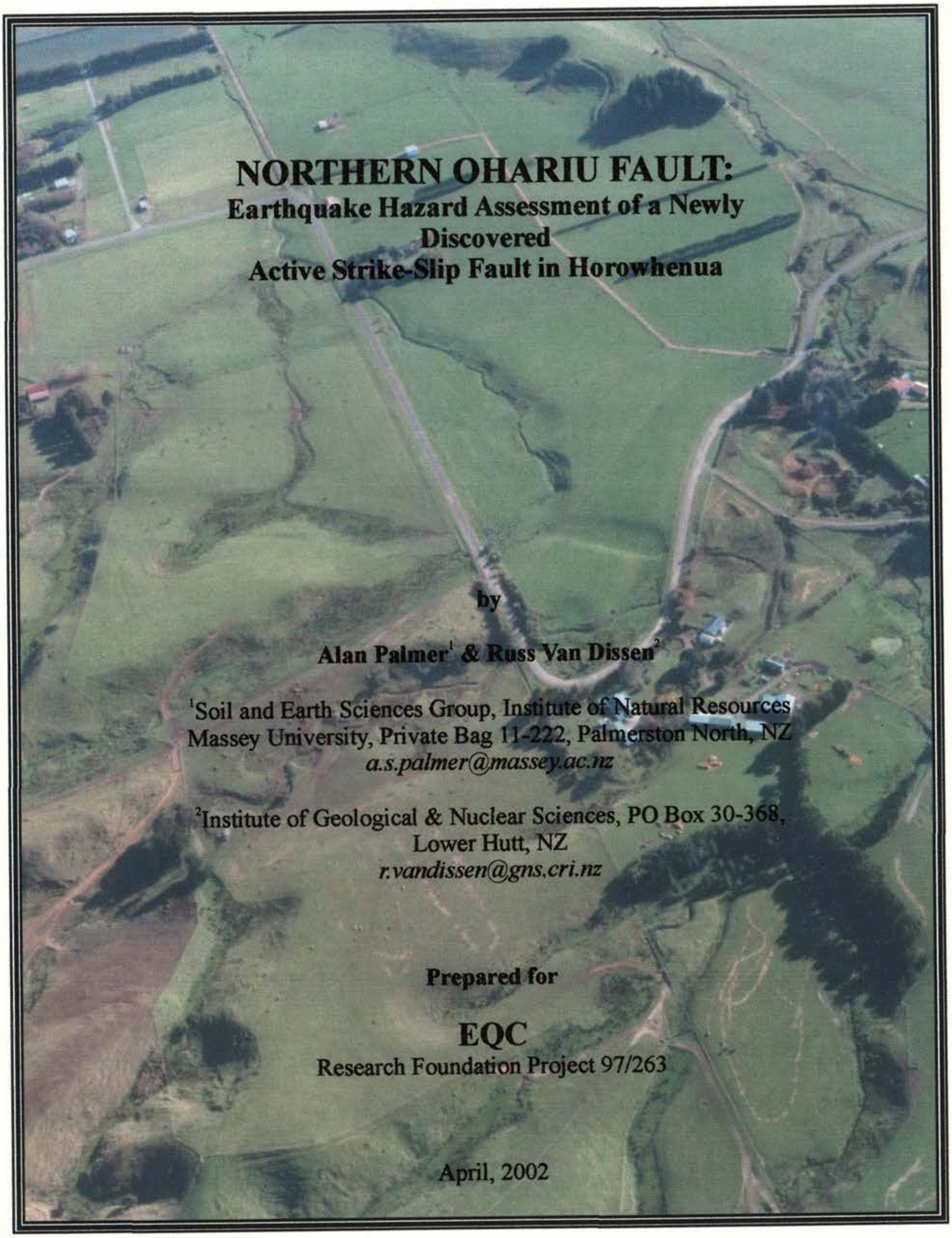

# NORTHERN OHARIU FAULT:
## Earthquake Hazard Assessment of a Newly Discovered Active Strike-Slip Fault in Horowhenua

by

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## 1.0 TECHNICAL ABSTRACT

The Ohariu fault, discovered about 100 years ago, extends northeastward from offshore of the Wellington south coast near Tongue Point through Porirua towards Paraparaumu. It has long been thought that the Ohariu fault "dies out" to the north in the Waikanae/Otaki area as a series of splays. However, in 1996 we discovered that the pronounced, 60 km long, NNE- to NE-trending topographic lineation that runs just inland of, and parallel to, the western flank of the northern portion of the Tararua Range between Otaki and Palmerston North is an active, right-lateral strike-slip fault. We name this newly discovered fault the Northern Ohariu fault because it appears to be the northern, along-strike, continuation of the Ohariu fault. Collectively the Ohariu and Northern Ohariu faults define a major active strike-slip fault that has a total length in excess of 130 km.

Offset geomorphic features such as alluvial terrace risers and valley margins, and estimated ages based on soil and loess stratigraphy are used to constrain the timing, amount, and rate of movement on the fault. The most recent surface rupture displacement on the fault is younger than about one thousand years, and older than several hundred years. The net surface rupture displacement that occurred during this event, measured at only two localities, was about 3-4 m. The fault has a lateral slip rate of 1-3 mm/yr, similar to that of the Ohariu fault to the south, a steep dip, and a subordinate up to the NW sense of displacement. The Northern Ohariu fault is considered capable of generating $M_w$ 7.2-7.5 earthquakes once every one thousand to several thousand years. Larger earthquakes, ca $M_w$ 7.7, would result if the Northern Ohariu fault were to rupture simultaneously with the Ohariu fault.

Fault rupture of the ground surface, strong ground shaking, liquefaction, and landsliding will be the principle earthquake hazards associated with a large ($\geq M_w$ 7.2) surface-rupture earthquake on the Northern Ohariu fault. Houses, transmission lines, pipe lines, and roads cross the fault, and 3-4 m of net surface-rupture displacement will adversely affect these structures. Damaging levels of strong ground shaking (≥ Modified Mercalli intensity 7) will result from a large Northern Ohariu fault earthquake, and will be felt as far south as Petone, as far north as Marton, and as far east as Dannevirke and Masterton. The highest and most damaging levels of shaking (≥ Modified Mercalli intensity 9) will occur closest to the fault and will encompass the communities of Te Horo, Otaki, Manakau, Kuku, Ohau, Muhunoa East, Levin, Shannon, Tokomaru, and Linton. Parts of the Horowhenua and Manawatu are known to be extremely susceptible to liquefaction. As such, we anticipate that liquefaction will be a significant feature of a Northern Ohariu fault earthquake, and will affect most severely the late Holocene sand country, low level river terraces, and flood plains of the Kapiti, Horowhenua, Manawatu, and Wairarapa lowlands from Paraparaumu in the south, Palmerston North in the north, and Foxton Beach, and Ekatahuna in the west, and east, respectively. Earthquake-inducted landslides will also be generated, and these will be most extensive along the western flank of the Tararua Range between the Otaki River in the south, and Kahuterawa Stream in the north.

## 2.0 LAYPERSON'S ABSTRACT

The Northern Ohariu fault is a newly discovered active fault that extends for some 60 km from between about Otaki to near Palmerston North. It appears to be the northern extension of the better known active Ohariu fault, and collectively these two faults define a major earthquake generating strike-slip fault that has a total length in excess of 130 km.

The Northern Ohariu fault is capable of generating large damaging earthquakes (magnitude $M_w$ 7.2-7.5) once every few thousand years. Even larger, more damaging, earthquakes ($M_w$ 7.7) could result if the Northern Ohariu fault were to rupture simultaneously with the Ohariu fault. The most recent large earthquake on the Northern Ohariu fault occurred between several hundred and about one thousand years ago, and resulted in 3-4 metres of surface rupture displacement of the ground surface.

Fault rupture of the ground surface, strong ground shaking, liquefaction, and landsliding will be the principle earthquake hazards associated with a large, surface-rupture earthquake on the Northern Ohariu fault. Houses, transmission lines, pipe lines, and roads cross the fault, and 3-4 m of net surface-rupture displacement will adversely affect these structures. Damaging levels of strong ground shaking will result from a large Northern Ohariu fault earthquake, and will be felt as far south as Petone, as far north as Marton, and as far east as Dannevirke and Masterton, with the most extreme levels of shaking occurring closest to the fault and encompassing the communities of Te Horo, Otaki, Manakau, Kuku, Ohau, Muhunoa East, Levin, Shannon, Tokomaru, and Linton.

Parts of the Horowhenua and Manawatu are known to be extremely susceptible to liquefaction. As such, we anticipate that liquefaction will be a significant feature of a Northern Ohariu fault earthquake, and will affect most severely the young, low-lying, sand country, river terraces, and flood plains of the Kapiti, Horowhenua, Manawatu, and Wairarapa lowlands from Paraparaumu in the south, Palmerston North in the north, and Foxton Beach, and Ekatahuna in the west, and east, respectively. Earthquake-induced landslides will also be generated, and these will be most extensive and severe along the western flank of the Tararua Range between the Otaki River in the south, and Kahuterawa Stream in the north. The steep slopes of the Manawatu gorge are also susceptible to failure during such an earthquake. Consequent with earthquake-induced landsliding is river aggradation, and the possible impacts this may have on flood control measures, and potential flooding resulting from catastrophic failure of landslide dams.

CONTENTS

## 3.0 INTRODUCTION

### 3.1 Objectives of Study

Prior to the mid-1990's, the existence of the Northern Ohariu fault (Figs. 1 & 2), and the hazard it poses was unknown. It is now certain that the fault is an active, right-lateral, strike-slip fault similar to the better known active, strike-slip faults in southern North Island, including the Wairarapa, Wellington-Mohaka, Ohariu, Shepherd Gully and Pukerua faults. The objectives of this combined geology and soils, field-based, study of the fault are as follows:

- Provide geologically derived estimates of the fault's slip rate, length, and single event surface rupture displacement size;

- Provide estimates of average maximum magnitude earthquake recurrence interval and size;

- Provide a map of the fault, and the geology and soils of key features that it offsets;

- Comment on communities and structures likely to be affected by either direct ground rupture or shaking generated by earthquakes associated with the fault.

### 3.2 Tectonic Setting

The present-day tectonic setting of the North Island of New Zealand is dominated by the oblique subduction of the Pacific plate beneath the Australian plate. East of the southern North Island the subduction thrust dips ~15° NW, and west of the North Island it steepens to ~26° NW. Beneath the Wellington region, the subduction thrust is 15-30 km deep (Robinson 1986, Ansell & Bannister 1996). As a consequence of oblique subduction, a zone of right-lateral strike-slip faults exists at the rear of the subduction margin, as described first in the New Zealand setting by Walcott (1978). The motion of the Pacific plate relative to the Australian plate, at the latitude of Wellington, is estimated at ~40 mm/yr at an azimuth of 265° (Fig. 1: DeMets *et al.* 1990).

The neotectonic structural grain of the southern North Island, including the plate boundary, trends ~N40°E. The oblique plate convergence can therefore be resolved into approximately equal amounts of shortening perpendicular to the boundary and strike-slip motion parallel to the boundary at rates of ~28 mm/yr. Although some strike-slip motion is likely offshore in the accretionary prism, the cumulative slip rate of the right-lateral strike-slip faults in the Wellington region sums to approximately 60-90% of the boundary-parallel motion [see Van Dissen & Berryman (1996), and references sited therein]: Wairarapa fault, ~7-10 mm/yr; Wellington fault, 6.0-7.6 mm/yr; Ohariu and Northern Ohariu faults, ~1-3 mm/yr; Shepherds Gully/Pukerua fault, ~1 mm/yr; Wairau fault, offshore extension, ~3-5 mm/yr. Over the last ~18 000 years, the ratio of horizontal to vertical slip along the traces of these faults is greater than 6:1, usually greater than 10:1, (e.g. Ota *et al.* 1981). No evidence of fault creep has been observed on any of these faults.

Most, if not all, major population centres in the Wellington/Manawatu region, encompassing over 400,000 people, are within 10 km of a major active strike-slip fault (Fig. 1). Only the

Wairarapa fault has ruptured the ground surface since European settlement (since circa A.D. 1840). For the other faults, including the Northern Ohariu fault (Fig. 2), the geologic record provides the only information regarding the occurrence, timing, and size of past large earthquakes, and it is the geological record of past movements on the Northern Ohariu fault that is the primary focus of this study. Table 1 lists the geological/soils site data we collected for the Northern Ohariu fault that are used to constrain the fault's recent past movement history.

