres) for each individual trace. These uncertainty values are shown as “UN_loc” (uncertainty in fault rupture location) in the attribute table of the GIS files.

Table 2 Definition of features/faults with different “EXPRESSION” and “ACCURACY” attributes.

Location		**Type of fault/feature**	**Uncertainty in location for Rotorua District (m)**
Expression	**Accuracy**		
surface trace	accurate	Ground surface rupture of an active fault. The fault scarp is not eroded (usually clear, sharp and not very high). Future surface rupture will occur close to the drawn line.	3-50
eroded scarp	approximate	Clear scarp of an active fault. Erosion has modified the scarp shape and thus future surface rupture could occur somewhere off the drawn line.	3-210*
no trace	concealed	The fault scarp cannot be identified on the surface because it is eroded or buried. We are sure there is an active fault there. Usually applied to joining traces between surface traces or eroded scarps (e.g., where faults crosses a river, faults scarp can be eroded or buried by the river).	10-120
no trace	inferred	We can not identify a scarp but there is a strong possibility that there is a fault there. Usually applied to the end of surface traces and eroded scarps, because they are likely to extend beyond the line identified on the map.	6-150
unknown	inferred	Same case as above but for cases where we can identify a subtle feature in the landscape (scarp, lineament) in extension of the surface trace or eroded scarp. These are also lines joining two “unknown-approximate” lines.	10-100
unknown	approximate	There is a clear scarp in the landscape but we are not sure it is a fault or another geomorphic feature (e.g., river terrace, old caldera rim). It is also be applied to faults (with clear scarps) that may, or may not, be active.	10-200

*If the scarp is very high the width of the location uncertainty can be very large.

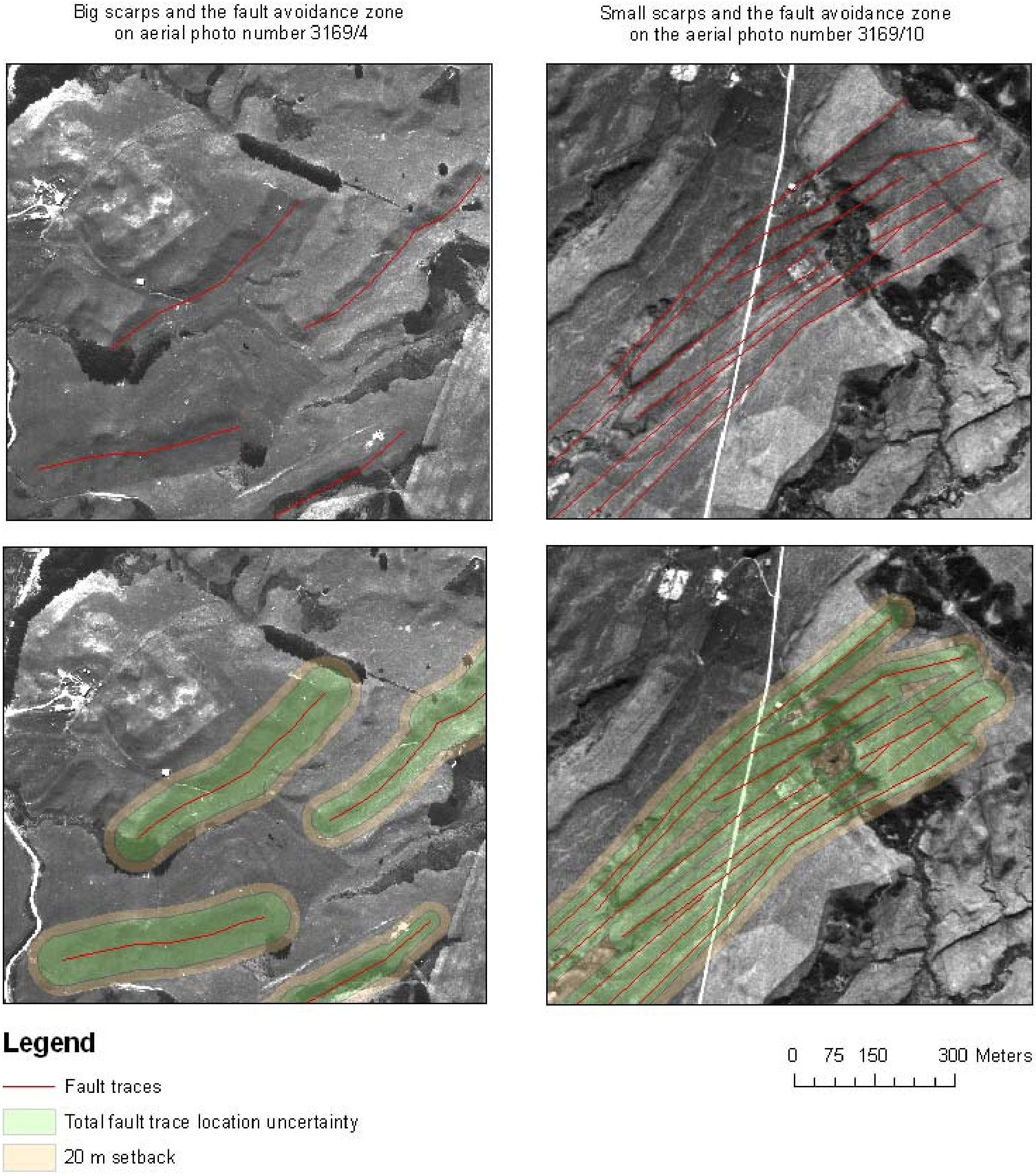

Figure 4 Two examples of definition of fault avoidance zone. A, fault with a large scarp has a large uncertainty in the location of the fault plane and other surface deformation features. B, small scarps have narrow uncertainty bands. C, Sketch showing the area where fault deformation is likely to occur during surface rupture for normal faults similar to those in the Rotorua District.

