Marlborough District Council

REGULATORY DEPARTMENT

Marlborough District Seismic Hazard Investigation Programme – Phase 1

Identification of active fault traces in Marlborough District
A Report prepared by Geotech Consulting Ltd

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Foreword

Geotech Consulting Ltd is retained by Marlborough District Council to investigate and report on seismic hazards in the District. The Phase 1 report is primarily concerned with locating active fault expressions and recording these in a manner useful in the District Plan context. The Report well canvasses the issues surrounding the accurate fixing of surface expressions and display's the information at a small scale. There are finer detailed maps available on request, these require specialist interpretation especially in field identification and explanation of the effects of movement in a particular locality.

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March 2003

Report prepared by GEOTECH CONSULTING LTD

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Prepared for:

Marlborough District Council

Refer to this report as:

Marlborough District Seismic Hazard Investigation Programme

- **Phase 1: Identification of active fault traces in Marlborough District**

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March 2003.

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IMPORTANT NOTES

Accuracy of Active Fault Maps

The maps contained in this report (and the associated GIS files) are essentially regional in scope and detail. While every effort has been made to accurately locate the active fault features there are a number of factors which inevitably conspire to reduce the map location accuracy. We outline the various reasons for this in section 2.2 of the main report. In general we do not recommend reliance on these maps at scales any more detailed than 1:50,000, and even at this scale the maps should be viewed as indicative that an active fault is located in the general vicinity, which may require more site specific location and assessment.

We emphasise that the maps and associated GIS files accompanying this report **are not suitable** for the detailed location of active faults for land development and land-use zoning purposes. They should not be viewed as a substitute for site-specific investigations and/or geotechnical engineering assessments for any project. Qualified and experienced practitioners should assess the site-specific hazard potential, including the potential for damage, at a more detailed scale.

IDENTIFICATION OF ACTIVE FAULT TRACES IN MARLBOROUGH DISTRICT

SUMMARY

Active faults are widely distributed across Marlborough District. The most active of these faults have ruptured the ground surface many times over the past 10,000 years of geological time. Surface rupture of active faults creates *fault traces,* that are apparent at the ground surface, and can be mapped as discontinuous linear features across the landscape ("fault lines").

If a building is constructed across an active fault trace there is potential for structural damage and injury of the building occupants if the fault rupture again, particularly where ground displacements could involve virtually instantaneous horizontal movement of the order of several metres (the expected displacement for the next rupture of the Wairau section of the Alpine Fault is 3.4 – 6.6m). Surface ground rupture of faults will be associated with strong earthquake shaking that has a widespread and serious effect over a much wider area than just the fault trace. This report is not intended to review and evaluate the wider issue of seismic hazard, but focuses on the specific hazard associated with potential ground rupture at active fault traces.

The Resource Management Act requires territorial authorities to undertake as one of their functions "the control of any actual or potential effects of the use, development or protection of land, including the implementation of rules for the avoidance or mitigation of natural hazards". Ground rupture along active fault traces is a natural hazard that can generally be avoided or mitigated providing that the location of the fault trace is well established at the time of land development planning and any subsequent building activity.

We have undertaken a digital GIS compilation of the relevant location information for known active faults in Marlborough District. We have focussed particularly on the

Wairau section of the Alpine Fault. This active fault trace enters the district in the Upper Wairau Valley, near Tophouse Saddle, and forms a discontinuous surface fault trace virtually all the way to Renwick. The continuation of this feature is also marked by a more subtle and poorly defined fault trace east of Spring Creek near Cloudy Bay.

Unlike many of the other major active faults in Marlborough District, the Wairau section of the Alpine Fault passes through developed and accessible farm land in the Wairau Valley and it is seldom more than a few hundred metres from SH 63. Because of increasing development pressure in these areas, it is timely to have reliable location information for this important feature. Unfortunately our checks of the currently available location information indicate that previous mapped locations of the fault on average are only accurate to within ±75m. Although we have now corrected the map location of faults at the localities that have been checked with GPS resurvey, it is a major undertaking to improve accuracy along the entire length of the fault. Furthermore, the reality of ground surface rupture in earthquakes is that some ground deformation extends over a wider zone of a similar general order. We recommend that planning maps show a wide zone for the fault location to allow for the potential location inaccuracies, and to more accurately reflect the possible extent of wider ground deformation.

In addition to the Wairau section of the Alpine Fault, we also have gathered location information for the Awatere and Clarence Faults, both of which are major active structures in the central and southern parts of the district. The Awatere Fault trace is close to areas of significant potential development in the eastern Awatere Valley but underwent surface rupture in the 1848 Marlborough Earthquake (approximately 7m of horizontal ground movement). Given the likely return period for fault rupture on this structure (600 - 2500 years) the risk of rupture in the next 50-100 years appears to be low. The Clarence Fault has a higher risk of rupture over an equivalent period but this fault trace is generally more remote, and is well away from development pressure. There are also many smaller faults scattered across the district with generally more poorly understood rupture histories. We have gathered as much location information as is currently available with respect to these smaller active features but we expect more useful data will result from future geological research. For this reason we recommend regular future updates of the GIS active fault compilation that we have provided with this report.

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IDENTIFICATION OF ACTIVE FAULT TRACES IN MARLBOROUGH DISTRICT

1) INTRODUCTION

1.1 Study brief and report objectives

The work undertaken in this first phase of the Marlborough District Seismic Hazard Investigation programme is essentially a compilation of spatial location information for the main active faults in Marlborough District, and in particular the Wairau section of the Alpine Fault. This information is required by Marlborough District Council to carry out their statutory functions in managing and mitigating the impacts of potential natural hazards. This phase of work is aimed at providing information to assist the mitigation of the potential impacts of surface ground rupture along active fault traces, as opposed to the wider hazard of earthquake shaking and it's associated secondary effects (liquefaction, landslides, subsidence etc).

This report focuses on the location and description of known active faults that could potentially rupture the ground surface, and is not intended as a compilation of information on all possible earthquake sources. Earthquakes sufficient to cause widespread damage in Marlborough District can also result from earthquake sources outside the district, including the offshore continental shelf. A probabilistic seismic hazard study is planned for a subsequent stage of the Marlborough District Seismic Hazard Investigation programme to address the wider issue of the potential earthquake shaking.