### 3.3 Previous Work & Background

Examination of aerial photographs along the western flank of the Tararua Range readily reveals a series of prominent NE- to NNE-trending lineations. However, for most of their length they were not shown as faults by Kingma (1967) on his 1:250 000 geological map. During soil mapping in the Otaki district in 1984, one of the authors (AP) noticed an active fault scarp/trace, upthrown to the west, crossing the Hautere Plains from Te Horo to Ringawhati Road, Otaki, but did not show it on a map of the area published subsequently (Palmer *et al.* 1988) because of a lack of supporting evidence. At the same time, Barnett (1984) (a co-author on the Palmer *et al.* paper) did discuss the likely fault. The fault displaces Ohakean (10 000-15 000 year) and older terrace gravel. Barnett termed this fault the Blackburn Road fault, but both he and Palmer did not comment on the possible continuity of the fault with the Ohariu fault to the south, or with a strong lineament in the Ohau-Tokomaru area to the north. Geological maps in the MSc thesis of Sewell (1991) show a fault extending along the southern portion of the lineament between Ohau and Tokomaru; however, he did not document or confirm the fault in writing (perhaps it was the topographic distinctness of the lineament which lead him to draw in the fault on his maps).

There have been a number of geology-related evaluations of the Mangahao Power Scheme (e.g. Hancox 1995), and seismic hazard evaluations (e.g. Hull & Smith 1993). These studies are mostly client reports and not generally available, and none have looked specifically at the possible fault-related origin of the strong topographic lineament in the Ohau-Tokomaru area which extends through the power scheme. Van Dissen (1997), using a number of aerial photographs presented in a confidential client report, provides conclusive evidence for the active fault origin of this lineament, and using limiting ages (provided pers. comm. by AP) for surfaces offset by the fault draws inferences about the fault's slip rate and earthquake recurrence interval. In this client report Van Dissen also coins the name Northern Ohariu fault to describe the newly discovered, active, predominantly right-lateral strike-slip fault, that extends north-northeastwards from near Te Horo to within 10 km south of Palmerston North.

In this current study of the Northern Ohariu fault funded by EQC, we used purpose-flown low altitude, high resolution, air photos of the fault (both oblique, and vertical with an approximate scale of 1:4500), and on-ground mapping of soils and geology along the fault, to better determine the fault's location and extent, and to better approximate the fault's rate of movement, single event displacement size, "characteristic" maximum earthquake magnitude, and recurrence interval of surface rupture earthquakes. This work, aspects of which have previously been presented in Van Dissen *et al.* (1998) and Van Dissen *et al.* (1999), forms the basis of the results presented in this report below. Also, based largely on this work, the recently published 1:250 000 geological map of Wellington (Begg & Johnston 2000) shows the Northern Ohariu fault as active.

The geographic position of the Northern Ohariu fault and the Ohariu fault, as shown in Fig. 1, strongly suggests that one is the along-strike extension of the other. From near Makara in the south to near Palmerston North in the north, a length of about 130 km, the most significant/major disruption along the traces of the two faults occurs in the Paraparaumu-Waikanae area. From south of about Paraparaumu, the trace of the Ohariu fault appears to be rather "smooth" and continuous, and from north of about Waikanae, the same can be said of the trace of the Northern Ohariu fault. The major disruption along the trace of the two faults in the Paraparaumu-Waikanae area is taken in this report as the rather ill-defined boundary between the two faults - the Ohariu fault to the south and the Northern Ohariu fault to the north. Geological field mapping has yet to define the nature and location of the northern extent of the Northern Ohariu fault. However, north of about Kahuterawa Stream, the fault becomes difficult to follow as a topographic feature. At present, Kahuterawa Stream is taken as the fault's northern extent. The along-strike distance between Waikanae and Kahuterawa Stream is about 60 km.

### 3.4 Late Quaternary Terraces and Fans

The Northern Ohariu fault crosses a number of different Late Quaternary terraces and fans in the study area, and the identification of these features enables an age to be estimated for these terraces and fans. A primary objective of our study was to look for offsets on these terraces and fans, and compare the offset on terraces and fans of different age to obtain limiting rates for fault movement. A fundamental, three-fold, classification of terraces and fans in the study area may be made as follows (Fig. 3; Table 2):

1. Low terraces formed by river degradation since the end of the last glacial, approximately 15 000 years ago.
2. Intermediate terraces and fans. These are the Ohakean terraces and fans formed by river aggradation in the last cold period of the last glacial.
3. High terraces and fans. All terraces and fans, both of river and marine origin that are old enough to have a loess cover that includes the ca 22 500 year old Kawakawa Tephra. In Horowhenua, these are all terraces and fans older than the last glacial, Ohakean terrace.

#### 3.4.1 Low terraces
At the end of the last glacial period, approximately 12 000-15 000 years ago, there was substantial revegetation, by forest, of areas that had been severely eroding in the Tararua Range and foothills. The supply of erodable detritus was limited, and rivers were able to cut down through gravels that had been deposited during the preceding glacial period. Uplift enabled down-cutting to continue to the present day with only minor interruption by aggradation. Late Ohakean (10 000-15 000 years old) degradation terraces are preserved on the south bank of Otaki River (Fig. 2) but are rare elsewhere. An extensive early Holocene (5000-10 000 years old) terrace is preserved at Otaki Racecourse (Fig. 2), but terraces of this age are also rare elsewhere. However, terraces of late Holocene age are common adjacent to the floodplains of most rivers and streams. Their constraining ages are discussed below in Section 3.5, and listed in Table 2.

#### 3.4.2 Intermediate terraces and fans
During the last glacial period (or Ohakean period), approximately 15 000-25 000 years ago, the Tararua Range and foothills were substantially devoid of forest cover, it being too cold and adverse for forest survival. The existence of large fans of gravel spread over the

lowlands, adjacent to the ranges, points to rapid rates of erosion. Rivers were not able to move all the eroded material at once, and were forced to aggrade. Fine sands and silts deposited on the aggrading surfaces during floods were later dried and blown on to older surfaces by wind, to form loess deposits.

Terraces of this age generally have little loess cover and are either stony to the surface, or thinly covered by alluvium and colluvium, or eolian sand, for example the extensive Hautere Plains, south of Otaki River (Fig. 2). However, fans of Ohakean age, may have loess that was derived from elsewhere during the growth of the fan. For example, a large fan was constructed by Waikawa Stream (Fig. 2) during the last glacial. In its southern portion, south of the present Waikawa Stream, it has no loess cover, but north of the stream, it is covered by loess (and alluvium) to a depth of up to 1.5 m. Significantly for Quaternary surface dating, the loess is younger than the ca. 22 500 year old Kawakawa Tephra.

### 3.4.3 High Terraces and fans

Most of the high terraces and fans in areas traversed by the fault are confined to adjacent to the foothills of the Tararua Range. River aggradation terraces and fans were formed during glaciations 30 000-50 000 years ago (Ratan terrace), and approximately 65 000-75 000 years ago (Porewan terrace). The Ratan terrace has one layer of loess (that includes Kawakawa Tephra), and is referred to as "Ohakean loess" since the loess is coeval with construction of Ohakean aged terraces and fans (see Fig. 3). The Porewan terrace has two layers of loess, Ohakean loess overlying loess of Ratan age. A weak soil formed in the Ratan loess prior to its later burial by Ohakean loess.

Discerning between these loesses to establish the age of the underlying terrace can be difficult, but the presence of Kawakawa Tephra, the morphology of the buried soil, and a colour change from yellowish brown Ohakean loess, to more orange Ratan loess can usually be detected. Ratan and Porewan terraces are common in the North Manakau to Florida Road area (Fig. 2; Table 1).

During the Last Interglacial period, 80 000-125 000 years ago, the climate was similar to the present day, the landscape was relatively stable, and sea levels were high. The sea advanced inland to the foothills of the ranges, depositing marine sand. Sands blew from the ancient beach to form dunes farther inland. The marine terrace formed is called the Tokomaru terrace, and the sands (both marine and eolian) are called the Otaki sandstone. The main Tokomaru terrace was formed at the height of the last interglacial about 125 000 years ago.

The Tokomaru terrace and Otaki sandstone are well preserved just north of Otaki on State Highway 1 (Fig. 2), at Manakau, and in the Florida Road area (see also Table 1). Palmer *et al.* (1988) described how the advancing sea, approximately 125 000 years ago, had cliffed older (Marton aged - see below) aggradation gravels just north of Otaki. Marine sand was then deposited against this cliff, and dune sand blew up over the cliff on to the higher surface.

The Marton terrace and fans were formed by aggradation of river gravels during the penultimate glaciation, approximately 125 000-150 000 years ago. Terraces and fans of this age are common along the length of the Northern Ohariu fault, particularly at Ringawhati Road, South Manakau Road, and North Manakau Road (Fig 2; Table 1). The greywacke gravels that make up the terrace and fans are noticeably more weathered than those younger than the Last Interglacial, having been subject to intense weathering during the interglacial prior to burial by younger loesses. Mantling the Marton terrace and fans is up to 7 m of loess, comprising Ohakean, Ratan, Porewan, and often a fourth loess (deposited during a cold interval in the Last Interglacial).

At several locations, most notably North Manakau Road and Makahika Station (Fig. 2; Table 1), the fault crosses or passes adjacent to, much older, weathered gravels beneath dissected terrace and fan surfaces. Many of the gravels can be cut by a spade or knife, and in places there is red weathering. Elsewhere in the lower North Island, red weathering is found only in deposits older than 300 000 years. These terraces and fans have thick loess cover, but the 350 000 year old Rangitawa Tephra, a regional marker bed, has not been found.

### 3.5 Using Soils to Date Quaternary Surfaces Crossed by Fault Lines

Soils can be used in a qualitative way to provide age estimates of surfaces offset by fault lines (Table 2). The features developed by soils during pedogenesis are controlled by the environment that the soils formed in. The environment can be encapsulated by five parameters: climate (primarily temperature and rainfall and its distribution); organisms (including all flora and fauna); relief (including altitude, slope and aspect); parent material (including lithology and texture) and time. All soil-forming processes are a response to the soil environment.

The soils that form on landscapes of different age are frequently developed in different parent materials. These parent materials may have been deposited in response to certain climatic conditions, and can themselves be used to provide age constraints.

The aim of this section is to describe how soils can be used to determine the age of landscapes crossed by active faults, and how soils might be used to constrain times of fault movement. Examples will be used where appropriate.

#### 3.5.1 Soils of the Recent (Holocene) river terraces

Soils on the Recent (Holocene) river terraces in Horowhenua are developed in alluvium deposited by the adjacent river, or in colluvium from the surrounding slopes. Their morphology is largely determined by frequency of flooding (see Table 2).

On the river flood plain are soils that normally flood at least once a year. Their texture may vary from silt to coarse gravels. **Otaki Soils** are developed in coarse sandy river gravels. A thin (5-15 cm) topsoil covers unaltered gravels, and stones commonly litter the surface. **Rangitikei Soils** also occur on flood plains that on average are inundated at least once a year. They are excessively, well or moderately well drained soils developed in alluvium that may range in texture from gravels to silts. Unlike Otaki soils, the stones do not come to the surface, allowing cultivation to take place. Rangitikei soil types are named for the texture of the topsoil (e.g. Rangitkei sandy loam, Rangitikei silt loam), and depth of finer grained material over gravel (e.g. Rangitikei shallow sandy loam). **Parewanui Soils** have a similar range of textures and therefore types, but are imperfectly or poorly drained with a rising water table. These three soils have A/C profiles, i.e. a thin topsoil over unaltered parent material. They are probably all less than 500 years old.

Alongside most streams and rivers in the region are terraces that flood only in the major storm events that occur every few decades. Flooding is sufficiently rare, and deposition rates low enough for the soils to have developed deeper and better structured topsoils, and show signs of alteration (B horizons) in the underlying parent material. **Manawatu Soils** are excessively to moderately well drained, and show a similar range of textural variation to the Rangitikei soils, but have A/B/C horizons. The parent material in the upper part of the subsoil is altered so that the soil has assumed a browner colour and has developed structure. **Kairanga Soils** like Parewanui soils are imperfectly to poorly drained with a rising water table. Their morphology reflects periodic wetness with grey mottles occurring in upper parts of the profile. Kairanga soils may also be subject to surface ponding, particularly in winter when water tables are high.