II. The second type of uncertainty is the error associated with transferring the fault location onto a map (capture error). This type of error is ultimately dependant on the quality and scale of that map. In this study, we have used geo-referenced aerial photos as our map for digitising the fault traces. The accuracy of the coordinates assigned to those aerial photos depends on the accuracy of the map used as a base for geo-referencing. We have used three different types of base maps: the LiDAR and recent orthophotos provided by RDC (labelled as RDC LiDAR and RDC Ortho in Table 3) and orthophotos from LINZ for areas where was not provided by RDC (LINZ Ortho in Table 1). We have assigned an "uncertainty of location for base map" to each of those base maps as shown in Table 3 in metres. This value refers to the uncertainty of the coordinates that any point on the map has with respect to the real geographic coordinates. When we geo-reference aerial photos with base maps we cannot achieve the same level of accuracy for the aerial photo as base map, due to the original distortion of the aerial photos. In Table 3, we also present the final uncertainty in location of the geo-referenced aerial photos. These two values combined comprise the uncertainty or error in map capture and they are recorded in the GIS files as the attribute field "UN_map_cap".

Table 3 Uncertainty values for location of faults

Base map data type	1. Uncertainty of location for base map data (m)	2. Uncertainty of georeferencing (m)	3. Un_map_cap (m) [3=1+2]	4. Un_loc (m)	5. Guide-lines Setback (m)	6. Fault avoidance zone (m) [6=3+4+5]
Linz Ortho	± 10	± 20	± 30	3 - 250	20	53 - 290
RDC Ortho	± 3	± 5	± 8	3 - 250	20	31 -278
RDC LiDAR	± 3	± 2	± 5	3 - 250	20	28 - 275

The total uncertainty in fault location is the sum of the two uncertainty values, "UN_loc" and "UN_map_cap", and is shown by the attribute field: "UN_total". In Figure 5, we show schematically the different types of uncertainty. In Figure 6, we show a small section of the RDC active fault map (Map 1). The figure graphically depicts the accuracy in location of each of the fault traces as a zone with an appropriate width uncertainty to plot the fault traces. For the active fault map, we have provided our best estimate of lines for the location of the fault plane (and provide GIS coverage for it) which is plotted in the middle of the uncertainty zone. These lines should not be used as the exact location of fault traces for cadastral purposes. Buffer zones corresponding to the width of the zone of fault location uncertainty ("UN_total") should be added to these lines to reflect the uncertainty on fault location.

For planning purposes (see section "Planning For Development Of Land On Or Close To Active Faults In The Rotorua District"), we have also added a 20 m setback zone to either side of the Fault Location Uncertainty areas, as recommended by the Ministry for the Environment Guidelines (Kerr et al., 2003) for the mitigation of fault rupture hazard (Figs. 5 and 6). The attribute "Ft_Avoid_zone" in the GIS files includes the "UN_loc", "UN_map_cap" and the 20 m recommend setback distance ("20_m_setback" field in the GIS files), and represents the whole fault avoidance zone associated with each fault trace. This fault avoidance zone is the main attribute that should be used for planning purposes.