1.2 Definitions of active faults, fault traces, and concepts of ground rupture in earthquakes

Faults are fractures in the earths crust along which there has been significant displacement of the two sides relative to one another. Depending on the sense of this relative displacement, faults can be divided into dip slip faults (i.e. vertical movement up or down the dip [inclination] of the fracture), and strike-slip faults where the relative movement is horizontal and along the line (strike) of the fault. In reality most faults are dominantly dip-slip or strike-slip but involve some form of oblique movement that is a combination of the two main types.

Figure 1 shows some of the wide range of dip-slip and strike-slip fault types and makes a further distinction between dextral and sinistral strike-slip movement. In the central and upper South Island most strike slip movement is dextral i.e. movement of the opposite side of the fault towards the right[1].

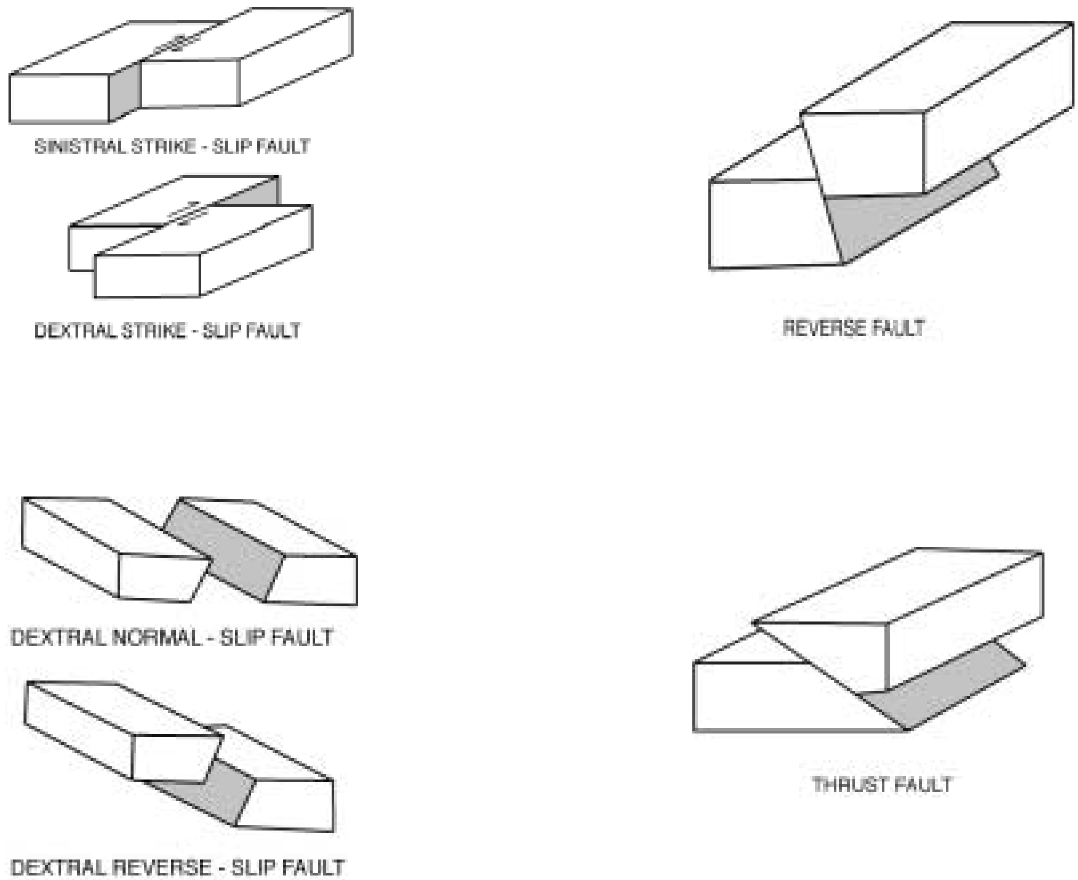

Figure 1: The most common types of fault.

[1] This convention applies regardless of which side of the fault the viewer is standing.

It is important to note that in New Zealand we have no faults that are continuously moving (at least in the upper crust i.e. depths from the surface to 5 – 8 km) and continuous fault creep movement at the ground surface is rare anywhere in the world.[2] Instead New Zealand faults undergo an episodic stick-slip pattern of relative movement. This movement releases elastic strain which is stored in the crust on each side of the locked active fault during "locked" period and this energy generates **earthquake shaking**. Earthquake shaking is the most serious widespread and destructive component of active fault movement but it presents a wider and more regional hazard that is less site specific than the hazard from ground rupture.

This report and map compilation is not intended to address the more general issue of earthquake shaking hazard in Marlborough District.[3] This active fault map and report is intended to provide information that allows mitigation of the site specific hazard created by the potential for ground rupture at active fault traces.

Fault traces are the intersection of a fault plane with the ground surface and can frequently be recognised by evidence of past displacement of the ground surface. Because over geological time the ground surface is frequently being either eroded or buried by sediment, fault traces are a feature of faults that are geologically active (refer discussion of activity further below). Fault traces frequently take the form of a **fault scarp** or **fault furrow**. Along any particular active fault there are normally young parts of the ground surface, such as sediment in active river fans, that is too recent to have been affected by past episodes of ground displacement (i.e. deposition of the sediment post-dates the most recent episode of fault displacement) Because of young deposits it is common for fault traces to die out and restart along their length, despite the subsurface continuation of the active fault. Fault traces can also die out where they are buried under thick soft sediments that pre-date the last movements, but are thick enough to absorb and mask the deeper movement, so that no new fracture propagates to ground surface.

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[2] The principle examples of continuous fault creep is confined to a relatively short section of the San Andreas Fault in central California.

[3] The wider issue of seismic hazard will be addressed in later stages of the Marlborough District Seismic Hazard Investigation programme.