There are very few age estimates available for both Manawatu and Kairanga soils. In Horowhenua, the alluvium in which Manawatu and Kairanga soils has developed has lapped on to Foxton aged sand dunes which are 2000-4000 years old. Motuiti dunes which are 500-1800 years old both overlie and underlie alluvium in which Manawatu and Kairangs soils are formed. The main terrace containing alluvially deposited Taupo Pumice (1850 years old), on the Rangitikei River is above (and therefore older than) the terrace on which Manawatu and Kairanga soils are developed. It would therefore appear that the alluvium in which Manawatu and Kairanga soils is developed, is mostly between 500 and 2000 years old, with minor additions of alluvium since.

In some particularly poorly drained areas of the river plains, peat has developed where accumulation of organic matter has been faster than accumulation of sediment. These are the Makerua soils, which are also found from place to place along the trench created by the fault. Peat, at any depth, can be directly dated by radiocarbon dating, and is therefore particularly useful in studies of fault-lines.

There are some recent river terraces that no longer flood. The soils on these terraces have had the opportunity to develop without interruption for longer than the Manawatu and Kairanga soils. **Karapoti Soils** are well and moderately well drained soils that have a similar range of textures and soil types as Manawatu soils. The weathered B horizon in these soils extends deeper and has stronger colour and structure than the Manawatu soils. **Te Arakura Soils** are imperfectly and poorly drained soils, similar to, but more developed than the Kairanga soils.

Near Otaki, Foxton aged dunes (2000-4000 years old), have advanced over Karapoti soils. Beside the Rangitikei River, Karapoti soils are developed in alluvium and on the terrace, that contains Taupo Pumice (1850 years), suggesting a slightly younger age for the soils.

### 3.5.2 Soils of the Ohakean (Last Glacial) aggradation surface

During the last glacial period, erosion rates in the Tararua Range and foothills were substantially greater than at present, because the cold climate lead to deforestation of the steep mountain-sides. The eroded material was only slowly moved downstream, and aggraded as vast low angle fans. The rivers most probaly had a braided form at this time. When the climate warmed, about 12 000 years ago, the rivers cut back down through the aggradation gravels.

Many parts of these aggradation terraces have remained stony to the surface, and the soils have formed directly into the gravels. The **Ashhust** stony silt loam has formed in gravels where the annual rainfall is less than approximately 1000 mm. The **Kawhatau** stony silt loam is found in similar gravels, but where the rainfall is greater than about 1000 mm/yr. The main difference between these two soils is that the subsoil of Ashhurst soils is yellowish brown and has a chemistry that reflects weaker leaching conditions, whereas Kawhatau soil has a slightly redder hue and is more leached.

Other parts of the Ohakean aggradation surface (terrace) are covered in loamy alluvium with minor contributions of loess and tephra, from 0.45 to 2 m deep. Four soils are recognised depending on drainage. **Hautere soils** are well drained, with grey mottling confined below 80 cm depth; **Te Horo soils** are moderately well drained with grey colours below 60 cm depth; **Paraha soils** are imperfectly drained with grey colours below 40 cm; while **Ohakea soils** are poorly drained with grey mottles to the base of the topsoil. Textures of these soils vary between and within profiles, but are mostly silty clay loam, silt loam or fine sandy loam.

Rivers began to cut down through the Ohakean terrace about 12 000 years ago. Therefore, the soils on this surface began forming at about this time, and have been forming ever since. Some of the finer grained alluvium may have been contributed by local streams more recently, and thus may be younger than ca 12 000 years. Close to the riser to older terraces, or adjacent to the foothills, aprons of colluvium cover the Ohakean aged deposits, and are also younger than 12 000 years even though the same soils are recognized. As the rivers cut down, degradational terraces were formed on the valley sides. These terraces are generally of small extent, undulating, and the soil pattern is more complex than on the main aggradation terrace. These terraces vary in age from about 12 000 years ago to about the middle Holocene (ca 5000 years ago); however, the same range of soils is recognised.

### 3.5.3 Soils of the high terraces

There are a number of older river terraces in Horowhenua that were formed in preceding glacial periods. The Ratan terrace (30 000-50 000 years old), Porewan terrace (65 000-75 000 years ago), and Marton terrace (125 000-150 000 years old), are common in the district. Also, when sea levels were higher, in interglacial periods, the sea advanced landward forming marine terraces. The Tokomaru terrace is widespread in Horowhenua and was formed in the last interglacial (about 125 000 years ago).

The high terraces are mostly covered in loess (wind blown silt) that was deposited during glacial periods. The loess in which the present soils have formed was deposited during the last glacial (Ohakean), and was blown from the broad river bed that later became the Ohakean terrace.

The soils are developed into loamy textured loess that has been weathering for about the last 12 000 years. Drainage is again used as the criteria to differentiate soils. **Levin soils** are well drained, with grey mottling confined below 80 cm depth; **Waitohu soils** are moderately well drained with grey colours below 60 cm depth; **Shannon soils** are imperfectly drained with grey colours below 40 cm; while **Rahui soils** are poorly drained with grey mottles to the base of the topsoil. Textures of these soil vary between and within profiles, but are mostly silty clay loam, silt loam or fine sandy loam.

In some places on the Tokomaru marine terrace, the marine and eolian sands that normally underlie the loess are found at the surface and soils have formed in them. Similarly, while Ohakean loess was being deposited, there was in some places coeval sand dune formation. Well and moderately well drained soils developed in these sands are called **Koputaroa soils**, while imperfectly and poorly drained soils are **Waitawa soils**. Whether sands from the Otaki marine terrace, or dunes of Ohakean age, the soils are thought to be approximately the same age. It is thought that the sands stabilised and soil formation began about 12 000 years ago.

### 3.5.4 Soils on the recent sand dunes, sand flats and peats

In the study area, the Northern Ohariu fault does not cross the Recent sand country, but does immediately to the south. The dunes apparently accumulated in three phases. The youngest dunes accumulated after coastal sands were destabilised by cattle as European farmers settled the area. The dunes were active about 100-140 years ago. Waitarere soils with thin topsoils over raw sands are found on the dunes, and Hokio soils are found on the poorly drained sand flats.

The **Motuiti** soils are found on dunes that began forming during a period of rapid coastal progradation following eruption and fluvial reworking of the Taupo Pumice 1850 years ago. Maori burning reactivated the sands about 700 years ago. It is thought that the dunes were stabilised by 500 years ago, and most soils date from about then. Motuiti soils have developed weakly structured and coloured B horizons in the upper part of the subsoil. On the sand flats **Puke Puke** soils are poorly drained soils occurring on low lying swampy areas, while **Himitangi** soils are found on drier parts of the sand plain.

The **Foxton** soils are found on dunes that accumulated between about 2000 and 4000 years ago. They have had sufficient time to develop deep (30 cm), dark A horizons, and more developed B horizons than the younger Motuiti soils. On the drier sand flats are **Awahou** soils, while on wet swampy sand flats, poorly drained **Carnarvon** soils with iron pans are found.

Both the Motuiti and Foxton dune phases are commonly associated with peat deposits where drainage is particularly poor. These soils are called **Omanuka** soils where the peat is more than 60 cm thick.

### 3.5.5 Soils of the greywacke foothills and Tararua Ranges

The Northern Ohariu fault traverses through the western side of the Tararua Range and foothills, which are composed of Mesozoic greywacke and argillite. Soils vary considerably according to slope, altitude, rainfall, past vegetation and age. Few soils are older than 12 000 years when the slopes reforested and stabilised at the end of the last glacial. Many soils are younger, on slopes that have eroded and restabilised during the Holocene. Some flatter ridge tops are loess and tephra covered and may hold stratigraphic records that date back several hundred thousand years. Elsewhere are scattered terrace remnants usually with an incomplete sequence of loess, tephra and colluvium cover beds.

## 4.0 RESULTS

Table 1 lists the site data, and key observations, including grid reference, for the ca 100 field sites that, collectively, comprises the bulk of the data-set that this report is based on. Another important data set are aerial photographs, both vertical and oblique. The field sites are grouped by geographic area and are listed from south to north. In the text below, we further describe the ten or so sites, or groups of sites, along the Northern Ohariu fault that contribute most to characterizing the fault's recent earthquake activity (i.e. its location, slip rate, single-event surface-rupture displacement size, elapsed time since most recent surface rupture, earthquake recurrence interval, and estimated magnitude(s) of past surface rupture earthquakes). As in Table 1, these sites are listed from south to north.

### 4.1 Te Horo – Otaki River

**Old Hautere Road** (Figs. 4 & 5)
Between Te Horo and the Otaki River (Figs. 2 & 4; sites a-c of Table 1), on the extensive Ohakean age (ca 10 000-15 000 years) aggradation terrace/fan of the Otaki River (Palmer *et al.* 1988) the scarp of the Northern Ohariu fault is distinct and relatively easy to follow (Fig. 5; e.g. grid ref. S25 912 439). It extends through farm land and an ever increasing number of lifestyle blocks. Near Old Hautere Road, the fault scarp runs north of, and sub-parallel to the road, and it is northeast-trending, southeast-facing, and has a height of 1.5-2.0 m. To the southwest, however, within ca 1 km of Te Horo the fault swings to a more easterly strike, corresponding to a change in upthrown side of the scarp, such that nearest to Te Horo the scarp is southeast-side up, yet further to the northeast, along Old Hautere Road and for most of the length of the fault, the scarp is northwest-side up.

**Harper Road** (grid ref. S25 927 447)
Air photos 307/7-9, taken in April 1948, show that north of Harper Road the scarp of the Northern Ohariu fault extends northeastward across the extensive Ohakean age terrace discribed above, and appears to drop down onto, and cut, a low-level alluvial terrace of the Otaki River (site d of Table 1; grid ref. S25 928 448). This terrace is approximately 15 m lower in elevation than the Ohakean terrace, and is thus younger than the Ohakean terrace. It has a Manawatu soil developed on it, which is a recent soil, and this implies, because the fault appears to cut the low-level terrace, that the most recent surface rupture of the Northern Ohariu fault at this site is late Holocene in age, probably within the last ca 1,000 years (see Table 2). Unfortunately, subsequent establishment of a kiwi fruit and apple orchard on this low-level terrace has destroyed the fault scarp. Examination of the 1948 air photos suggests that further to the northeast, but still south of the Otaki River, the fault is overlain by a lower, younger, unfaulted alluvial terrace with a Rangatikei soil developed on it.

Near Harper Road, and along most of Old Hautere Road, the fault scarp is northeast-side up, and the scarp on the low-level terrace south of the Otaki River is offset to the northwest compared to the position of the scarp on the higher Ohakean terrace, suggesting that the fault dips to the northwest and has a reverse component of displacement at this locality.

### 4.2 Otaki River – Waitohu Stream

**Ringawhati Road** (grid ref. S25 937 453)
Immediately to the southwest of the intersection of Ringawhati and Rahui Roads, the fault scarp extents across a "low level" degradational terrace of the Otaki River (site e of Table 1). This terrace is significantly lower in elevation, and thus younger, than the extensive Ohakean age aggradational terrace at Old Hautere Road (Figs. 4 & 5), and has previously been mapped as early-mid Holocene in age by Palmer *et al.* (1988). As at Old Hautere Road, the scarp is northwest-side up, but here, on a younger terrace, the scarp height is less. About 300 m farther to the southwest, the fault scarp is truncated by a still lower, and thus younger, alluvial terrace mapped as "Older Recent alluvium" by Palmer *et al.* (1988). This terrace appears to be unfaulted, and is assumed to post-date the most recent surface rupture along this portion of the Northern Ohariu fault.

Along Ringawhati Road, between Rahui Road and Waitohu Stream, the fault trace, expressed as a broad, northeast-trending, anticlinal-shaped warp/fold, extends across a Marton aged terrace (ca 140 000 years, Palmer *et al.* 1988; site f of Table 1). In places, the broad trace has been clearly rejuvenated by recent movements on the fault.

**Waitohu Stream** (grid ref. S25 955 466)
Within ca 0.5 km southwest of Waitohu Stream, the fault scarp drops down onto, and cuts young alluvial terraces of Waitohu Stream (site g of Table 1). The youngest of the faulted terraces have Manawatu and Kairanga soils (Table 2), suggesting that surface rupture of the fault has occurred within the late Holocene, probably within the last ca 1000 years.