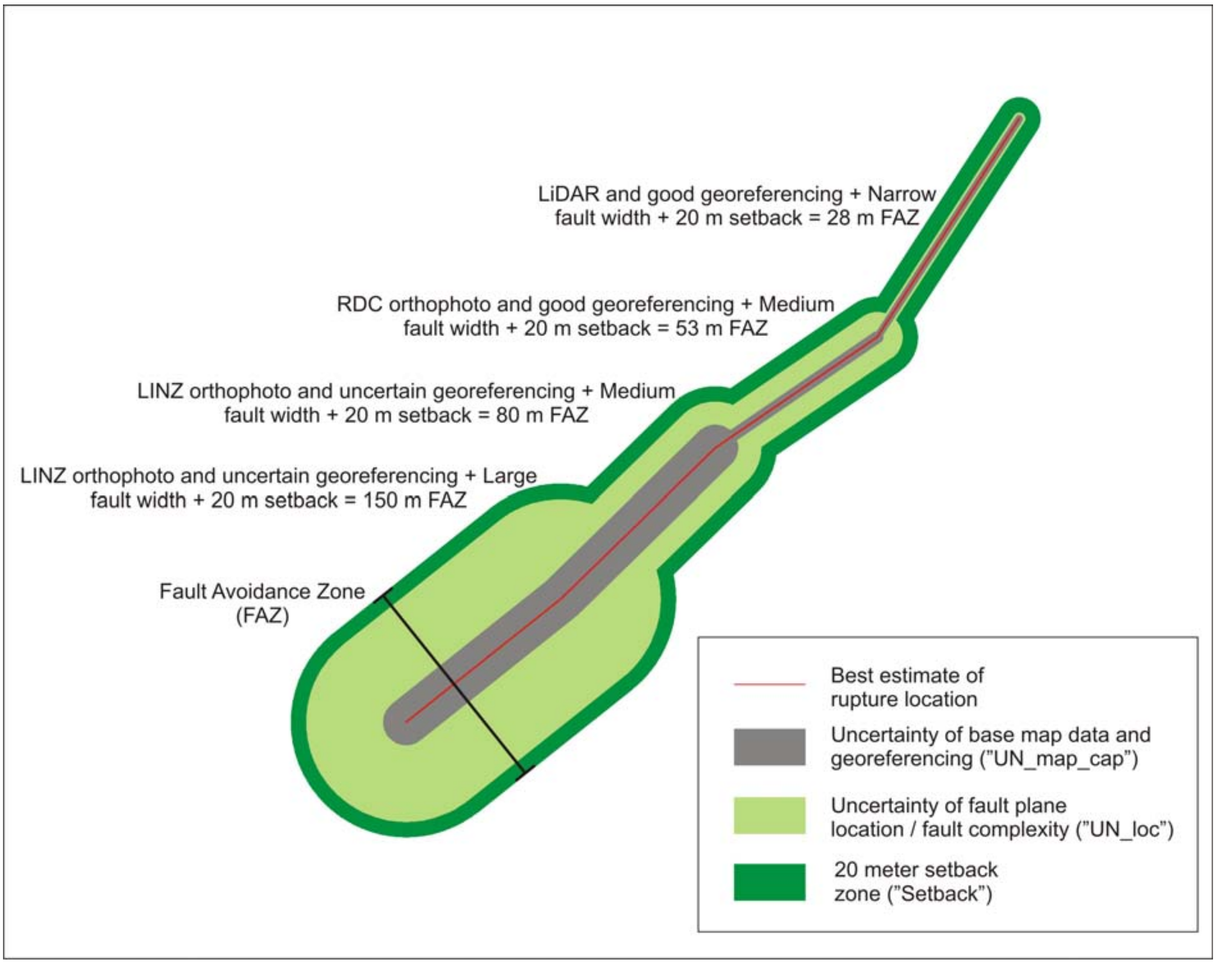

Figure 5 Sketch showing the uncertainties on faults location and map capture for Rotorua District faults.