Active Faults are faults that are considered likely to undergo renewed movement within a period of concern to society. Unfortunately this “period of concern” tends to vary between different classification systems and national conventions. The original New Zealand active fault classification system was that proposed and adopted by the New Zealand Geological Survey for various older geological maps (for example Lensen, 1976). This considered active faults to be faults with evidence of repeated movement in the last 500,000 years. This may be a valid “period of concern” to geological society but it is not relevant in most planning applications.

United States conventions define active faults as faults with evidence of movement in the Holocene geological epoch (the last 10,000 years) and this is a more realistic period to use as a guide to future risk.

We outline below a recent classification system for active faults proposed by Pettinga et al. (1998) that proposed three activity classes.

- Activity Class I: faults which cut or displace Holocene surfaces (i.e. younger than 10,000 years old)
- Activity Class II: faults which cut or displace deposits of the late last glaciation (i.e. younger than 25,000 years old), and where Holocene deposits are not displaced or proven displaced.
- Activity Class III: faults that are considered probably active but do not clearly affect geomorphic surfaces less than 25,000 years old.

Generally speaking the active faults of concern in Marlborough District are Class I faults (i.e. movement, and frequently repeated movement, in the Holocene). Because of regular rejuvenation these most active faults are the easiest to recognise in the landscape, and as a result they have generally been adequately mapped by geological researchers regardless of the scale of their field area. In the previous geological mapping of the district there has seldom been a distinction made between the various fault activity classes, because the paleoseismic data required to make this classification is not available. Unfortunately it may take many more years of more detailed geological mapping projects to recognise less active Class II and III faults because, in a rapidly changing landscape such as Marlborough, their traces are so quickly covered and obscured. However, from a planning perspective it could be reasonably argued that only Class I active faults should be included as “no-build corridors”, even though bad luck could still lead to the reactivation of a Class II or III fault during a new buildings life time after more than 10,000 years of inactivity.

1.3 Relevance of active fault traces to planning, building control and natural hazard mitigation

The Resource Management Act 1991, including the subsequent 1994 amendments, requires territorial authorities to undertake as one of it’s functions “the control of any actual or potential effects of the use, development or protection of land, including the implementation of rules for the avoidance or mitigation of natural hazards”.

Natural hazards are defined in the definitions section of the Act as “ any atmospheric or earth or water related occurrence (including earthquake, tsunami, erosion, volcanic and geothermal activity, landslip, subsidence, sedimentation, wind, drought, fire, or flooding) the action of which adversely affects, or may adversely affect human life, property, or other aspects of the environment.”

Fault displacement at an active fault scarp is a natural hazard that is not specifically mentioned in this definition but is clearly included by virtue of it being an “earth related occurrence”, the association of fault rupture with “earthquakes”, and the common occurrence of “subsidence” associated with ground surface movement of one, or other side of the fault.

The adverse affect of ground displacement at an active fault trace arises from instantaneous horizontal or vertical relative ground movement of the order of several metres (for example 3.4 – 6.6 m of dextral horizontal displacement is expected for the next rupture of the Wairau section of the Alpine Fault). This movement can break apart and extensively damage any structure that straddles the fault plane, and in some unlucky circumstances, the ground rupture can lead to injury or even death of the building occupants.

There is also nearly always a wider zone of associated secondary movement near the main fault trace that takes the form of ground buckling, tilting and subsidence as the surrounding area “adjusts” to accommodate the primary movement at the main fault trace. These secondary movements are generally around 10-20% of the magnitude of the main movement, but for large faults this can still equate to vertical and horizontal displacements in the order of 0.5 to 1m. The width of this zone varies unpredictably but is frequently 50 – 100m each side of the main fault movement.

2) THE GIS ACTIVE FAULT MAP COMPILATION

2.1 Sources of data in the GIS active fault map compilation

We summarise in the table below the data sources for our GIS active fault map compilation, with the most extensive and/or reliable reference shown in bold.

Fault and *fault section*	Data Sources
Wairau, *west end*	**Johnston,1990**; Lensen, 1976; Fougere, 2003
Wairau, *central*	**Lensen, 1976**; Zachariasen et al. 2001
Wairau, *Bedford Road & Renwick*	**Lensen, 1976**; Begg and Johnston, 2000; This study, based on 1943 NZRAF photography for some local areas.
Wairau, *Spring Creek subsection*	Grapes and Wellman, 1986; **This study**, based on re-examination and more accurate location of the trace as revealed in the 1967 NZRAF air photos used by the original authors and Brown, 1981 (swamp location along trace).
Awatere, *eastern section including Vernon Fault*	**Benson et al. 2001**; Begg & Johnston, 2000; Pettinga et al. 1998.
Awatere, *Molesworth*	**Pettinga et al. 1998**; McCalpin, 1996.
Clarence, *eastern*	**Pettinga et al. 1998**;
Clarence, *western + Elliot and Fowler*	**Pettinga et al. 1998**.
Other faults; Waihopai, Hog Swamp, London Hills, Waikawa.	**Townsend, 2001; Townsend & Little, 1998;** Pettinga et al. 1998; Lensen, 1962; Horrey,1989; McManus,1996.

Table 2.1: Data sources in the GIS compilation of active faults in Marlborough District (main references in bold).

As is implied in Table 2.1, new work in this phase of the Marlborough District Seismic Hazard Investigation has been confined to field checks of key areas of the Wairau, Awatere and Vernon Faults (including some GPS locations), and improved location of the Spring Creek subsection of the Wairau section of the Alpine Fault. A subsequent phase of field work is intended to further improve mapping detail of the Wairau section of the Alpine Fault in the Spring Creek and Renwick areas, in conjunction with paleoseismic trenching of the fault trace.

2.2 Accuracy of active fault trace location

We make an important distinction here between field location accuracy and the accuracy of the original active fault maps on which this compilation is based.
Generally the accuracy of the field location of active faults is dependent on the extent to which the fault scarp is obvious and clearly visible on the ground (i.e. confidence increases for a steep and sharp scarp as opposed to a wide zone of buckling). Confidence in field location is indicated by the terms “definite”, to “approximate”, or “inferred”. Recent and regularly rejuvenated fault scarps always appear more obvious in the field than older and more weathered scarps associated with less active faults. The accuracy of field location varies according to field location category and activity classes as outlined in Table 2.2 below.