### 4.3 South Manakau Road

**Corbetts Road** (Fig. 6)
Near Corbetts Road, ca 7 km north-northeast of the Otaki River, there is an apparent right-lateral topographic/alluvial terrace offset of approximately 450 m (Fig. 6; sites 30, 31 & 85 of Table 1). The offset is measured from the northeast wall of the un-named, northwest-flowing stream that crosses the fault at grid ref. S25 981 493 (a of Fig. 6), to the alluvial terrace/hillslope contact marked a' on Fig. 6. It is assumed that the un-named northwest-flowing stream once cut the into the hillslope downstream of the fault and deposited the extensive terrace, now loess covered, that defines the terrace/hillslope contact marked a' on Fig. 6. However, the ca 450 m of apparent right-lateral displacement between this contact downstream of the fault and the present-day stream course upstream of the fault should be considered a maximum estimate for tectonic displacement along the fault since terrace abandonment, and consequent accumulation of tectonic displacement. This is primarily because the pre-abandonment stream morphology is uncertain. It is possible that during deposition of the extensive terrace the stream may have cut northeastward into the hillslope immediately downstream of the fault, thus adding a component of apparent lateral displacement that is not tectonic in origin. The alluvial gravel that comprises the extensive loess covered terrace are assumed to be aggradational fill deposited during cold climate conditions, and soil auger holes on the terrace reveal three loess units overlying weathered gravel. The presence of three loess units suggests that the terrace surface is Marton in age (ca 140 000 years). A maximum right-lateral displacement of ca 450 m in ca 140 000 years implies a maximum lateral slip-rate of ca 3 mm/yr.

The above scenario assumes that river cutting of the hillslope that is now offset ca 450 m by the fault occurred during a time of aggradation, a time when stream power is at a relative low (see Bull 1979). This may not be the case, and it may be more reasonable to consider that much of the hillslope cutting took place during a time of relatively high stream power when the river was in the height of its degradation phase that preceded the Marton aggradation. The timing of this degradation phase would be ca 200 ka ago, and would imply a maximum right-lateral slip rate of ca 2 mm/yr.

### 4.4 Waikawa Stream & North Manakau Road

Of the alluvial terrace sequences along the rivers and streams that cross the southern half of the Northern Ohariu fault, the most complete is along the NE bank of Waikawa Stream (sites 57-61 of Table 1; grid ref. S25 998 517). Here, well defined terrace surfaces range in age and elevation from Holocene to Marton (<10 000 - ca 140 000 years), and ca 80 m to 100 m, respectively. Older extremely weathered, and dissected alluvial gravel, into which the Marton terrace is cut, are also present (elevation ca 120-140 m). These extremely weathered gravels are capped by up to 6 m of loess, but the Rangitawa tephra (ca 340 000 years) has yet to be found within the loess, suggesting that these weathered gravels are either younger than, or coeval with, the Rangitawa tephra and thus Stage 8 or 10 in age. These weathered gravels, as well as the younger less weathered gravels, lie within the river valley system that defines the "current" catchment, implying that the "current" catchments along the NW Tararuas were largely developed by Stage 8 or 10 time. There is an older surface(s) - expressed as low-relief, concordant ridges - that defines the top of the landscape (elevation ca 500 m), and it is into this surface(s) that the "current" catchments are developed.

### 4.5 Tangimoana Road – Muhunoa East (Figs. 7 & 8)

Near the end of Tangimoana Road, in the vicinity of Makorokio Stream (grid ref. S25 033 550), the range-front of the western Tararuas steps to the right, and the strike of the Northern Ohariu fault changes by ca 20-25°, from NE to the south, to ENE in the north (Fig. 2). At this locality a small graben has developed along the fault, and, as a consequence, there are fault scarps that face both to the northwest and to the southeast (Fig. 7).

At the end of Tangimoana Road the scarp of what appears to be the main eastern strand of the fault is several metres in height, and is southeast-side up. Immediately to the west, an Ohakean age riser is right-laterally offset. About 900 m to the northeast, the sense of throw on the scarp has changed, it is now northwest-side up, and has a height of ca 1.1 m across a Ratan age (ca 30 000-50 000 years) terrace (Figs. 7 & 8; sites 1 & 1b of Table 1; grid ref. S25 039 555). Near the red woolshed (the right-hand-most of the two large farm buildings in Fig. 8) the fault right-laterally displaces an Ohakean age terrace riser (10 000-15 000 years) by ca 10-20 m (a-a' of Fig. 5), yielding a lateral slip rate of ca 0.7-2 mm/yr. This is a minimum rate for the fault as a whole because about 300 m to the northwest is the sub-parallel western strand of the fault that forms the other side of the graben, and for which a slip rate has yet to be determined.

About 50 m northeast from the red woolshed, the eastern strand of the fault laterally displaces the channel-wall of a small spring by 3±1 m (b-b' of Fig. 8; site 1c of Table 1). This channel has been cut into an Ohakean age terrace, and is thus younger than the terrace. The size of the offset is the smallest observed along this portion of the fault, and may represent the amount of lateral displacement resulting from the most resent surface rupture displacement on the eastern strand of the fault.

To the northeast, by about 400 m, the western strand of the fault appears to become the main trace. Here it swings in trend to a more easterly strike, before again swinging back to the general east-northeast trend of the fault. Just to the southeast of Muhunoa East School there are at least four north-flowing channels (small valleys) that are right-laterally displaced across the fault by about 50-60 m (site 5a of Table 1; grid ref. S25 043 558). The ages of these channels, and associated lateral offsets, are not well constrained.

### 4.6 Florida Road & Ohau River (Figs. 9-12)

At the "hair pin" turn in Florida Road (Fig. 9; grid ref. S25 050 564) the double scarp of the fault displaces a number a terraces ranging in age from Marton to Holocene (ca 140 000 - <10 000 years). Further to the northeast, at grid ref. S25 057 569, there is a right-lateral offset of an Ohakean age terrace riser (site h of Table 1). While difficult to measure precisely because drainage ditches have been cut along the base of the riser upstream of the fault and along the fault, and because a small alluvial fan partially buries the riser/fault contact upstream of the fault, it appears that the lateral offset is in the order of 20-30 m. This suggests a lateral slip rate of approximately 1-3 mm/yr.

On the south side of the Ohau River, east-southeast from the end of Florida Road, a second site has been identified where a geologically young, metre-scale displacement can be measured (Fig. 10; site i of Table 1; grid ref. S25 067 571). This is the smallest, and presumably youngest, displacement that has yet been identified along the fault, and is taken as a measure of the amount of surface rupture displacement that occurred at this site during the most recent earthquake on the Northern Ohariu fault. Fig. 10 shows a young terrace riser (a-a') right-laterally displaced by the fault (arrowed) by 2.5-3.0 m, and vertically displaced by ca 1.5 m, northwest side up. This amounts to about 3.0-3.5 m of net displacement if a near vertical fault dip is assumed (at the four places along the fault where the dip of the fault can be measured, it ranges from about 75° NW to 75° SE). The age of this displacement can be estimated from the development of the soil exposed in the silage pit marked "s" on Fig. 10. The soil, developed on a faulted alluvial terrace surface, is a recent soil with a reasonably well developed Bw horizon, and its age is estimated at ≤5000 years. To the left of a-a' (i.e., to the southwest) there are younger terraces that do not appear to be faulted. These terraces are younger than the most recent movement on the fault, and the soil development on these terraces is suggestive of an age of several hundred years. Thus, at this site it is interpreted that the most recent surface rupture earthquake on the Northern Ohariu fault occurred within the last 5000 years and was associated with 3.0-3.5 m of net surface rupture displacement, and that the fault has not moved within the last several hundred years.

Northeast of the above site, and south of the Ohau River, the fault is expressed as an east-northeast trending furrow (Fig. 11; grid ref. S25 073 574), and a broad mole-track-like feature (grid ref. S25 079 577) across the extensive Ohau River Ohakean aggradation terrace (site j of Table 1). Further to the east-northeast, close to where the fault should intersect the steep south bank of the Ohau River at Gladstone Road Reserve, there is an exposure of Ohakean aggradation gravel (ca 15 m thick) overlying an organic-rich silt unit that contains wood and roots (site k of Table 1; grid ref. S25 074576). About 2 m above modern river level, wood was collected from this organic-rich silt unit for radiocarbon dating, and yielded an age of > 40 000 radiocarbon years (Wk-5292).

For about the next 4 km further to the east-northeast, the precise location of the fault is largely uncertain (with the exception of site l of Table 1; Fig. 12), primarily because, in all likelihood, it is buried under recent alluvium and low level (late Holocene) terraces of Ohau River and Makahika Stream.

### 4.7 Makahika Stream & Makahika Station (Figs. 13-16)

Southeast of Makahika Stream (Fig. 13), a slip on the west bank of Waiti Stream exposes the crush zone of the fault (marked "cz" on Fig. 13; site 77 of Table 1). Further to the northeast, the fault scarp passes through a bedrock saddle (marked "s" on Fig. 13; grid ref. S25 122

605), and then drops down, and displaces, Holocene and Ohakean age alluvial terraces (e.g. site 78 of Table 1). Still further to the northeast, the trace of the fault is denoted as an east-northeast trending mole track across alluvial terraces (Fig. 14; site 36 of Table 1), and an uphill-facing scarp in bedrock (Fig. 15; grid ref. S25 135 614).

Northeast of Makahika Stream, along the northern third of the Northern Ohariu fault, alluvial terraces and young geological materials are not geographically extensive. Thus it is difficult along this stretch of the fault to conclusively document its recent activity. However, distinct fault-related topography, as is shown in Figs. 13, 16 & 17, that is directly on-trend with documented active traces of the fault makes it clear that the Northern Ohariu fault extends northeastward from Makahika Stream, along the northeast-trending upper reaches of Mangaore Stream, through the upper-most portion of the Blackwood Stream catchment, along the northeast-trending portion of the Tokomaru River towards Kahuterawa Stream. At present, the Northern Ohariu fault cannot be mapped, with confidence, any further northeast than Kahuterawa Stream because northeast of Kahuterawa Stream the topographic "distinctness" of the fault rapidly diminishes. It is here that the Northern Ohariu fault and the Wellington fault are closest; they are sub-parallel to each other, and only 7 km apart.

## 5.0 DISCUSSION

The primary goal of this investigation has been to better define the earthquake hazard posed by the newly discovered Northern Ohariu fault. Towards this end, we have attempted to place constraints on the fault's location (Fig. 2), slip rate, single-event surface-rupture displacement size, and elapsed time since most recent surface rupture. In the paragraphs that follow, we summarize the relevant field data that constrain these fault rupture parameters, and derive best-estimate values for these parameters. These values are, in turn, used to estimate earthquake recurrence interval, and magnitude(s) of past surface-rupture earthquakes on the fault. Also, because we consider that the Northern Ohariu fault and the Ohariu fault are the along-strike continuations of each other (see Fig. 1), we compare our rupture parameters for the Northern Ohariu fault with those that have been previously published for the Ohariu fault by Heron *et al.* (1998).

At the end of this Section, we comment on the various impacts that a large surface-rupture earthquake on the Northern Ohariu fault would have on communities and engineering structures proximal to the fault.

### 5.1 Slip Rate

A maximum right-lateral slip rate of 2-3 mm/yr is estimated for the Northern Ohariu fault at Corbetts Road (Fig. 6; sites 30, 31 & 85 of Table 1), based on the ca 450 m maximum right-lateral displacement of an alluvial terrace/hillslope contact that is interpreted to be Marton in age or just older (between ca 140 000-200 000 years). At Tangimoana Road (Fig. 6; site 1b of Table 1), a minimum lateral slip rate of 0.7-2 mm/yr is estimated based on the minimum 10-20 m lateral offset of an Ohakean age (ca 15 000 years) terrace riser. Near Florida Road (site h of Table 1) a lateral slip rate of 1-3 mm/yr is estimated based on the 20-30 m lateral offset of an Ohakean age terrace riser. Taken collectively, we consider that the best estimate for the right-lateral slip rate of the Northern Ohariu fault is 1-3 mm/yr.

In relation to the Ohariu fault, the late Quaternary right-lateral slip-rate for both faults appears to be similar. The Ohariu fault has a lateral slip rate of 1-2 mm/yr (Heron *et al.* 1998), compared to 1-3 mm/yr for the Northern Ohariu fault.

### 5.2 Size of Single-Event Surface-Rupture Displacements

Near Tangimoana Road, the eastern strand of the fault laterally displaces the channel-wall of a small spring by 3±1 m (Fig. 8; site 1c of Table 1). On the south side of the Ohau River, east-southeast from the end of Florida Road, a young terrace riser is right-laterally displaced by 2.5-3.0 m, and vertically displaced by ca 1.5 m, northwest side up (Fig. 10; site i of Table 1). This amounts to about 3.0-3.5 m of net displacement, assuming a near vertical fault dip. These are the smallest offsets yet identified along the Northern Ohariu fault, and are taken as a measure of the amount (ca 3-4 m) of surface rupture displacement that occurred during the most recent earthquake on the fault.