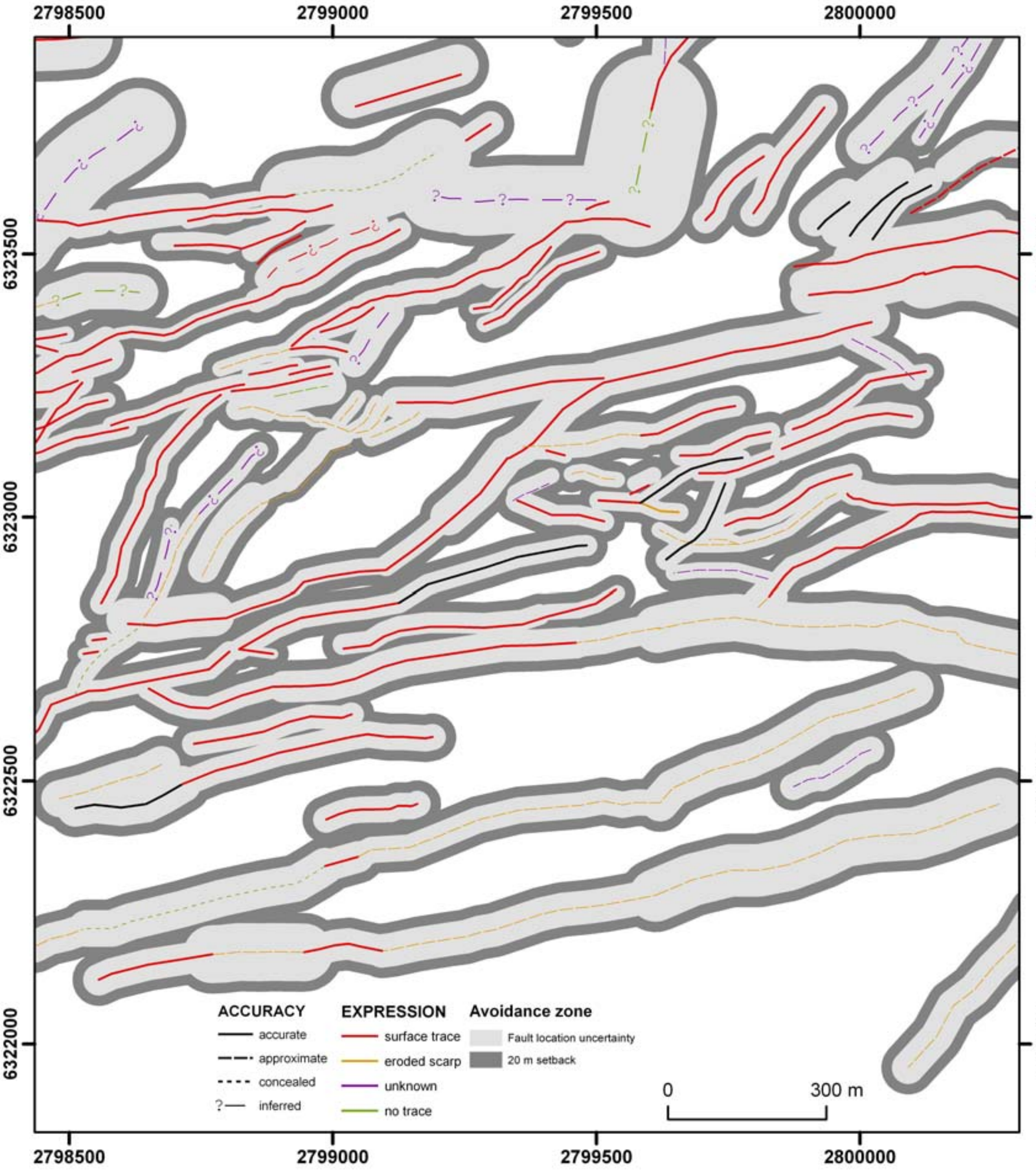

Figure 6 Section of the final map active fault map with final fault avoidance zones.

3.4 Fault attributes

The digital files that we present with active faults of the Rotorua District contain the same attribute fields as the national active fault database (Jongens and Dellow, 2003) with additional attributes relevant to this study. However, within the active faults database not all the attributes have been documented given the large number of active fault traces in the study area. Only a few attribute fields are relevant to this study and for those we have tried to present all the data available. For an entire list and description of attribute fields of the active faults database see Jongens and Dellow (2003).

For planning purposes, relevant fields are those related to the accuracy on fault location (described above) and to the recurrence interval and the recurrence interval class. Of those, the fields “EXPRESSION”, “ACCURACY” and “METHOD_ACC” are part of the active fault database, while “UN_Loc” , UN_map_cap”, “UN_total” and “Ft_avoid_zone” have been added for the purpose of this study. We present attributes for these fields for all fault traces in the study.

Attribute fields related to recurrence interval are “RI” and “RI Class”. The recurrence interval, “RI”, is simply the average time between surface-rupturing earthquakes on an individual fault. These recurrence data generally come from paleoseismic studies that involve excavating trenches and dating of geologic materials that are variably deformed by adjacent faults. Earthquake faulting ‘event horizons’, i.e., the ground surface at the time of faulting, are recognised and dated to establish individual earthquake ages. Then, the amount of time between events is used to estimate the average recurrence interval (“RI”) of faulting. Where there are no paleoseismic data, the recurrence interval may be calculated using the fault slip rate and displacement data, or by a comparison to faults of similar style and activity (Van Dissen et al., 2003). These indirect methods have an increased level of uncertainty compared to methods that permit earthquakes to be dated. The “RI” attribute is a field from the active fault database (Jongens and Dellow, 2003) and it gives an average recurrence interval number. We have added the field “RI_Class” that relates to the classification for building close to active faults defined by Kerr et al. (2003) and that is explained in section 5.0.

4.0 LARGE EARTHQUAKES AND PROBABILITY OF STRONG GROUND SHAKING IN THE ROTORUA DISTRICT

In this section we present the major faults that are mapped within the Rotorua District and give general values of the expected earthquake magnitude associated to the faults and the recurrence time of those events (Fig. 2, Table 1). These data provide an indication of the general activity of faults in the area. Major faults in the Taupo Rift mainly consist of several fault strands that merge in depth into major faults. These are shown in Figure 2. Relevant data associated with major faults and presented in this section are generally used for seismic hazard assessment studies, i.e., assessment of ground shaking hazard. This information is not appropriate to be used for ground deformation hazards in relation to developing close to active faults, because it does not characterise each individual fault trace (see next section for data relevant to planning purposes).

Faults in the Rotorua District area are capable of producing large earthquakes up to Mw 6.9 (Villamor et al., 2001). Previous and current studies have assessed the earthquake potential of some of the active faults in the area for probabilistic seismic hazard assessment (Villamor et al., 2001; Stirling et al., in prep). The 2010 National Seismic Hazard Map (NSHM), which is currently close to completion, represents the most updated compilation of earthquake characteristics of active faults across New Zealand (Stirling et al., in prep). In Table 1, we present the results of the NSHM for faults in the Rotorua District. Some faults have not been characterised yet (some have been defined more recently, Villamor et al., in press, and/or in this report), but they will be characterised in future years and incorporated into future updates of the NSHM.

Faults in the Taupo Rift have high variability of slip rates through time. This variability is caused by high variability of displacement per event (also known as single event displacement) and of recurrence interval (Nicol et al., 2006, 2009). For example, Berryman et al. (2008) present a detail study of the Paeroa Fault where they assess a total vertical slip rate for the fault of 1.5 mm/year and an average fault recurrence interval for large earthquakes (those rupturing the surface) of 4000 years (four ruptures in the last 16,000 years). However, the last two ruptures have occurred within a period of 1500 years, and thus the interval between the ruptures is ~ 700 years. Other active faults of the study area that show high variability in recurrence interval area the Whirinaki Fault (Canora et al., 2008), a strand of the Maleme Fault zone (McClymont et al., 2009) and strands of the Ongahoro Fault (Nicol et al., in press).