Accuracy	Activity Class		
	Class I	Class II	Class III
Definite	±10m	±25m	±75m
Approximate	±50m	±75m	±200m
Inferred	No surface expression; location assumes that the adjacent segments of the identified fault may be linked, and a connection is drawn along strike by projection or inference.		

Table 2.2: Field location accuracy for active fault traces.

As note earlier, most of the active fault location data that is available for Marlborough District applies to Class I active faults, or faults for which no class has been assigned (and it has to be assumed these are Class I). Therefore for most of the district the Class I field location error applies. However, unfortunately in addition to the errors that arise in our ability to accurately identify the faults in the field, there is the generally greater inaccuracy that arises from errors in existing map presentations of the various categories of field location. These errors increase where the map presentations are at less detailed scales (for example original location data at 1:250,000 as opposed to more detailed 1:50,000 data).

To make some reasonable assessment of the combined errors for the areas where we have the greatest detail (i.e. original data of Lensen ,1976 at 1:50,000 or better) we have selected a range of locations along definite traces of the Wairau section of the Alpine Fault. We also have digital fault information in this area (in some cases based on the earlier Lensen,1976 work) that has been compiled for the GIS database associated with the recent 1:250,000 Wellington geology map (Begg and Johnson, 2000). We have designated the area for which we have this most detailed data Zone A on our various maps and figures (refer Figure 4).

At ten locations along fault strike we have compared the field location of the fault trace obtained by new GPS relocation (at sub-metre accuracy after post- processing) to the previous plotted position on the best available existing maps. We found errors that varied up to ± 90m (Lensen, 1976) and ± 100m (Begg & Johnston, 2000) with a mode around ± 50m (Lensen, 1976) and ± 30m (Begg & Johnson, 2000).

Accuracy	Accuracy Zone		
	Zone A	Zone B	Remaining Area
Definite	±75m	±125m	±175m
Approximate	±125m	±175m	±250m

Table 2.3: Overall average location accuracy of source maps based on GPS relocations. Note this is indicative only and at some locations errors could be larger.

Based on these results, in Table 2.3 we outline the potential errors in Zone A, and appropriate potential errors for the other accuracy zones (Zone B and the remaining area), where the data comes from 1:100,000 and 1:250,000 sources respectively.

For printouts from the GIS we recommend that the fault line thickness be selected to match the appropriate errors, and in this manner the wide lines will define a wide “fault zone”. As well as reflecting potential location errors, these wide zones have the added advantage of reminding the end-user that the fault rupture will not just affect a narrow line, but is also likely to cause some ground deformation over a wider zone with a similar order of magnitude to the location error. In Table 2.3 we indicate the line thickness that matches these errors at a range of map scales.

Accuracy	Map Scales		
	1;50,000	1:25,000	1:10,000
±75m	3mm	6mm	15mm
±125m	5mm	10mm	25mm
±150m	6mm	12mm	30mm
±175m	8mm	14mm	40mm
±250m	10mm	20mm	50mm

Table 2.4: Appropriate recommended line thicknesses to represent the potential location errors of active fault traces in the GIS database at a range of map scales. Note that the widths are twice the numerical error because of the plus or minus.

2.3 Completeness of the fault trace data and the suggested regularity of future updates

At the time of writing we are confident that there is no significant new work on the location or interpretation of active fault traces in Marlborough District of which we are unaware. We have endeavoured to obtain the best currently available active fault location information but more research work, at progressively greater detail, will inevitably occur. There is also a new 1:250,000 geology of Kaikoura Map sheet planned for publication in the next few years which will compile new information from a wide range of sources, including new field mapping. We recommend regular future updates of the GIS database, initially on a five yearly interval (i.e. post the publication of the Kaikoura sheet), and then at further intervals to be determined.

3 THE MAIN ACTIVE FAULTS IN MARLBOROUGH DISTRICT

3.1 General description of active earth deformation in Marlborough District

Marlborough District encompasses a region of widespread active earth deformation that is associated with the main boundary zone between the Australian Plate and the Pacific Plate. Figures 2 & 3 show the onshore plate boundary through the central and northern South Island

The Alpine Fault forms the main plate boundary through the central South Island but the character of the fault changes along its length as plate motion is partitioned onto other structures, and in particular the four main strands of the Marlborough Fault Zone that connect to (or coalesce with) the Alpine Fault in the Marlborough area.

The central Alpine Fault is oblique to the plate motion, and in addition to the dominant dextral horizontal strain, there is a significant component of shortening at the plate boundary. The component of shortening results in uplift on the southeast side of the Alpine Fault and this is responsible for the formation of the Southern Alps. In most of the central area the Alpine Fault marks the western boundary of the Southern Alps range front.

There is a progressive change in fault strike associated with the “big bend” of the Alpine Fault between Springs Junction and Lake Rotoroa. Geological mapping of the bends area (Rose 1986; McLean 1986) shows low angle thrust faulting to the west of the Alpine Fault, involving slivers of Mesozoic and older rock assemblages, thrust over a Pliocene foreland basin that has been filled with schist debris shed across the fault from the uplifted Southern Alps adjacent to the Marlborough Fault Zone.

The Marlborough Fault Zone lies to the east of the north Alpine Fault and comprises a major system of northeast trending strike-slip faults that include the Hope, Clarence, and Awatere Faults as well as the continuation of the Alpine Fault into the Wairau valley. Marlborough District includes all of the two most northern faults of the

Marlborough Fault Zone i.e. the Awatere Fault, and the Wairau section of the Alpine Fault [4]. Marlborough District also includes significant sections of the Clarence Fault. The faults in the Marlborough Fault Zone are oriented approximately parallel to the plate motion vector and because of this the sense of fault movement on these faults is generally strike-slip (i.e. horizontal displacement) over most of their length.

In the section that follows we describe the main strands of the Marlborough Fault zone that are located within Marlborough District (i.e. the Wairau section of the Alpine Fault and the Awatere and Clarence Faults) and then briefly note some of the other more minor Class 1 active faults that are located within the district. Figure 4 is a summary map of all the active faults located in the district and we include more detailed maps for the main fault strands as we discuss these in more detail in the sections that follow.