As with slip rate, the size of the most recent surface rupture displacement on the Ohariu and Northern Ohariu faults appears to be similar. The most recent surface rupture earthquake on the Ohariu fault resulted in about 3-5 m of predominantly right-lateral displacement at the ground surface (Heron *et al.* 1998), and the most recent surface rupture earthquake on the Northern Ohariu fault resulted in about 3-4 m of predominantly right-lateral displacement at the ground surface (though this value is based on only two measurements, and is thus less well constrained than for the Ohariu fault).

### 5.3 Elapsed Time Since Most Recent Surface Rupture

The timing of the most recent surface rupture event on the Northern Ohariu fault is constrained using inferred ages, based on relative soil development and topographic position in the landscape, of faulted and unfaulted alluvial terraces. At two sites along the fault, one near the Otaki River (site d of Table 1) and the other near Waitohu Stream (site g of Table 1), the youngest faulted alluvial terrace has a Manawatu soil developed on it, which is a recent soil, and this implies that the most recent surface rupture of the Northern Ohariu fault is late Holocene in age, probably within the last ca 1000 years. Soil development on unfaulted terraces suggest that at least several hundred years have elapsed since the most resent surface rupture. Thus, our best estimate for the timing of the most recent surface-rupture of the Northern Ohariu fault is that it younger than ca 1000 years, and older than ca several hundred years.

Regarding the timing of the most recent surface-rupture of the Ohariu fault, Heron *et al.* (1998) entertain the possibility that sections of the Ohariu fault south of Porirua (Makara-Porirua) and north of Porirua (Porirua-Waikanae) may represent separate rupture segments of ca 25 and 35 km long, respectively, separated by the suspected ca 1.5 km right-sidestep in Porirua Harbour, and on which the most recent ruptures were closely spaced in time. However, they conclude that the simplest interpretation is of a single segment totaling 60 km or more (Makara-Waikanae). Regressions of total rupture length and single event displacement published by Wells & Coppersmith (1994) yield a total rupture length exceeding 100 km for an average single-event displacement of ca 3 m or greater. Geomorphic estimates of lateral displacements of 3-5 m on the Ohariu fault favour the single segment interpretation. Accepting the single segment interpretation for the Ohariu fault, the timing of the most recent surface-rupture can be closely constrained at 1070-1130 years ago.

## 5.4 Earthquake Recurrence Interval

Except for the most recent surface rupture event on the Ohariu fault, individual paleoearthquakes on both the Ohariu and Northern Ohariu faults have yet to be dated, and thus individual inter-earthquake times for either fault are not known. As a consequence, a combination of the fault's single-event surface-rupture displacement size and its slip-rate must be relied on to provide an estimate of the fault's average earthquake recurrence interval. The average recurrence interval for the Northern Ohariu fault is estimated to be in the order of one thousand to several thousand years, based on a single-event displacement size of ca 3-4 m, and a slip rate of 1-3 mm/yr. The average recurrence interval for surface rupture earthquakes on the Ohariu fault is estimated to be in the order of 1500-5000 years, based on a single-event surface-rupture displacement size of 3-5 m, and a slip rate of 1-2 mm/yr.

## 5.5 Estimated Magnitude of Surface Rupture Earthquakes

Typically there are two methods by which earthquake magnitude can be estimated (predicted) for future rupture of an active fault. The first method relies on empirical regressions that relate earthquake magnitude to various measurable fault parameters such as surface rupture length, and single-event displacement size (e.g. Wells & Coppersmith 1994). The second method attempts to estimate the actual energy that would be released by rupture of the fault. This is done by calculating a seismic moment for the fault which is directly proportional to the area of fault rupture, the average displacement over the area of fault rupture, and the rigidity of the rocks surrounding the fault. From a seismic moment, a Moment Magnitude ($M_w$) can be estimated (e.g. Hanks & Kanamori 1979).

Wells & Coppersmith (1994) present empirical relationships among magnitude ($M_w$), rupture length, rupture width, rupture area, and surface displacement based on the analysis of over two hundred historical earthquakes. Specifically, they present regressions that relate earthquake magnitude to surface rupture length, and net surface rupture displacement; these regressions can be used to estimate the likely earthquake magnitude that will result from future surface rupture of the Ohariu and Northern Ohariu faults. As discussed previously, the best estimate for the rupture length for the Ohariu fault is ca 60 km (based on Heron *et al.*'s favored single segment interpretation, and including the discontinuous fault scarps north of Paraparaumu, but excluding the offshore portion of the fault for which there are few data), and for the Northern Ohariu fault it is also about 60 km. The net surface rupture displacement resulting from the most recent earthquake on the Ohariu fault is about 3-5 m, and on the Northern Ohariu fault it is about 3-4 m. Based on the rupture length regression of Wells & Coppersmith, for strike slip faults, a 60 km long rupture would be expected to result in a $M_w$ 7.2±0.3 earthquake; and using their average net displacement regression, again for strike slip faults, a 3-4 m net surface rupture displacement would be expected to result in a $M_w$ 7.5±0.3 earthquake.

A seismic moment of $1.1\text{-}1.4\times10^{20}$ Nm can be estimated for rupture of both the Ohariu and Northern Ohariu faults if the following rupture parameters are used, or assumed: rupture length, 60 km; dip, 90°; rupture width, 20 km; average displacement on the fault plane, 3-4 m; rigidity, $3\times10^{11}$ dyne/cm$^2$. A seismic moment of $1.1\text{-}1.4\times10^{20}$ Nm equates to an earthquake of $M_w$ 7.3-7.4.

From the above, it seems reasonable to conclude that both the Ohariu fault and the Northern Ohariu fault are capable of generating earthquakes in the order of $M_w$ 7.2-7.5. An estimate of the Maximum Credible Earthquake that either fault may be able to produce can be made by assuming that both faults rupture during the same earthquake. This would result in an earthquake of roughly double the seismic moment as that calculated for rupture of either fault individually, or an earthquake of approximately $M_w$ 7.4-7.8. At present, the available data does not allow us to determine whether or not the Ohariu and Northern Ohariu faults represent independent earthquake sources, or a single, much larger, earthquake source.

## 5.6 Earthquake Hazards Associated with Rupture of the Northern Ohariu Fault, and Communities and Structures Likely to be Affected by Rupture of the Fault

The principle earthquake hazards likely to result from a large surface-rupture earthquake on the Northern Ohariu fault include fault rupture of the ground surface, strong ground shaking, liquefaction, and landsliding. Below we outline some of the possible consequences that these hazards may impose on communities and engineering structures sited near, and across, the fault.

### 5.6.1 Fault rupture of the ground surface

Displacement of the ground surface resulting from fault rupture is perhaps one of the more obvious earthquake hazards. The Northern Ohariu fault has a length of ca 60 km (Figs. 1 & 2), and an estimated single-event, net, surface rupture displacement of ca 3-4 m (predominantly right-lateral strike slip). It is not hard to imagine the problems that such a displacement would cause to structures such as houses, transmission lines, pipe lines, and roads that cross the fault.

The Kapiti coast and Horowhenua are popular places to live, and an increasing number of farms are being sub-divided for residential development. In relation to the Northern Ohariu fault, this is particularly the case near Otaki, between Te Horo and Waitohu Stream along Old Hautere and Ringawhati Roads. Here, there are an ever increasing number of lifestyle blocks that straddle the fault. Some houses, both existing and currently under construction, are built very close to the fault, and, in some instances, across the fault.

Also, between the Otaki and Ohau Rivers, there are major electrical transmission lines that follow the Northern Ohariu fault. For long stretches, the transmission lines are sited directly over the fault, and in several cases, adjacent pylons are sited on opposite sides of the fault. In these instances rupture of the fault will either shorten or lengthen the distance between the pylons. In the case where the southwestern pylon is on the northwest side of the fault, and the adjacent pylon to the northeast is on the opposite (southeast) side of the fault, rupture of the Northern Ohariu fault, because it is primarily a right-lateral strike-slip fault, will shorten the distance between the two pylons and increase the amount of slack in the transmission lines between them. In the other case, where the southwestern pylon is on the southeast side of the fault, and the adjacent pylon to the northeast is on the northwest side of the fault, rupture of the fault will lengthen the distance between the two pylons and decrease the amount of slack in the lines between them. In the later case, damage to lines and/or pylons may result.

The No. 1 hydro tunnel of the Mangahao Hydro Electric scheme crosses the Northern Ohariu fault near Tokomaru No. 3 Reservoir.

There are quite a few roads that cross the Northern Ohariu fault (Fig. 2), and, when the fault ruptures, these can be expected to be displaced by 3-4 m across the fault.

***Roads that cross the Northern Ohariu fault:***
State Highway 1 (?), Old Hautere Road, Otaki Gorge Road, Rahui Road, Ringawhati Road, North Manakau Road, Tangimoana Road, Florida Road, Poads Road, Gladstone Road, Mangahao Road, Scotts Road, Kahuterawa Road (?)

### 5.6.2 Strong ground shaking

Strong ground shaking is the most pervasive of all earthquake hazards, and is responsible, either directly or indirectly, for most of the damage and life loss caused by an earthquake. The level of shaking that a site experiences during an earthquake is, to a large extent, governed by the size of the earthquake, the distance between the site and the earthquake, and type of material that underlies the site.

To gain an impression of the area that will be affected by strong ground shaking resulting from a Northern Ohariu fault earthquake, we have modeled the extent of shaking by assuming a $M_w$ 7.2 earthquake on a steep dipping, strike-slip Northern Ohariu fault, and using the Modified Mercalli (MM) intensity attenuation relationship of Smith (2002). The MM intensity scale is a description of the severity of shaking at a site. It is divided into 12 categories, with MM1 describing the lightest of shaking and MM12 the most extreme. A complete description of the MM intensity scale, and its application in New Zealand, is found in Dowrick (1996), but, for the purpose of this discussion, it is sufficient to note that the onset of significant damage occurs at MM7, and damage increases with increasing intensity. MM7 can be described as strong to very strong shaking with people experiencing general alarm and difficulty in standing; MM8 is very strong to destructive shaking with people experiencing alarm that approaches panic; by MM9, the shaking is destructive to very destructive.

Below we list the communities that lie within the MM9, MM8, and MM7 isoseismals, respectively, of our modeled Northern Ohariu fault rupture. Communities within the MM7 isoseismal are expected to experience MM7 or greater shaking, communities within the MM8 isoseismal are expected to experience MM8 or greater shaking, and communities within the MM9 isoseismal are expected to experience MM9 or greater shaking. It is also important to point out that the magnitude of the modeled earthquake ($M_w$ 7.2) is the low end of the likely magnitude range listed in Section 5.5. It is quite possible that rupture of the Northern Ohariu fault will generate a larger magnitude earthquake, especially if it ruptures simultaneously with the Ohariu fault. If this is the case, then higher levels of shaking would be experienced at greater distances away from the fault, such that, for example, some of the communities listed below within the MM7 isoseismal will experience MM8 shaking.

***Communities within MM9 isoseismal*** *(destructive to very destructive shaking):*
Te Horo, Otaki, Manakau, Kuku, Ohau, Muhunoa East, Levin, Shannon, Tokomaru, Linton

***Communities within MM8 isoseismal*** *(very strong to destructive shaking):*
Paraparaumu, Waikanae, Te Horo Beach, Otaki Beach, Waikawa Beach, Hokio Beach, Waitarere, Foxton, Foxton Beach, Palmerston North, Woodville, Pahiatua, Eketahuna

***Communities within MM7 isoseismal*** *(strong to very strong shaking):*
Wainuiomata, Petone, Lower Hutt, Upper Hutt, Porirua, Paekakariki, Himatangi Beach, Tangimoana, Feilding, Bulls, Marton, Danneverke, Pongaroa, Masterton, Carterton,

Greytown, Featherston

A common feature of may earthquakes is differential compaction and settlement of fill slopes resulting from strong shaking. This often affects roading, particularly at approaches to bridges and overpasses.

Following a large earthquake on the Northern Ohariu fault, or, for that matter, any fault in the Wellington region, there is a good chance that the main shock will be followed by a number of strong aftershocks. It will be important to remember that after the main shock, a severely damaged, but still standing structure, may subsequently collapse as a result of the shaking generated by one of these aftershocks.