For the entire Rotorua District area, Nicol et al. (2009) suggested that recurrence time between successive fault ruptures can vary from 500 to 10,000 years for single fault traces as well as for major faults. They also suggest that fault displacement per event is also very variable (0.4 to 1.5 m for a single faults trace), which implies that the earthquake magnitudes associated with faults are also variable. In other fault belts in the world with faults that are isolated (distant for other faults), faults tend to rupture with more uniform recurrence times and displacements per event. The variability in the earthquake magnitude and recurrence interval for faults of the Taupo Rift is reflected in the maximum and minimum values shown in Table1 for, for example, the Paeroa and the Whirinaki faults.

Nicol et al. (2006, 2009) suggest that this variability is due to fault interactions. These interactions arise because faults are close to each other and the stress generated when one fault ruptures can reach other fault planes and, either increase the tectonic loads and bring them closer to rupture, or decrease the tectonic load and postpone the rupture.

Information similar to that presented in Table 1 together with other datasets such as the seismicity and geodetic data are used to produce probabilistic seismic hazard maps (Stirling et al., in prep). Those maps represent the probability that a certain level of ground shaking will be exceeded in a certain time interval. For example in Figure 7, we present the current seismic hazard map of New Zealand (Stirling et al., 2002). This map (Fig. 7b) shows the ground shaking level (defined as the acceleration that the ground will be subjected to) expected with 10% probability in about 10 years for different regions of the country. These maps are used to evaluate requirements for seismic-resistant design of a site, a region or a country. Depending on the aim of the study, seismic hazard maps can be produced with higher or lower levels of resolution, from site specific studies (to define the seismic loads expected on a new construction) to nationwide (to define nationwide best practise engineering standards).

In the Rotorua District, the level of ground shaking varies from 0.2 to 0.5 g (g or gravitational acceleration = 9.8 m/s^2) for 10% probability in the next 10 years (Fig. 7b). The map of Figure 7 can only be used as a proxy for expected ground shaking levels for the Rotorua area because: a) faults have been simplified to produce a nationwide map; and b) the map only uses information from a few of the faults that were defined at the time of its construction (see Table 1 and Fig. 2 for most updated mapping of active faults; see Fig. 7a for faults used in the 2002 National Hazard Seismic Map). The new map that is close to completion (2010; Stirling et al., in prep) will contain some more faults (Table 1) but not all that have been defined more recently (partly in this study). Although the 2010 map will represent a great improvement from the 2002 version, its resolution will still be too coarse to be used for detail regional scale planning. More detailed regional hazard maps are required to fully understand ground shaking hazards in an area (see e.g., seismic hazard map of Canterbury Region, Stirling et al., 2008).

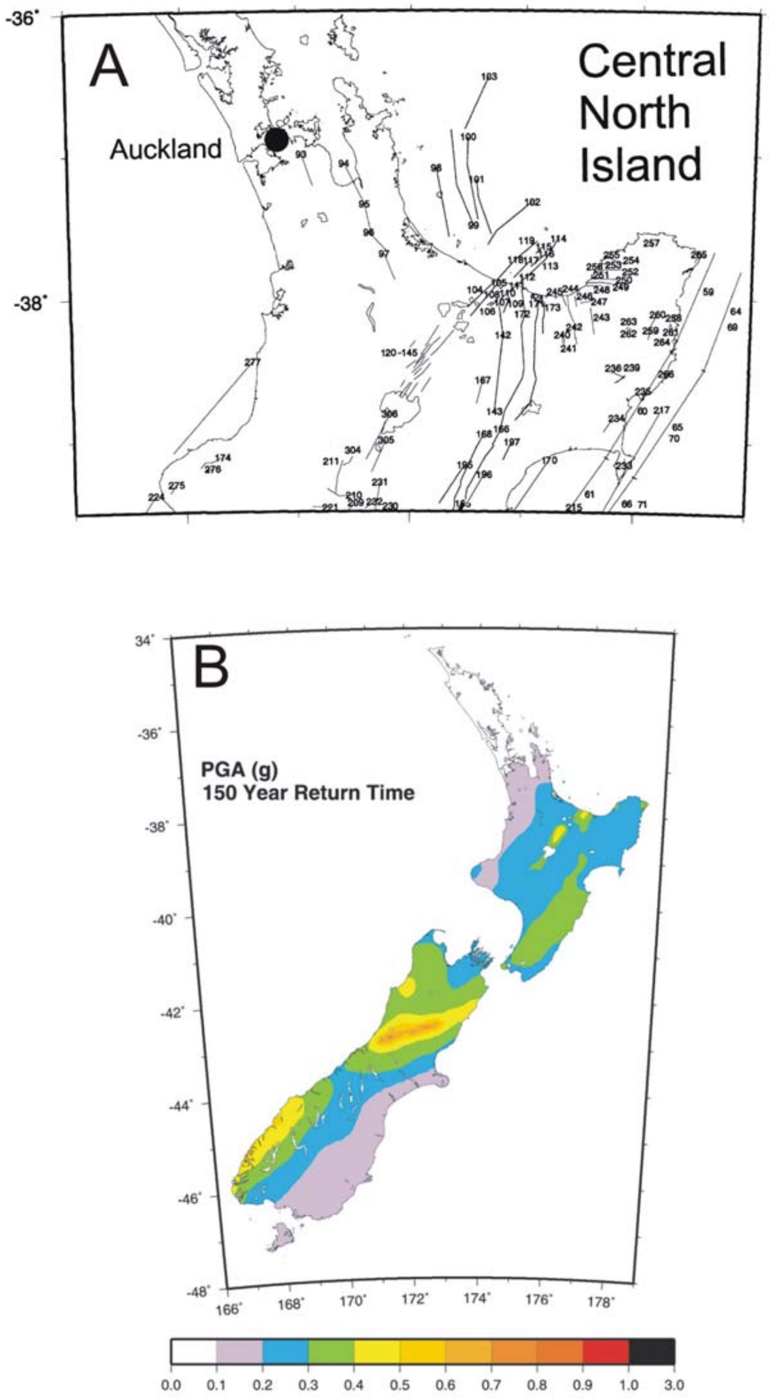

Figure 7 National seismic hazard map of New Zealand (Stirling, et al., 2002). A, Fault sources defined for the 2002 seismic hazard map. B, Peak ground acceleration for a probability of 10 % in 10 years.