3.2 The Wairau section of the Alpine Fault

The Wairau section of the Alpine Fault presents the greatest potential ground rupture hazard in Marlborough District. This hazard is in part due to the location of the active fault trace in middle of the densely populated, and rapidly developing, lower and middle Wairau Valley. However the high hazard is also because of the past earthquake history that suggests there is a relatively high likelihood of a future fault rupture within conventional planning periods (i.e. the next 50 -100 years). In the section below we describe the fault location, and then review the evidence that indicates that there is a significant potential for future rupture.

Description of the Wairau section of the Alpine Fault trace.

The Wairau section of the Alpine Fault enters the western Marlborough District near the Tophouse Saddle and SH 63 (Figure 5). For ease of geographic reference in our description below we divide the fault into three subsections.

Wairau Valley subsection

[4] The Wairau section of the Alpine Fault northeast from Lake Rotoiti used to be called the Wairau Fault but current geological nomenclature more correctly classifies this as a section of the Alpine Fault

See Maps of Marlborough District showing known active fault traces of relevance to planning and consents and map of the active trace of the Wairau section of the Alpine fault

Immediately northeast of Tophouse Saddle the Wairau section of the Alpine Fault forms an intermittent narrow and distinct fault trace striking SW-NE that offsetts old river terraces of the Upper Wairau River. For considerable distances the locus of recent fault movement has been in the modern river bed, effectively removing and disguising geomorphic evidence of past fault movement, so that the fault appears on the maps as a dashed line.

At the Branch River there is the first significant length of continuous fault trace (8km) before the fault once again briefly follows the modern river and approaches the Wye River fan. The fault trace recommences immediately southwest of the Wye River, but is obscured by modern gravel at the Wye River mouth. The fault trace then reappears immediately northeast of the Wye River to continue as a virtually continuous fault scarp. At Hillersden the fault trace crosses SH 63 and north-eastwards from this point the fault remains consistently southeast of the State Highway (Figures 6 & 7). The fault trace bifurcates (splits) into two fault traces approximately 6km northeast of Hillersden (near the settlement of Wairau Valley). The fault orientation (strike) also changes slightly at this point from approximately 075^{o} to 070^{o}.

The southern most fault trace generally stays close to the hill country south of SH 63, and in part enters the hill margins in the vicinity of Centre Valley and Marchburn, to continue to the western Waihopai River valley where there are some associated secondary fault traces. The fault trace continues east through farmland on the eastern side of the Waihopai River towards Renwick, and in places has a broad zone of associated ground deformation and secondary faulting, generally on the south side of the main trace. At Renwick the clear surface expression of past fault movement is lost as the fault approaches the Omaka River.

The northern most fault strand in the Wairau Valley subsection enters the modern Wairau River bed at Black Valley stream and it is likely that this connects at depth to the Bedford Road subsection described below.

Figure 6: The active trace of the Wairau section of the Alpine Fault in the middle Wairau Valley near Hillersden (028/430553), viewed looking down the valley (east).

Figure 7: The same fault trace 200m east of Figure 6, this time viewed from SH 63 looking north.

Bedford Road subsection

Two short sections of fault trace are apparent on the high terrace immediately north of SH 63 and crossing Bedford Road (the small road due north to Seresin Winery). The most prominent fault trace ends at the high terrace edge while the more subtle south trace appears to progressively die out. Recent grape planting has largely obscured the surface expression of both of these fault traces.

Spring Creek subsection

For many years there was no other trace of the Wairau Fault recognised in the Wairau Valley. This was attributed to the increasing thickness of the alluvium at the east end of the valley that presumably has absorbed and masked past offsets. However, Grapes and Wellman (1986) describe a fault trace that is only apparent in one set of high altitude aerial photographs taken by the NZ Airforce in 1967. In these photographs the fault trace has a strike (orientation) of 065 degrees and appears as an ill-defined but relatively straight line connecting some local areas of subsidence and more swampy ground. There has been farming and land modification in many of these areas and this may in part have masked the fault trace. On the ground the trace is very hard to recognise with any confidence, and we have shown the trace as a dashed line through most of the Spring Creek area. Only at the beach ridges near the old Marshlands School can the trace be located as a conventional fault scarp where it is approximately 1.5m high (up to the NW) with a possible horizontal dextral fault offset around 8m.

Estimates of long term slip rate on the Wairau section of the Alpine Fault.

Concepts of fault offset and long term slip rate

During an earthquake an active fault ruptures in a discrete single movement (fault offset) and the energy of the earthquake shaking represents the release of stored elastic strain that has built up over the preceding period over which the fault has been “locked”. The hazards that result are the fault offset of the ground surface at the surface fault trace (the main concern of this report) and the more widespread impacts associated with the earthquake shaking that radiates many hundreds of kilometres from the actual fault source. In each discrete earthquake event the corresponding fault offset broadly equates with the amount of elastic strain that has accumulated during the “locked” stage, so that following the earthquake the fault returns to a stress free state. For a geologically mature[5] active fault the interval between successive earthquakes (the *recurrence interval* or *return period*) tends to become more regular and the recurrence interval is the least for the most important active faults that accommodate the highest amount of geological strain.

Although fault movement is episodic, and only occurs over a few seconds during the actual earthquake, geologists and seismologists use the concept of *long term average slip rate* to compare the significance and relative activity of a fault. Unfortunately the use of the word “slip” in this way often confuses laypeople who assume the fault is continually “slipping” which is not the case.

The central Alpine Fault near Franz Josef has an estimated long term average slip rate of 25-30mm/yr[6] which is the highest for any single fault in New Zealand. This high average slip rate means elastic strain builds up on the fault relatively quickly and the corresponding return period between earthquakes is short (100 -300 years). Most other faults have significantly lower average slip rates and longer recurrence intervals between successive earthquakes. It should be noted that although an active fault may have a slip rate as low as 1mm/yr it can still represent a significant potential earthquake source if the last earthquake was a sufficiently long time ago and the limit for accumulated elastic strain is approaching.