### 5.6.3 Liquefaction

Liquefaction is the process by which water-saturated sediment temporarily loses strength, usually because of strong shaking, and behaves as a fluid. If liquefaction is sufficiently severe and extensive, buildings may settle or tilt; buried structures, such as underground pipes and tanks, may float upwards; and roads and flood control stop-banks may fail.

Parts of the Horowhenua and Manawatu are known to be extremely susceptible to liquefaction. For example, the 1942 June 24 Wairarapa earthquake generated liquefaction sand boils near the Manawatu River between Opiki and Foxton Beach (Downes *et al.* 2001). A surface-rupture earthquake on the Northern Ohariu fault will generate levels of shaking in the Horowhenua and Manawatu far in excess to those generated by the 1942 June 24 Wairarapa earthquake. We anticipate that liquefaction will be a significant feature of a Northern Ohariu fault earthquake.

MM7 is generally regarded as marking the onset of liquefaction in susceptible materials. As such, we anticipate that rupture of the Northern Ohariu fault will generate liquefaction from as far south as Petone, as far north as Marton, and as far east as Dannevirke and Masterton. With increasing intensity, the severity of liquefaction increases, and we suspect that liquefaction will be extensive and severe in the late Holocene sand country, low level river terraces, and flood plains of the Kapiti, Horowhenua, Manawatu, and Wairarapa lowlands from Paraparaumu, and Palmerston North in the south, and north, respectively, and Foxton Beach, and Ekatahuna in the west, and east, respectively.

### 5.6.4 Landsliding

Strong earthquake shaking can induce landsliding, and most of the historical earthquake-induced landslides in New Zealand have occurred on steep to very steep (30°-45°) bedrock slopes, slopes undercut by erosion, and steep cut slopes along roads and railway lines (Hancox *et al.* 2002). Failures in alluvial materials occur mainly along river channels, terraces, and coastal cliffs. A similar pattern of landslide damage is expected for a large earthquakes on the Northern Ohariu fault.

As with liquefaction, MM7 is generally regarded as marking the initiation of moderate to large earthquake-induced landslides. This being the case, then earthquake-induced landslides resulting from a Northern Ohariu fault rupture could be expected throughout the entire Tararua Range, and as far south as the northern Rimutaka Range, as far north as the southern Ruahine Range, and as far east as the Waewaepa and Puketoi ranges. With increasing shaking intensity, both the number and size of earthquake-induced landslides increases, and in areas of steep slope, within the MM9 isoseismal, earthquake-induced landsliding is extensive. The MM9 isoseismal of the modeled Northern Ohariu fault rupture encompasses the western flank of the Tararua Range between the Otaki River in the south, and Kahuterawa Stream in the north.

Related consequences of earthquake-induced landsliding include river aggradation and the possible impacts this may have on flood control measures, and potential flooding resulting from catastrophic failure of landslide dams.

## 6.0 CONCLUSIONS

The Northern Ohariu fault is characterized by right-lateral displacement of drainage features of up to several hundred meters, a subordinate up to the NW sense of displacement, a single event net surface rupture displacement of 3-4 m (measured at only two localities), an average horizontal slip rate of 1-3 mm/yr, and a recurrence interval of one thousand to several thousand years. The most recent surface rupture displacement on the fault is younger than ca one-thousand years, and older than several hundred years. The Northern Ohariu fault, as well as the Ohariu fault to the south, are considered capable of generating $M_w$ 7.2-7.5 earthquakes. Larger earthquakes, ca $M_w$ 7.4-7.8, would result if both faults were to rupture simultaneously. Better dating of past surface rupture earthquakes on both faults is needed in order to resolve this important earthquake hazard issue.

Fault rupture of the ground surface, strong ground shaking, liquefaction, and landsliding will be the principle earthquake hazards associated with a large ($\geq M_w$ 7.2) surface-rupture earthquake on the Northern Ohariu fault. Houses, transmission lines, pipe lines, and roads cross the fault, and 3-4 m of net surface-rupture displacement will adversely affect these structures. Damaging levels of strong ground shaking will result from a large Northern Ohariu fault earthquake, and will be felt as far south as Petone, as far north as Marton, and as far east as Dannevirke and Masterton. The highest, most damaging, levels of shaking will occur closest to the fault and will encompass the communities of Te Horo, Otaki, Manakau, Kuku, Ohau, Muhunoa East, Levin, Shannon, Tokomaru, and Linton.

Parts of the Horowhenua and Manawatu are known to be extremely susceptible to liquefaction. As such, we anticipate that liquefaction will be a significant feature of a Northern Ohariu fault earthquake, and will affect most severely the late Holocene sand country, low level river terraces, and flood plains of the Kapiti, Horowhenua, Manawatu, and Wairarapa lowlands from Paraparaumu in the south, Palmerston North in the north, and Foxton Beach, and Ekatahuna in the west, and east, respectively. Earthquake-induced landslides will also be generated, and these will be most extensive and severe along the western flank of the Tararua Range between the Otaki River in the south, and Kahuterawa Stream in the north. The steep slopes of the Manawatu gorge are also susceptible to failure during such an earthquake. Consequent with earthquake-induced landsliding is river aggradation, and the possible impacts this may have on flood control measures, and potential flooding resulting from catastrophic failure of landslide dams.

Of the alluvial terrace sequences along the rivers and streams that cross the southern half of the Northern Ohariu fault, the most complete is along the NE bank of Waikawa Stream. Here, well defined terrace surfaces range in age and elevation from Holocene to Marton (ca 140 000 years), and ca 80 m to 100 m, respectively. Older extremely weathered, and dissected alluvial gravels, into which the Marton terrace is cut, are also present (elevation ca 120-140 m). These extremely weathered gravels are capped by up to 6 m of loess, but the Rangitawa tephra (ca 340 000 years) has yet to be found within the loess, suggesting that these weathered gravels are either younger than, or coeval with, the Rangitawa tephra and thus Stage 8 or 10 in age. These weathered gravels, as well as the younger less weathered gravels, lie within the river valley system that defines the "current" catchment, implying that the "current" catchments along the NW Tararuas were largely developed by Stage 8 or 10 time. There is an older surface(s) - expressed as low-relief, concordant ridges - that defines the top of the landscape (elevation ca 500 m), and it is into this surface(s) that the "current" catchments are developed.

We consider that we have addressed the stated objectives of this research project. As such, the results of this work have direct relevance to the scientific, earthquake engineering and insurance communities. For example, earthquake magnitude estimates for the fault will allow ground motions to be calculated for rupture of the fault. Knowledge of the fault's location will allow planners and engineers to mitigate against the rupture hazard of the fault. Earthquake recurrence interval data for the fault, as well as magnitude estimates, will allow the fault to be explicitly incorporated into seismic hazard models for the region. The study will allow Regional authorities to adjust their assessment of hazard requirements under the Resource Management Act.

## 7.0 ACKNOWLEDGMENTS

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## 9.0 TABLES AND FIGURES

### TABLES:



### FIGURES

**Table 1. Listing of Sites and Site Data, Northern Ohariu Fault**

| Figure in Text | Grid Reference (NZMS 260) | Site No. | Key Points |
|---|---|---|---|
| **TE HORO-OTAKI RIVER** | | | |
| | R25 895432 | a | Multiple, closely spaced N-facing ca 1m high scarps on stony Ohakean terrace (Ashhurst stony silt loam soil). Approximate SW extent of traceable fault. |
| Fig. 4 | S25 908436 | b | 1.5-2m high SE-facing scarp, offsetting Ohakean terrace (Ashhurst stony silt loam soils). |
| Fig. 5 | S25 925446 | c | 1.5m high SE-facing scarp crossing Otaki Gorge Road. Ohakean terrace and Ashhurst stony silt loam soil. Scarp is very clear and relatively continuous between sites a and c. Scarp continues NE to edge of Ohakean terrace riser. |
| | S25 927447 | d | Spring at foot of riser of Ohakean terrace. Aerial photographs taken in 1948 (307/7-9) show fault trace striking NE across Manawatu terrace (Manawatu soils, less than 1000 years old), but not on Rangitikei terrace and river flood plain. Therefore movement in last ca 1000 years. |
| **OTAKI RIVER – WAITOHU STREAM** | | | |
| | S25 937453 | e | Early-mid Holocene terrace with Paraha soil is offset, but younger Rangitikei terrace is not. |
| | S25 939455 | f | Ringawhati Road follows the fault (upthrown 1-3m to W) for 400m. Fault strikes NE toward Waitohu Stream. Surface is Marton terrace with Levin and Waitohu soils developed in loess. |
| | S25 955466 | g | On 1948 photographs (306/8-10), the fault trace is very clear on young river terraces of Waitohu Stream, and shows clear right-lateral strike-slip displacement, but has now been partially destroyed by land development and drainage. Offset surface has Manawatu and Kairanga soils; therefore, most recent movement is younger than ca 1000 years. |
| **SOUTH MANAKAU ROAD** | | | |
| | S25 979496 | 30 | Cutting in track. Approximately 2m of loess over 2m of relatively fresh gravels and 7.8m of very weathered gravel. Loess is |

| | | | |
|---|---|---|---|
| | | | Ohakean, and younger gravels are Ratan age. |
| | S25 979497 | 31 | Auger hole on flat paddock on axis of fan. Waitohu soil in mottled loess to 1.3m; brown unmottled loess to 1.6m; weak paleosol with root channels to 1.8m; orange brown (10YR 5/8) sandy silt loam loess to 3.1m; on weathered gravels at 3.1m. Ohakean and Ratan loesses on Porewan or older terrace. Site 31 is on same surface as site 85. |
| | S25 987502 | 32 | Road cut exposure and auger hole beside forestry road. Waitohu soil in mottled loess; tephra 70-80cm; blocky paleosol 1.05-1.45m; orange mottled loess to 1.7m; blocky brown paleosol 1.7-2.1m; (road level) yellowish brown loess to 3.5m; unconformity; red (2.5YR 5/6) weathered clay to 3.9m; white (10YR 8/1) sandy clay loam to 4.5m; mottled very gritty sandy clay loam to 4.9m. Ohakean loess with Kawakawa tephra, over Ratan and Porewan loesses. Unconformity cuts into much older (>350ka?) sediments. |
| | S25 989501 | 33a | Fault scarp on young alluvial terrace in pine forest; upthrown by 1m to NW; scarp height increases on older surfaces to south; trend of fault 040-050°; alluvial silts dammed up against fault scarp and partly bury it, with Kairanga soil developed in mottled silts on fresh gravels at 1.1m. Fault is exposed on northern side of stream in a steep bank; coarse bouldery gravel unconformably overlies mixed gravel, sand and pug, and is offset vertically by 70cm near stream level; pug zone ca 1.1m wide. "Unfaulted" Kairanga soil immediately upstream of fault interpreted to be only a few hundred years old. |
| | S25 989501 | 33b | On upthrown side of fault at same site. Ohakea soil in silts over gravels, indicate age of at least mid-Holocene. Therefore fault has ruptured ground surface within the Holocene, but not in last several hundred years. |
| | S25 989501 | 34 | Soil on "faulted" remnant terrace on hillside 50m W of fault. 50cm brown silty clay loam with good structure over 20cm very mottled silt loam with weak structure; on weakly-moderately weathered sandy gravels. Paraha soil estimated mid to early Holocene age. Sites 33 and 34 constrain the last movement on the fault between mid Holocene and several hundred years ago. |
| | S25 973486 | 83 | Whitehead dairy farm, 200m W of 110kv lines, 300-400m SE of cowshed. 0-110cm mottled loess; 110-120cm sandy Kawakawa Tephra; 120-175cm mottled loess (base of Ohakean loess); 175-320cm orange coloured very mottled clay rich loess-unbottomed. Shannon silt loam in Ohakean loess over Ratan loess. Surface is at least Porewan. |
| | S25 973488 | 84a | 200m S of Whitehead cowshed. 90cm of very mottled silty colluvium over gravels. Paraha silt loam on Ohakean gravels. |
| | S25 973489 | 84b | 50m NW of site 84a. 60cm of stony silty colluvium on gravels. Paraha silt loam on Ohakean gravels. |
| Fig. 6 | S25 981498 | 85 | Deer farm, 300m NE of house, 200m NW of pylon. Auger hole to test age of surface. 0-70cm well drained loess; 70-102cm mottled loess; 102-130cm mottled sandy loam (colluvium); 130-175cm mottled loess; 175-200cm greasy sandy loam (Kawakawa Tephra); 200-230cm mottled loess (base of Ohakean loess); 230-360cm 7.5YR 5/8-5/6 silty clay loam with a few reddish brown and grey mottles (Ratan loess); 360-410cm (10YR 6/3) silty clay loam with many (10YR 4/6) prominent |

mottles, and a few root channels with reddish brown coatings (Porewan loess); 410-435cm very weathered soft mottled greywacke gravels. Weathering of gravels suggests terrace is at least Marton age. At this site, the maximum offset of the valley wall into Marton Gravels is 450m. If Marton gravels are ca 140ka, then right-lateral slip rate is ca 3mm/yr. If valley wall was formed by down cutting in previous interglacial (200ka), then rate is closer to ca 2 mm/yr.