5.0 PLANNING FOR DEVELOPMENT OF LAND ON OR CLOSE TO ACTIVE FAULTS IN THE ROTORUA DISTRICT

In this section we present information relevant to building close to active fault lines. For this we follow the recommendations of the MfE Active Fault Guidelines for district planning (Kerr et al., 2003). The three key elements in the adoption of the MfE Active Fault Guidelines for district planning are the fault avoidance zone, the fault "Recurrence Interval Class", and the "Building Importance Category". These elements are put together in the MfE guidelines to define the type of buildings that are, or are not, allowed to be built close to an active fault line depending on fault activity.

5.1 Defining Fault Avoidance Zones

The fault is usually defined as a zone of deformation rather than a single linear feature. The zone may range in width from metres to hundreds of metres (Table 1). Structures sited directly across an active fault, or close to a fault, are in a potentially hazardous area, and could be damaged in the event of fault rupture. As is suggested in the MfE Active Fault Guidelines (Kerr et al., 2003, see also King et al., 2003), a Fault Avoidance Zone is created by defining an additional ±20 m setback around the likely fault rupture zone (or in this case the zone of surface deformation) (Fig. 7).

In the section "Fault Mapping" we have explained in detail how we have defined the area where a fault plane is likely to be located. We have estimated the Fault Avoidance Zones for all the active fault traces in the Rotorua District. The fault avoidance zone is a combination of the: uncertainty in the location of a fault which includes the faults complexity zone ("UN_loc"); the uncertainty in the location of the fault complexity zone with respect to the real map coordinates, i.e., uncertainty in the map scale at which the information has been captured ("UN_map_cap"); and the setback of 20 m recommended by MfE Active Fault Guidelines. In the GIS database attached to this report this attribute field is called "Ft_Avoid_zone" and it is the field that should be used for planning purposes (see Fig .6 and Map 1).

5.2 Recurrence Interval Class

The MfE Active Fault Guidelines define six different recurrence interval classes that define different levels of fault activity (Kerr et al., 2003). These RI Classes with their recurrence ranges in brackets, are: RI Class I (0-≤2000 yr); II (2000-≤3500 yr); III (3500-≤5000 yr); IV (5000-≤10,000 yr); V (10,000-≤20,000 yr); and RI Class VI (20,000-≤125,000 yr). The calculated average recurrence interval for a given fault "RI" is matched against one of these classes. Earthquake recurrence is not believed to be strictly regular, (i.e. some intervals may be shorter; some longer) so an average RI is the best way to treat the hazard related to a given active fault. Of the near to 6000 fault traces mapped only ~ 40 have paleoseismic studies that provide information on recurrence interval class.

5.3 Building Importance Category

In the event of fault rupture, buildings constructed on a fault line will suffer significant stress and could suffer extensive damage. Buildings adjacent to the fault and within the Fault Avoidance Zone may also be damaged. The MfE Active Fault Guidelines define five Building Importance Categories (BCI; Table 4) based on accepted risk levels for building collapse considering building type, use and occupancy. This categorisation is weighted towards lifesafety, but also allows for the importance of critical structures, e.g. schools or post-disaster facilities, and the need to locate these wisely. The Building Importance Category is based on Building Act but was slightly modified for the purpose of the MfE guidelines (Kerr et al., 2003).

Table 4 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

5.4 Relationship between Recurrence Interval and Building Importance Class

The MfE Active Fault Guidelines advocate a risk-based approach to dealing with development of land on, or close to active faults. The risk associated with 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.

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 (Table 5). 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.

Table 5 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).

Recurrence Interval Class	**Average Recurrence Interval of Surface Rupture**	**Building Importance (BI) Category Limitations** (allowable buildings)	
		Previously subdivided or developed sites	**“Greenfield” sites**
I	≤2000 years	**BI Category 1** temporary buildings only	**BI Category 1** temporary buildings only
II	>2000 years to ≤3500 years	**BI Category 1& 2a** temporary & residential timber-framed buildings only	
III	>3500 years to ≤5000 years	**BI Category 1, 2a, & 2b** temporary, residential timber-framed & normal structures	**BI Category 1& 2a** temporary & residential timber-framed buildings only
IV	>5000 years to ≤10,000 years	**BI Category 1, 2a, 2b & 3** temporary, residential timber-framed, normal & important structures (but not critical post-disaster facilities)	**BI Category 1, 2a, & 2b** temporary, residential timber-framed & normal structures
V	>10,000 years to ≤20,000 years		**BI Category 1, 2a, 2b & 3** temporary, residential timber-framed, normal & important structures (but not critical post-disaster facilities)
VI	>20,000 years to ≤125,000 years	**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	
Note: Faults with average recurrence intervals >125,000 years are not considered active			

5.5 Recurrence class for active fault traces in the Rotorua District

While there are several studies that contain abundant information on major fault characteristics, there is only limited information on recurrence interval class for individual fault traces in the Rotorua District. This is because at the surface, most of the major faults of the Rotorua District are expressed as multiple faults strands and thus it would be necessary to study all fault strands in detail to be able to assess the recurrence interval associated with each individual trace.