[5] Faults evolve over geological time tending to smooth aspherities and irregularities on the fault plane so that under a given stress regime the interval between successive earthquakes becomes more regular c.f. Wesnousky, 1989 & 1990.

[6] Refer for example to the collated data presented in Yetton (2000)

Long term average slip rate for Wairau section of the Alpine Fault

The first detailed estimates of long term slip rate on the Wairau section of the Alpine Fault comes from the work of Lensen (1968) and Lensen (1976). Lensen (1976) notes the consistent dextral offset of approximately 70m on many different geomorphic markers located on the so-called Wairau Surface (Wellman, 1955). This extensive aggradation outwash surface can be followed almost continuously from the Tophouse area down the Wairau Valley to Renwick.

Lensen correlated this surface with the penultimate advance of the last glaciation and estimated an age of approximately 18,000 years. This corresponds to a slip rate estimate of 3.9 mm/yr. Suggate (1988) also supports this correlation and approximate age, based mainly on the similar extensive Speargrass surface of this age in the adjacent Buller catchment. Lensen (1968 &1976) also outlines his reasoning for estimating the amount of horizontal offset of the fault in each successive earthquake (*single event displacement*). The smallest observed fault offsets are in the order of 3.4 - 6.6m and most of the larger offsets appear to be some combination of repeated movements of approximately this order.

Grapes and Wellman (1986) take an alternative view of the age of the Wairau surface, suggesting this could be as young as 10,000 years old, and the slip rate as high as 7mm/yr. However an age as young as this is unlikely in view of the current accepted chronologies for the most recent glacial advances (for example Suggate, 1990). More correctly Grapes and Wellman (1986) point out that Lensen (1976) has discounted the possibility that the surface may be associated with the most recent glacial advance and therefore be 14 – 15,000 years old. If the Wairau surface is around this age then the long term slip rate increases slightly from the Lensen (1976) estimate to 4.7 – 5 mm/yr.

Kneupfer (1988) and Kneupfer (1992) describe the results of weathering rind dating of various fluvial surfaces in the Branch River area and the Wairau Valley. Kneupfer suggests a slip rate of 3-5mm/yr is a reasonable estimate.

More recently Zachariasen et al. (2001) estimate slip rates over the last four thousand years, based on displaced features and radiocarbon ages in trenches excavated across the fault near the settlement of Wairau Valley. Their estimates are in the order of 4 – 5mm/yr and the authors note the consistency with other studies. They also note evidence for single event fault offsets of between 5 and 7m.

Most recently Fougere (2002) has undertaken weathering rind dating of fault offset fluvial surfaces in the upper Wairau Valley near Tophouse and combined this data with older offset glacial geomorphic markers. He derives a long term slip rate of around 4.2mm/yr but with a significant potential error margin (±1.4mm/yr). At one site there is a horizontal fault offset of between 3.9 and 4.9m that he infers is the most recent earthquake offset which is broadly consistent other estimates (i.e. 3.4 - 6.6m Lensen[1968] and 5-7m, Zachariasen et al. (2001)])

In summary most studies conclude that the long term slip rate on the Wairau section of the Alpine Fault is within the range of 3.5 – 5.5 mm/yr and the displacements in each successive earthquake are in the range of 3.3 - 7.0 m, but most probably around 5 -6m.

Past earthquake rupture history of the Wairau section of the Alpine Fault

There have been no historical earthquake ruptures of the Wairau section of the Alpine Fault. Although Eiby (1980) suggests the 1848 Marlborough earthquake was centred in the Wairau valley and involved movement of the Wairau section of the Alpine Fault, subsequent authors refute this (for example Wellman & Grapes, 1986; Grapes *et al.* 1998; Benson et al. 2001). Part of the evidence refuting historical rupture of the Wairau Fault is the existence of ancient beach ridges that have not been faulted at the coast at the termination of the Spring Creek subsection of the fault trace. This trace dies out approximately 700m landward of the modern beach line and, while natural die out of the fault trace can not be entirely ruled out, it is more likely that this pattern arises because there had been no fault rupture since deposition of this beach sediment. The age of the beach sediment has been estimated by Wellman & Grapes (1986) by making assumptions regarding shoreline progradation rates. They suggest that the most recent 700m of beach sediment in this area has accumulated in the last 800 years and on this basis the authors estimate that the last rupture of the fault was more than 800 years ago. However, because of the absence of reliable age data at the point at which the fault trace ends, this is a substantial approximation and the Wellman & Grapes (1986) this estimate of the lapsed time since the last fault surface rupture should be treated with caution.

Zachariasen et al. (2001) outline the results of paleoseismic trenching investigation of the Wairau section of the Alpine Fault. They trenched at three locations (designated Wadsworth, Dillons and Marfell) approximately 50 km northeast of the Tophouse trench of Yetton (2002)[discussed below]. One of these trenchs (the Wadsworth Trench) provides good data that suggests that the most recent earthquake rupture of the Wairau section of the Alpine Fault at this location occurred after 760 BC and before AD 1000.

Yetton (2002) presents evidence of rupture on the Wairau section of the Alpine Fault in the Tophouse area at some time between AD 200 and AD 1840 (European settlement). There is also evidence for a much older rupture of this section of the fault approximately 12,500 years ago. However, the activity of the fault implies there must also have been many other ruptures of the fault in the intervening period.
If the rupture recorded by Yetton (2002) at the Tophouse site is the same earthquake event as that described a further 50km to the northeast by Zachariasen et al. (2001), then the combined dates from these trenches suggest that the most recent rupture event on the Wairau section of the Alpine Fault occurred between AD 200 and AD 1000.

Most recently Fougere (2002) notes a young mode of weathering rind ages of gravel clasts on offset terraces immediately adjacent to the fault. He attributes the age mode to the exposure of the gravel clasts by earthquake shaking associated with rupture of the Wairau trace of the Alpine Fault (clast exposure is an observed phenomena close to fault traces in historical earthquakes). The age mode corresponds to AD 550 ± 150 yrs, which is a good fit to the previous inferences but the date is based on a relatively small number of sites and weathering rinds. However, this is currently the best constrained estimate of the time of last rupture of the Wairau section of the Alpine Fault.