## WAIKAWA STREAM & NORTH MANAKAU ROAD

| | | |
|---|---|---|
| S25 997511 | 57 | Very weathered, rounded, greywacke dominated alluvial gravel SW from Waikawa Stream. All clasts can be broken with hammer, and most clasts are easily cut with pocket knife. Gravel is probably pre-Marton in age. |
| S25 993527 | 58 | Hole dug on flat terrace. 0-28cm - 10YR 4/3 silt loam with few stones; 28-60cm - yellowish-brown stony silt loam; on brownish grey sandy gravels. Hautere stony silt loam on Ohakean gravels. |
| S25 998519 | 59 | Higher terrace than site 58, 50m E of W.J. Wood horse stud. 0-100cm well drained 10YR 5/5-6/4 silt loam loess; 100-120cm as above but with common reddish brown mottles; 120-135cm - 10YR5/6 silt loam loess; on gravels. Levin silt loam in Ohakean loess on Ratan terrace. |
| S25 000521 | 60 | High terrace at about 100m elevation, 200m E of 11kv line. 0-120cm - 10YR 6/4-2.5Y 6/5 silty clay loam with very few mottles; 120-130cm - 10YR 5/6 sandy loam (Kawakawa Tephra); 130-170cm - 10YR 5/6 silty clay loam (base of Ohakean loess); 170-230cm - 10YR 5/8 silty clay loam with blocky structure, a few fine root channels and common black to dark reddish brown stains and coatings; 230-300cm slightly paler - 10YR 5/6 silty clay loam with coarse blocky structure (base of Ratan loess); 300-340cm - 10YR 5/5 with many coarse prominent - 7.5YR 4/4 mottles; gritty soft silty clay loam with occasional small (< 1cm) rounded very smooth pebbles; a few fine root channels with dark reddish brown coatings; 340-380cm - 7.5YR 5/6 clay loam with common grit and/or iron concretions and a few fine root channels lied with dark reddish brown coatings; 380-400cm as above but with common reddish brown and grey mottles (base of Porewan loess); 400-460cm - 10YR 6/4-2.5Y 6/4 silty clay loam with common grey and reddish brown mottles; blocky structure and many fine root channels lined reddish brown coatings; a few angular pebbles up to 1cm; 460-490cm as above but with common soft and hard fine greywacke pebbles; on gravels. Some of the gravels are soft and easily crushed by the auger, while others are harder. Levin silt loam soil on Ohakean, Ratan and Porewan loesses plus colluvium, on Marton (or possibly older) gravels. |
| S25 004 523 | 61 | Greater than 6m thickness of loess on extremely to very weathered gravel at ca 120-140m elevation. |
| S25 984533 | 82 | Arrandale farm, high terrace adjacent to foothills. 0-160cm well drained loess with Kawakawa Tephra at 130-140cm; 160-190cm pebbly sandy colluvium, on gravels. Levin silt loam in Ohakean loess on Ratan gravels. |
| S25 982532 | 81 | 1.8m loess over gravel; Kawakawa Tephra at 1.4m, therefore Ratan terrace. |

## KUKU

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| S25 994540 | 72 | 67cm colluvium or alluvium over gravel. Ohakean fan with cover of fine alluvium. |
| S25 989541 | 73 | 130cm fine alluvium or loess over gravel. Kawakawa Tephra not seen, therefore Ohakean fan with fine alluvium or loess cover. |
| S25 988543 | 74 | 1.45m silts with no Kawakawa Tephra over gravel. Ohakean age fan. |
| S25 994535 | 75 | 1.45m loess to Kawakawa Tephra; Ratan loess at 2m; gravel (Porewan terrace) at 2.77m. |
| S25 995530 | 76 | 1.5m loess to Kawakawa Tephra; 2m to top Ratan loess; 2.8m to gravels (Porewan terrace). |
| S25 994555 | 79 | 1.55m silty alluvium or loess over gravel; no Kawakawa Tephra, therefore probably Ohakean fan. |
| S25 987547 | 80 | 1.6m silty alluvium or loess over gravel; no Kawakawa Tephra, therefore Ohakean fan. |

## KUKU EAST ROAD

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|---|---|---|
| S25 997558 | 62 | Gently undulating surface on N side of road, 500m E of SH1. Stony sandy loam with weak Bw horizon. Manawatu shallow sandy loam. Therefore surface is late Holocene age. |
| S25 996560 | 63 | 105cm sandy alluvium with weak Bw horizon over gravels. Manawatu fine sandy loam. Surface is late Holocene. Both sites 62 & 63 are on a late Holocene terrace surface of Ohau River. |
| S25 996555 | 64 | On sand hill 100m S of road. 57cm of well drained silty loess over Otaki Dunesand. Levin silt loam on sand. |
| S25 998556 | 65a | Beside road and stream culvert is 1.2m loess or silty alluvium over up to 2m fine gravels then more loess or alluvium to stream level. Could be Ratan or Ohakean gravels lapping on to loess over Otaki Dunesand. |
| S25 001556 | 65b | 100 N of road. Up to 1.2m silty colluvium or loess in channels over 3-4m of weakly weathered gravels. Gravels thought to be of Ohakean age with Paraha soil developed in the silty colluvium. |
| S25 019557 | 66 | End of N-branch of Kuku East Road. 150cm unmottled loess over gravel. Levin silt loam and Ohakean loess over Ratan fan surface. |
| S25 024556 | 67 | 125cm of loess, mottled at 75cm, over gravels. Waitohu silt loam in Ohakean loess over Ratan fan surface. |

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| | S25 020553 | 68 | Narrow interfluve between drainage ways on fan. 90cm mottled loess over gravel. Shannon silt loam in Ohakean loess over Ratan fan surface. |
| | S25 013537 | 69 | S-branch of Kuku East Road, near end. Auger hole 40m W of road and 80m S of woolshed. 205cm well drained silty loess, including Kawakawa Tephra at 140-150cm, over 50cm pebbly silty colluvium, on gravels. Levin silt loam in Ohakean loess on Ratan fan surface. |
| | S25 009531 | 70 | 0-120cm mottled loess; 120-135cm Kawakawa Tephra; 135-170 unmottled loess; 170-230cm slightly stony sandy clay loam on gravels. Shannon silt loam soil in Ohakean loess over Ratan fan surface. Note that Ratan fans in this area, and to the north appear to have drowned fans of Marton age or older, which poke through in places. Soil profile at this site is very similar to that at site 69. |
| | S25 015549 | 71 | Auger hole 20m N of road. 0-60cm unmottled loess; 60-120cm mottled loess; 120-150cm unmottled loess; 150-170cm sandy Kawakawa Tephra; 170-190cm mottled loess; 190-240cm very mottled silty clay loam with common iron stained root channels; 240-270cm very mottled fine gravelly sandy loam; 270-290cm very mottled blue grey soft clay; 290-380cm light bluish grey very soft clay; 380-410cm live brown very stiff sandy clay loam with common root channels; 410-440cm light olive brown soft sandy clay; unbottomed (too soft to auger). Probable interpretation - Waitohu silt loam in Ohakean loess over lake beds of unknown age at toe of fan. |

## TANGIMOANA ROAD – MUHUNOA EAST

| | | | |
|---|---|---|---|
| | S25 047553 | 41 & 47 | Auger holes on high terrace E of fault to establish its age. 0-30cm - 10YR 3/2 silt loam with nut structure; 30-80cm - 10YR 5/6-5/8 silt loam with nut and crumb structure (Levin silt loam soil); 80-120cm - 10YR 5/3 silt loam; 120-190cm - 10YR 5/5 silt loam; slightly sandy from 145-155cm with slightly orange tinge (Kawakawa Tephra); Ohakean/Ratan loess boundary at 190cm; 190-270cm - 10YR 5/8 silty clay loam with fine blocky structure; 270-280cm - 10YR 5/5 massive silty clay loam; 280-340cm - 10YR 5/6 silty clay loam with blocky structure and many fine root channels; coatings on peds and root channels are pale brown -reddish brown (paleosol on Porewan loess); 340-415cm - 10YR 5/5 silty clay loam with blocky structure, few root channels and a few reddish mottles; 415-420cm - 7.5YR 5/8-4/6 silty clay loam with abundant black -dark reddish brown concretions about 0.5cm diameter; 420-490cm - 10YR 6/3-6/4 very plastic and soft silty clay loam, common 7.5YR 5/8 coarse mottles and vertical streaks, common concretions as above; common fine black sand sized ferromagnesian crystals (base of Porewan loess); 490-520cm - as above but root channels and concretions more common (paleosol?); 520-620cm - 10YR 6/4 silty clay loam, firm and massive with few black concretions and fine root channels; 620-650cm - 10YR 6/4 silty clay loam with many grey and reddish brown mottles and a few stones; on gravels at 650cm. Gravels are slightly-moderately weathered. The gravels and terrace are thought to be of Marton age. |
| Figs. 7 & 8 | S25 039555 | 1 | Verry woolshed, 20 m E of fault scarp. 1-1.5 m scarp up-thrown to W. Auger hole to test age of terrace. 0-176cm - 10YR 5/6 silty loess with Levin silt loam soil and Kawakawa Tephra at 100cm depth; on weakly weathered gravels at 176cm. Therefore |

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| | | | offset terrace is Ratan age. |
| Fig. 8 | S25 039555 | 1b | Narrow Ohakean terrace at Verry woolshed is vertically offset by ca 0.7m, 10-20m right lateral offset since Ohakean terrace surface formed (max. 15ka), giving ca. 0.7-2mm/yr lateral slip rate (minimum). |
| Fig. 8 | S25 040556 | 1c | About 50 m NE from Verry woolshed. 3±1m right-lateral displacement of channel-wall of a small spring. Channel is cut into Ohakean terrace, thus younger than Ohakean. Smallest observed offset along this portion of the fault, and may represent the amount of lateral displacement resulting from the most recent surface rupture on the eastern strand of the fault. |
| Fig. 8 | S25 039556 | 2 | Peat bog on Holocene surface, 80m NE of Verry woolshed, in line with fault. Holocene surface is very undulating and possibly offset. |
| Fig. 8 | S25 039556 | 3 | Soil description on low terrace to determine its age. 0-85cm mottled silty alluvium with a few pebbles; 85-110+cm mottled sandy loam with greywacke pebbles. Soil is Te Arakura silt loam of mid to late Holocene age. |
| | S25 041555 | 4 | Greywacke exposed in stream-bank at base of hill. |
| | S25 040557 | 5 | Ratan gravels including a 20cm thick silt exposed in stream-bank. |
| | S25 043558 | 5a | About 100m ESE of Muhunoa East School. Most distinct of four right-laterally displaced (guided) streams (small valleys). Amount of lateral displacement ca 50-60m. |
| Fig. 8 | S25 039556 | 6 | Soil profile to check age of low terrace. 64cm of mottled pebbly sandy alluvium on gravels. Te Arakura sandy loam. |
| Figs. 7 & 8 | S25 038554 | 7 | 100m SW of Verry woolshed. Fault scarp and Ratan gravels partly exposed in terrace edge |
| Figs. 7 & 8 | S25 038554 | 8 | Complex low terraces 180m SW of woolshed. Mostly Kairanga and Te Arakura soils, but narrow discontinuous Ohakean terraces are also inset into the main Ratan terrace. |
| Fig. 7 | S25 036555 | 9 | Narrow interfluve 50m W of fault, which is upthrown 1m to W at this point. 1.5m loess with mottles below 43cm and Kawakawa tephra at 90cm; on weakly weathered gravels. Shannon silt loam and Ohakean loess overlying Ratan gravels. |
| Fig. 7 | S25 036555 | 10 | Fault exposed in a 1m deep drain. Upthrown 1m to W. Peat on eastern side is 0.8m deep. |
| Fig. 7 | S25 036555 | 11 | Degraded Ratan terrace just W of fault. Shannon silt loam on gravels at 1m. |
| Fig. 7 | S25 035553 | 12 | Fault not obvious. Prominent scarp 4-5m high faces W is either a terrace edge or fault upthrown to east. Soil profile on lower |