The fault traces that have enough information to assign a recurrence interval are those with detailed paleoseismic trenching studies. Often this information is used to characterise nearby faults that have no recurrence interval information. However, because fault traces in this area splay and merge in short distances, transfer of information from one trace to another (i.e., assigning attributes obtained in a fault trace to another trace) should be done with care. For example, not all parallel fault traces that comprise a major fault have ruptured in every earthquake associate with the major fault (see e.g., Berryman et al., 2008) and, thus the individual parallel strands will not have the same recurrence interval. Also when transferring the information along the fault trace, it is important to analyse if that fault trace splays into several fault traces. In the case that a trace with paleoseismic data splays into several, it is likely that the splays may have less number of surface ruptures, and thus a larger recurrence interval, than the trace with paleoseismic information.

Paleoseismic studies in the area show recurrence intervals between 500 and 10,000 years for individual fault traces (e.g., Nicol et al., 2006, 2009). This is a wide range and straddles over four different Recurrence Interval Classes to IV. The extremely large density and complex geometry of active fault traces in the Rotorua District and the wide range of recurrence interval class in the area makes it impossible to provide general recommendations on the type of buildings for which surface fault traces should be avoided in the district. Each case would have to be studied individually.

However, we have been able to define the fault avoidance zone for all the mapped traces. In the case of lack of information with respect to the recurrence interval of a single fault trace, we recommend, following the MfE guidelines, the only building with BIC 1 may be permitted within the fault avoidance zones. Otherwise, if buildings with larger BIC are to be built within the avoidance zones defined in this study, a detailed study to locate the fault plane and fault complexity more accurately and to assess the recurrence interval class associated to the fault trace should be required. Detailed studies should consist of exploratory excavations to expose the fault plane and complexity zone. Exposure of the fault plane and associated surface deformation should reduce the area of uncertainty on fault location and allow paleoseismic investigations that can assess the recurrence interval of the fault trace.

The different definition of “active fault” for the Taupo Rift, compared to the rest of New Zealand, does not affect the implementation of the MfE guidelines. We consider that faults that may have ruptured close to 125,000 years ago but not in the last 20,000 years are not active, and thus they are not represented in our active fault map. In principle these faults should not be included in the district active fault maps because we do not consider them active. However, if one were to apply literally the principles of the MfE guidelines, the absence of these faults on the maps would not affect hazards in the area because they are classified as recurrence class VI, and constructions of any type of building is permitted close to this type of fault.

6.0 CONCLUSIONS

We have produced an updated active fault map of the Rotorua District (Map 1) and compiled information that is relevant to active fault hazards. The two main hazards directly related to active faulting and that are likely to occur in Rotorua District are: strong ground shaking and surface deformation. In the RDC area, we identify at least 45 major active faults that are capable of generating large earthquakes (M_w 5.5 to 6.9) that will produce strong ground shaking in the district. Individually, faults in this area rupture with recurrence intervals between 500 and 10,000 years, so the likelihood for ground shaking in the area is high because of large number of faults. In this report, we provide earthquake data (maximum magnitude, slip rate and recurrence interval) for at least half of these faults. These data are of interest for seismic hazard studies in the area.

In the Rotorua District, the level of ground shaking varies from 0.2 to 0.5 g (g or gravitational acceleration = 9.8 m/s^2) for 10% probability in the next 10 years. Information on probability of exceedance of high levels of ground shaking in the Rotorua area is currently contained in a nationwide seismic hazard map (Stirling, et al., 2002). This map provides first order information of seismic hazard in the Rotorua District area. The national maps are usually updated every ~5 to 8 years. The new map to be released late this year will improve the results for Rotorua District but will not contain all information on fault activity in the Rotorua District (most recent studies, including this report have improved the active fault mapping of the area). In addition, the resolution of nationwide is too coarse to be used for District level planning. It is recommended that region specific maps are produced to fully understand the level of ground shaking hazard in the area.

Ground deformation associated with surface fault rupture only occurs at the fault location. However, Rotorua District has the largest density of active faults in New Zealand, and thus large areas of the district are likely to be affected by surface rupture (ground deformation) hazard. The surface expression of major faults in this area is complicated. Multiple parallel fault traces that rupture the surface merge into a major fault in depth. Also, at the surface, faults splay into several fault traces and merge back into few traces along strike. Major faults connect laterally to other major faults though complicated accommodation zones. The high number of fault traces and the complicated faults pattern make it difficult to acquire information on fault rupture hazards for all fault traces.