First order assessments of the likelihood of a future earthquake rupture of the Wairau section of the Alpine Fault.

A first order estimate of the likelihood of a future rupture of the Wairau section of the Alpine Fault can be made using the Lensen (1968) estimates of single-event slip from the Branch River terraces, in conjunction with the minimum time since the last event, and the available estimates of the long term slip rate.

Lapsed time since the last earthquake rupture:

Maximum time since the last earthquake rupture -	1800yrs
Best available estimate of time since last rupture[7]-	1450yrs
Minimum time since the last earthquake rupture -	1000yrs

Maximum long term slip rate –	5.5 mm/yr
Middle of estimate range-	4.5 mm/yr
Minimum long term slip rate –	3.5mm/yr

Maximum elastic strain available at the current time :	0.055m/yr x 1800yrs = 9.9m
Most likely elastic strain available:	0.045m/yr x 1450yrs = **6.5m**
Minimum elastic strain available:	0.035m/yr x 1000yrs = 3.5m

Best estimate of past single-event earthquake offset (Lensen, 1968): **3.4 - 6.6m.**

Thus, based on the past observable horizontal offsets, a rupture of this order of offset in the near future on the Wairau section of the Alpine Fault appears to be likely. However, if the next earthquake offset is at the high end of the range (say 6.6m), and the slip rate at the low end (3.5 mm/yr) with a most recent event at 1000 years ago (the most recent possible based on the available data), then this

[7] Fougere [2002]

crude assessment method would suggest there could still be around 900 years until rupture. Countering this is the inference of Yetton (2002) that the lapsed time since the last rupture was closer to the possible AD 200 maximum than the AD 1000 minimum and the suggested date of Fougere (2002) for the last rupture of around AD 550.

The significant difference in the implications that derive from these estimates (i.e. imminent or "overdue" rupture verse rupture in the next 500 years) demonstrates the need to better constrain the timing of the last earthquake event in as many places as possible. The implications also emphasise the urgency and importance of developing a robust set of planning rules, in conjunction with accurate fault location maps, to avoid the construction of new buildings across the active trace of the fault.

Table 3.1 below provides a summary of the key seismic hazard data for the Wairau section of the Alpine Fault.

Average long term slip rate	3.5 – 5.5 mm/yr
Likely surface offset in each successive earthquake event	3.4 - 6.6m
Date of last surface fault rupture	1000 – 1800 years ago, most likely around 1500 years ago.
Return period of successive earthquake ruptures	600 – 1800 years
Lapsed time since the last rupture	> 1000 years, probably 1500 years
Crude assessment of the relative likelihood of rupture in the next 50-100 years.	Moderate – High

Table 3.1: Summary table of key seismic hazard data for the Wairau section of the Alpine based on the references cited in the text.

3.3 THE AWATERE FAULT

Description of the Awatere Fault

The Awatere Fault (Figure 8) enters the west of Marlborough District as a complex series of discontinuous fault traces (frequently referred to as the Molesworth section of the Awatere Fault). These fault traces progressively combine with strands of the Clarence Fault, to continue as a single more persistent fault trace from the headwaters of the Awatere River (Molesworth Station), northeast to the coast between Clifford and Cloudy Bay. This straighter and more continuous fault trace is generally referred to as the eastern section of the Awatere Fault. In addition to the main trace of the Awatere Fault there are two notable areas of secondary faulting and local complexity, the first at the fault section junctions near Molesworth Station, and the second associated with the Dumgree Splay and the Vernon Fault approaching State Highway 1 and Seddon.

Summary of key seismic hazard data for the Awatere Fault

Table 3.2 below is a summary of the key seismic hazard data for the Awatere Fault. Nearly all of this information comes from detailed mapping and paleoseismic investigation of the fault that has been carried out over the last 10-15 years by various researchers at Victoria University of Wellington, culminating recently in a series of papers included in Benson et. al (2001).

Unlike the Wairau section of the Alpine Fault, the Awatere Fault has undergone fault rupture in historical times. Although Eiby (1980) attributed the Marlborough Earthquake of 1848 to rupture of the Wairau Fault, there is compelling evidence (including historical records of fault offset) that show that this large earthquake was associated with surface ground rupture of the Awatere Fault (Grapes and Downes, 1998). The ground surface offsets in the earthquake appear to have been approximately 7m horizontally (dextral sense of movement) and it is likely that the entire eastern section of the Awatere Fault ruptured (Benson et al. 2001).

See Map of the active trace of the Awatere and Clarence Faults

Average long term slip rate	5 – 6mm/yr
Likely surface offset in each successive earthquake event	7m
Date of last surface fault rupture	AD 1848
Return period of successive earthquake ruptures	600 – 2500 years
Lapsed time since the last rupture	Approx. 150 years
Crude assessment of the relative likelihood of rupture in the next 50-100 years.	Low
Table 3.2: Summary table of key seismic hazard data for the eastern section of the Awatere Fault based on Benson et. al 2001.	

From the perspective of future hazard the historical rupture of the Awatere Fault is very significant. It appears that the return period of earthquake rupture, at least on the eastern section of the fault, is in the order of 600 – 2500 years. The lapsed time since the last rupture of approximately 150 years suggests that the likelihood of a future surface ground rupture of the Awatere Fault in the next 50 – 100 years (i.e. conventional planning periods) is low.

Unfortunately little is known about the paleoseismicity and potential surface rupture hazard presented by the Vernon Fault, which splays north off the eastern Awatere Fault at Dumgree. The average long term slip rate of the Vernon Fault has been estimated to be less than 2mm/year (Benson et. al [2001]). Given the orientation of the Vernon Fault, it most likely to be associated with rupture of the Awatere Fault, as opposed to rupture of the Wairau section of the Alpine Fault. However, on the basis of the relatively low long term slip rate it is unlikely that the Vernon Fault ruptures every time the Awatere Fault ruptures, although this possibility can not be entirely ruled out.

3.4 THE CLARENCE FAULT

Description of the Clarence Fault

The Clarence Fault (Figure 8) is another primarily dextral strike-slip fault that forms an important part of the Marlborough Fault Zone. One section of this fault forms a complex trace in conjunction with the Elliot Fault in the southwest corner of Marlborough District. In this southwestern area there are a multitude of fault traces associated with a compressive “pop up” feature approximately 50 km long that persists to the southeastern district boundary. Further east in Kaikoura District, the fault strands merge to form a continuous single trace in the middle Clarence River valley, and the eastern end of this section of the fault re-enters Marlborough District. Mapping by Browne (1992) demonstrates that the Clarence Fault does not continue to coast at Cape Campbell and that the surface trace terminates approximately 5km west of Ward.

Summary of key seismic hazard data

Kieckhefer (1979) worked near the southwest end of the Clarence Fault and documents 76-80m of dextral horizontal displacement on the Clarence-Elliot fault system in the last 18,000 years which equates to an average slip rate of 3.6-4.4mm/yr. There is evidence of repeated fault ruptures in the Holocene and Kieckhefer (1979) estimates each rupture in the area that he studied to be around 5m of dextral strike-slip movement. Keickhefer (1979) also investigated the nearby Fowlers Fault, located 10km further north of this area, and estimated the post-glacial slip rate to be about 1-2mm/yr.

Van Dissen and Nicols (1998) outline the results of field work in the Middle Clarence Valley section of the fault, most of which is outside of Marlborough District. From their work they deduce single event offsets of around 7m per rupture event, a slip rate of 4.7mm/year, and a recurrence interval of approximately 1500 years. The most recent rupture event was between 950 years and 2000 years before present. Table 3.3 presents a summary of the available data.

Average long term slip rate	4.6 mm/yr (no errors given)
Likely surface offset in each successive earthquake event	7m
Date of last surface fault rupture	More than 1000 years ago
Return period of successive earthquake ruptures	1500 years
Lapsed time since the last rupture	1000 – 2000 years ago.
Crude assessment of the relative likelihood of rupture in the next 50-100 years.	Poorly constrained but moderate, and possibly high.

Table 3.3: Summary table of key seismic hazard data for the Clarence Fault based on Van Dissen and Nicols, 1998.

3.5 OTHER ACTIVE FAULTS IN MARLBOROUGH DISTRICT

There are numerous other smaller active fault traces in Marlborough, many of which have been relatively poorly studied. It is likely that with further field work more active fault traces will be recognized, particularly in the more remote western areas of the district.

We show in our GIS compilation of active fault traces the location of several relatively small faults near the east coast between Seddon and the Waima River. This includes the London Hill Fault, the Hog Swamp Fault and the Medway Fault System (including the associated Flaxbourne and Haldon Hills Faults). Not all of these structures are Class 1 active faults (i.e. definite movement in Holocene), at least not along all of their length (Townsend & Little, 1998). However, they have currently been included in the database until their activity class is more formally classified in the forthcoming new Kaikoura 1:250,000 map sheet. We recommend that when this new map is published the active fault database be updated and the inclusion of these faults can be revised.

We have also included in the database the eastern end of the Waikawa Fault. Although this fault is not shown as active in the recent 1:250,000 Wellington geological map (Begg and Johnson, 2000), earlier detailed work in the area (Horrey, 1989) showed evidence for a late Holocene rupture of the fault trace in Waikawa Bay. Horrey (1989) was not able to estimate typical displacements or return period for this active structure. Subsequent reassessment of the stratigraphic correlations of Horrey (1989) by McManus (1996) suggests the most recent rupture occurred between 12,000 and 18,000 years ago and the appropriate activity class is Class III. The geophysical surveys by McManus (1996) also suggest that there is a wide zone of faulting of at least 100m, and possibly considerably more.

4. CONCLUSIONS

Marlborough District has a significant number of major active faults that form part of a zone of active deformation associated with the on-shore plate boundary between the Pacific and Australian plates. Active faults that have surface traces at the ground surface, and which cross areas of human development, create a natural hazard because of the potential for future fault rupture.

The Resource Management Act and Building Act require territorial authorities to avoid or mitigate natural hazards such as the potential for ground rupture at active fault traces. The avoidance and mitigation process requires the systematic identification and location of active fault traces in Marlborough District. We have undertaken a review and compilation of all the relevant previous geological mapping of the active faults in the district in a digital GIS format. We have also checked the location accuracy of the previous mapping to provide a guide to possible errors.

Generally the accuracy at the best defined sections of fault that we have checked is in the order of ±75m but greater location errors are possible where the fault traces are less clear on the ground, and/or are located in more remote areas where the original mapping has generally been at a relatively coarse scale. We recommend that these potential errors be clearly stated in all print-outs from the GIS system.

The greatest potential ground rupture hazard in Marlborough District is presented by the active trace of the Wairau section of the Alpine Fault. This active fault trace enters the district in the Upper Wairau Valley, near Tophouse Saddle, and forms a discontinuous surface fault trace that passes through developed and accessible farm land in the Wairau Valley that is seldom more than a few hundred metres from SH 63. The fault trace is obvious all the way down the Wairau Valley as far east as

Renwick, and the inferred continuation of this feature is marked by a subtle and poorly defined fault trace east of Spring Creek near Cloudy Bay.

The limited research to date into the past rupture history of this fault suggests that future horizontal ground movements of the order of 3.3 – 6.6m can be reasonably expected. It is not possible to confidently predict the probability of rupture over the next 50 – 100 years (i.e. conventional planning periods) however a crude first order assessment suggests the likelihood of rupture in this time frame is moderate to high. Because of increasing development pressure in many of these areas of the Wairau Valley, it is timely to have reliable location information for this important feature.

We have also collated information on the location and previous rupture history of the Awatere and Clarence Faults, in addition to several smaller active faults in the district. Although from the geological perspective the Awatere and Clarence Faults are now apparently more active than the Wairau section of the Alpine Fault, they are not under the same level of development pressure from a residential land-use perspective. In addition, the most accessible of these faults (the Awatere Fault, particularly the eastern section) underwent surface ground rupture of approximately 7m in the 1848 Marlborough Earthquake. The relatively long return periods for past earthquake rupture of this fault suggests that the likelihood of a future rupture in the next 50 – 100 years is low.

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