Although faults can often be located accurately, there is no technology to prevent earthquake damage to buildings built across faults (Kerr et al., 2003). For this reason, we recommend the use of the Ministry for the Environment (MfE) guidelines to avoid building across hazardous faults (Kerr et al., 2003). Faults in this area have recurrence interval classes I to V. This means that they have different levels of activity and have to be assessed individually to be able to recommend the type of construction that should be allowed close to each fault. We provide fault avoidance zones for all fault traces in the district (following the requirements of the MFE guidelines). We recommend that if no further studies are undertaken on a fault line, buildings of Building Importance Category (BIC) 2a to 4 be excluded from the fault avoidance zones given in this report. Paleoseismic investigations are recommended for site specific studies to be able to reduce the width of the fault avoidance zone and /or to characterise the fault recurrence interval and better define the type of building allowed close to the fault.

7.0 RECOMMENDATIONS

The following recommendations will help Rotorua District Council manage the active fault hazards in the district:

- The Rotorua District Council could use MfE guidelines for Planning for Development of Land on or Close to Active Faults to assess and avoid ground deformation Hazards in the Rotorua District.

- The Rotorua District Council could identify areas of fast development and undertake specific fault studies to improve the understanding of ground shaking and ground deformation (surface rupture) hazards for those specific areas.

- The Rotorua District Council could commission a district or region wide probabilistic seismic hazard map to identify areas of high ground shaking. This information can: assist evaluations on seismic resilience of the council; assist emergency response (combined with building vulnerability); and complement other hazard maps, such as landslide and liquefaction.

8.0 ACKNOWLEDGEMENTS

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10.0 GLOSSARY

Epistemic uncertainty	Uncertainty due to variability of input and/or model parameters when the corresponding variability characterization is not available. Uncertainty due to an unknown process or mechanism.
Fault trace	Intersection of a fault with the ground surface; also, the line commonly plotted on geologic maps to represent a fault. In this report, active fault traces are those sections of a fault that have expression on the surface. Several parallel and along-strike fault traces form a major fault.
Geodetic	Refers to the determination of the size and shape of the Earth and the precise location of points on its surface.
Geo-reference	To georeference something means to define its existence in physical space. That is, establishing its location in terms of map projections or coordinate systems. The term is used both when establishing the relation between raster or vector images and coordinates but also when determining the spatial location of other geographical features. Examples would include establishing the correct position of an aerial photograph within a map or finding the geographical coordinates of a place name or street address.
GIS	Geographic Information systems (GIS), geographical information system, or geospatial information system is any system that captures, stores, analyzes, manages, and presents data that are linked to location.
Gravitational acceleration	In physics, gravitational acceleration is the specific force or acceleration on an object caused by gravity.
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. The prevalent method to determine distance to an object or surface is to use laser pulses. Like the similar radar technology, which uses radio waves, the range to an object is determined by measuring the time delay between transmission of a pulse and detection of the reflected signal. LIDAR can create high resolution topographic maps.
LINZ	Land Information of New Zealand. LINZ is a New Zealand government department responsible for land titles, geodetic and cadastral survey systems, topographic information, hydrographic information, managing Crown property and a variety of other functions.
Liquefaction	Soil liquefaction describes the action of soils suddenly moving from a solid to a liquefied state when stressed by some external force.

M_w	Moment Magnitude. A number that characterizes the size of an earthquake, based on measurement of the maximum motions recorded by a seismograph for earthquake waves of a particular frequency. Scales most commonly used in the Western United States are (1) local magnitude (ML) (commonly referred to as "Richter magnitude'-), (2) surface-wave magnitude (MS), and (3) body-wave magnitude (mb). None of these scales satisfactorily measures the largest possible earthquakes because each relates to only certain frequencies of seismic waves and because the spectrum of radiated seismic energy changes with earthquake size. The recently devised moment magnitude (M_w) scale, based on the concept of seismic moment, is uniformly applicable to all sizes of earthquakes.
Ngakuru graben	A tectonic graben is a depressed block of land bordered by parallel faults. This type of tectonic structure is present in the Ngakuru area, south of Rotorua.
Orthophoto	An orthophoto or orthophotograph is an aerial photograph geometrically corrected ("orthorectified") such that the scale is uniform: the photo has the same lack of distortion as a map. Unlike an uncorrected aerial photograph, an orthophotograph can be used to measure true distances, because it is an accurate representation of the Earth's surface, having been adjusted for topographic relief[1], lens distortion, and camera tilt.
Paleoseismic	Refers to earthquakes recorded geologically, most of them unknown from human descriptions or seismograms. Geologic records of past earthquakes can include faulted layers of sediment and rock, injections of liquefied sand, landslides, abruptly raised or lowered shorelines, and tsunami deposits.
Quaternary	The Quaternary Period is the most recent of the three periods of the Cenozoic Era in the geologic time scale. It follows the Tertiary Period and spans 2.588 ± 0.005 million years ago to the present.
Seismicity	The geographic and historical distribution of earthquakes.
Setback zone	A strip along a fault, where certain development activities are recommended to be prohibited or significantly restricted.
Tectonic extension	“Tectonic” refers to crustal rock-deforming processes that affect relatively large areas. Extensional tectonics is concerned with the structures formed, and the tectonic processes associated with, the stretching of the crust or lithosphere.
Volcanic arc	A volcanic arc is a chain of volcanoes positioned in an arc shape in map view. Generally, they are formed as an oceanic tectonic plate subducts under another tectonic plate and produces magma at depth under the over-riding plate. The magma ascends to form an arc of volcanoes parallel to the subduction zone.