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| | | | surface is Shannon silt loam. |
| Fig. 7 | S25 034551 | 13 & 21 | On higher surface described at site 12, 150m N of house at end of Tangimoana Road. Waitohu silt loam with grey mottles by 65cm depth. Kawakawa Tephra at 160cm. At 185cm, loess assumes a more orange hue (Ratan loess); on weakly weathered gravels at 276cm (Porewan gravels). |
| Fig. 7 | S25 035549 | 14 | Farther E on fan surface. Shannon silt loam soil. |
| Fig. 7 | S25 036546 | 15 | Greywacke exposed in small stream at base of hill. |
| Fig. 7 | S25 037547 | 16 | Greywacke scarp ca 10m high, upthrown to W, with swamp on eastern side. |
| Fig. 7 | S25 037547 | 17 | Loess covered greywacke hillock, slope 10 degrees NW. Levin silt loam. |
| Fig. 7 | S25 038549 | 18 | Levin silt loam. |
| Fig. 7 | S25 041552 | 19 | Greywacke hillock in Ratan terrace, aligned with scarp described at site 16, but Ratan terrace does not appear to be offset or warped. |
| Fig. 7 | S25 041553 | 20 | Ratan terrace 200m SE of Verry woolshed. Waitohu silt loam. |
| Fig. 7 | S25 032551 | 22a | Stream at end of Tangimoana Road. Stream has inset Ohakean terrace. Fault is not obvious, but a spring and bog occur where the fault should cross the stream. |
| Fig. 7 | S25 032556 | 22b | On fan surface. Levin silt loam. |
| Fig. 7 | S25 033555 | 23 | On warped fan surface. Waitohu silt loam. |
| Fig. 7 | S25 034554 | 24 | Waitohu silt loam |
| Fig. 7 | S25 035556 | 25 | Sag pond adjacent to zig zag in Tangimoana Road. > 1m peat against scarp upthrown 1-1.5m to W. The total scarp height is 4-5m. |
| Fig. 7 | S25 033557 | 26 | Waitohu silt loam. |
| Fig. 7 | S25 035559 | 27 | On lower flat beside stream that cuts through the fault scarp. Te Horo stony silt loam. |

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| Fig. 7 | S25 036559 | 28 | Waitohu silt loam. |
| Fig. 7 | S25 035556 | 29 | Waitohu silt loam. |

## FLORIDA ROAD, OHAU RIVER

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| Fig. 9 | S25 049565 | 43 & 49 | Auger hole on sloping terrace offset by fault 100-200m to E. Aim is to determine the age of the terrace. 0-185cm Ohakean loess with Kawakawa Tephra at 140-145cm; soil at surface is Waitohu silty clay loam; 185-230cm - 10YR 5/6 silty clay loam with fine block structure and common fine root channels (paleosol on Ratan loess); 230-290cm - 10YR 5/8 with common 7.5YR 5/8 and 10YR 6/3 vertical mottles; 290-340cm - 10YR 5/6-5/7 silty clay loam with a few fine root channels lined with black coatings; a few grey and reddish brown mottles (paleosol on Porewan loess; 340-360cm as above but with many mottles and many fine black to reddish brown concretions; 360-400cm - 10YR6/6 silty clay loam, firm and massive, a few concretions and mottles as above; becomes sandier with depth; 400-440cm - 10YR5/6 with a few 5YR 4/6-5/8 mottles, a few black concretions and common dark reddish brown coatings in common root channels; sandy clay loam (colluvium); 440cm on slightly weathered sandy gravels. The terrace and gravels are most likely of Marton age (125-150ka). |
| Fig. 9 | S25 050567 | 44 | Large dune on E-side of Florida Road. Dune draped over greywacke bedrock high to NE. Sands are weakly consolidated greyish brown and 6-8m thick beside road; no loess cover. Below sands is a 1m lignite, the source of several springs; at base is 6-8m of rusty stained fine sandy gravels. The sands are considered to be Otaki Dunesand (ca 125ka) overlying Marton aged terrace gravels (125-150ka). |
| Fig. 9 | S25 049567 | 45 | Smaller dune on W-side of road. 4m weakly consolidated greyish brown sand over 1m strong brown sandy loam with blocky structure (Paleosol); overlies 4-6m of moderately weathered iron stained sandy gravels. Otaki Dunesand overlying Marton age gravels. |
| Fig. 9 | S25 046568 | 46 | Large dune on terrace edge, aligned W-E. 1.25m loess (no Kawakawa Tephra seen) over yellowish brown sand. The dune is 15m high. Indurated cross bedded sands are visible on the N-side in a farm track. Springs at base of sand may indicate a lignite (as for site 44). On iron stained sandy gravels. Levin silt loam soil in thin loess overlying Otaki Dunesand overlying Marton gravels. |
| Fig. 9 | S25 048564 | 50 | Soil profile to test age of low surface crossed by fault. 1.1m of silty colluvium over sandy gravels; mottled below 60cm, therefore Te Horo soil on Ohakean terrace. |
| Fig. 9 | S25 048564 | 51 | Repeat of site 50, 50m to E. Also Te Horo silty clay loam on Ohakean terrace. |
| Fig. 9 | S25 045565 | 52 | Near the hairpin corner on Florida Road. Auger hole to test the age of the fan surface. 0-200cm Ohakean loess and Levin silt loam soil, with Kawakawa Tephra at 160-170cm; 200-320 cm Ratan loess, noticeably more orange in colour than Ohakean |

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| | | | loess; 320-590cm undifferentiated loess; 590-600cm brownish yellow sandy clay loam; very weathered greywacke gravels crushed by auger. Therefore fan is at least Marton age and possibly older. |
| | S25 061565 | 53 | Ratan fan surface. Ohakean loess over gravel. |
| Fig. 9 | S25 054567 | 54 | Otaki Dunesand with loess cover. |
| | S25 057569 | h | Extensive Ohakean age terrace of Ohau River is displaced by fault. Possible right-lateral offset of Ohakean riser of ca 20-30m; difficult to measure because drainage ditches have been cut along the base of the riser upstream of the fault and along the fault, and because a small alluvial fan partially buries the riser/fault contact upstream of the fault. Site implies lateral slip rate of ca 1-3 mm/yr. |
| Fig. 10 | S25 067571 | i | S side of the Ohau River, ESE from the end of Florida Road. Young terrace riser is right-laterally displaced by 2.5-3.0 m, and vertically by ca 1.5 m, NW-side up. Soil developed on faulted terrace is a recent soil with a reasonably well developed Bw horizon - age estimated at ≤5000 years. Soil developed on younger, unfaulted terrace is suggestive of age of several hundred years. Interpreted that most recent surface rupture earthquake occurred within last 5000 years and was associated with 3.0-3.5 m of net surface rupture displacement, and fault has not moved within last several hundred years. |
| Fig. 11 | S25 073574 | j | NE of site i, and S of the Ohau River, fault is expressed as an ENE trending furrow, and broad mole-track-like feature across extensive Ohakean aggradation terrace. |
| | S25 074576 | k | Steep S bank of Ohau River at Gladstone Road Reserve. Exposure of ca 15m thickness of massive, course, Ohakean aggradation gravel overlying organic-rich silt unit containing wood and roots. Wood from organic-rich unit is dated at > 40 000 radiocarbon years (Wk-5292). |

## POADS ROAD, OHAU RIVER

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| Fig. 12 | S25 081579 | l | Possible subtle fault scarp across Holocene degradation terrace of Ohau River. To SW, fault scarp is expressed as a mole-track across higher Ohakean aggradation terrace. |
| | S25 093579 | 56 | 6+m of loess and colluvium in auger hole that did not reach gravel. However, coarse alluvial gravel is exposed in farm track up to site. Surface is at least Marton age. |
| | S25 091584 | m | Crushed bedrock and minor pug exposed on S bank of Ohau River. |
| | S25 094587 | n | Crushed bedrock and minor pug exposed on N bank of Ohau River. |

## MAKAHIKA STREAM & MAKAHIKA STATION

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| Fig. 13 | S25 130601 | 35 & 39 | Auger hole on high extensive dissected surface SE of Makahika Station; 0-95cm Levin silt loam soil developed in brown (10YR 5/4-5/6) silt loam loess; 95-110cm sandy loam tephra; 110-130cm brown loess; 130-160cm strong brown (7.5YR 5/7) paleosol with root channels and moderate structure; 160-215cm paler orange-brown silty clay loam with 1cm reddish brown soft iron pan at base; 215-270cm yellowish brown (10YR 5/6) silty clay loam with few root channels and reddish brown coatings on peds and channels; 270-360cm yellowish brown (10YR 5/6) silty clay loam with iron stained blocky peds and common root channels; common sand sized feldspar ghosts; paleosol; becomes slightly sandier at base; 385-485cm mottled grey and strong yellow sandy clay loam grading down to sandy loam; a few rounded greywacke pebbles below 400cm; more gravelly at base; gravels mostly very weathered; mottled at base; on moderately weathered gravels. Ohakean (with Kawakawa Tephra), Ratan and Porewan loesses over clean well sorted sand which may be Otaki sandstone, over terrace gravels of Marton age or older. |
| Figs. 13, 14 & 16 | S25 130610 | 36 | Auger hole on terrace remnant adjacent to and ca 50 m E of fault; 6.5m above Ohakean surface; 0-1m Levin soil developed in brown (10YR 5/5) silt loam; 100-110cm Kawakawa Tephra; yellowish brown sandy loam; 110-160cm brown silt loam; 160-230cm yellowish brown silty clay loam with few root channels and blocky structure in upper part (paleosol) and thin iron pan at 210cm; 230-300cm greyish brown (10YR 5/2) silty clay loam with many 0.5cm black concretions and root channels (paleosol); 300-320cm grey medium sand; 320-330+ cm yellowish brown fine pebbly sand; pebbles very weathered. This site has at least two and possibly three (Ohakean Ratan and Porewan) loesses over gravels. It may be the same terrace as at site 35. The remnant abuts a greywacke hill topped by very weathered gravels much older than at sites 35 and 36. The Ohakean terrace south of the remnant has a distinct 10m wide and 50-100cm high bulge trending ca 050° that marks the fault trace. Just 100m N of the remnant is a spring and swamp on the fault trace which would be a good trench site. |
| Figs. 13 & 16 | S25 134609 | o | Exposure of weathered to very weathered, sub-rounded to rounded, course alluvial gravel (max. observed clast diametre ca 30cm). Gravel is more weathered than gravel at site 35. |
| Figs. 13 & 16 | S25 134608 | 37 | Flats where eastern fault strand heads N into heavy bush. Hole dug to describe soil on flat aggradation surface only 3-4m above stream level. 0-25cm topsoil (10YR 4/3) silty clay loam with stones; 25-50cm (10YR 4/4-5/4) silty clay loam with 20-30% greywacke stones and strong fine nut structure; over olive brown sandy gravels. Soil is considered to be Kawhatau silty clay loam and the surface is Ohakean or early Holocene in age. Therefore the "eastern strand" has not disrupted this surface for at least 5000 years. |
| Fig. 13 | S25 114594 | 40 | Auger hole on crest of ridge in pine plantation to test age of surface. 0-32cm (10YR 4/3) silt loam with strong fine nut structure: 32-60cm (10YR 5/4-6/4) silt loam with block and fine nut structure; slightly sandier at base (Kawakawa Tephra); 60-85cm (10YR 6/4) silt loam with a few reddish mottles (base of Ohakean loess); 85-130cm (10YR 6/7) silty clay loam with block and nut structure and common root channels lined with strong brown coatings (paleosol on Ratan loess); 130-180cm (10 |

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| | | | YR 5/8-7.5YR 5/8) silty clay loam with fewer root channels but more strong brown coatings on peds and thin (<2mm) iron pans; 180-215cm (10YR 5/4-2.5Y 5/4) silty clay loam with 30% 7.5YR 5/8 fine prominent mottles and prominent coarse sand sized feldspar ghosts; 215-240cm as for 130-180cm (base of Ratan loess); 240-270cm 10YR 5/8 silty clay loam, strongly mottled 7.5YR 4/6 and 10YR 6/4 with common fine root channels and blocky structure, root channels and peds have 10YR 8/2 and 7.5YR 4/6 coatings (paleosol on Porewan loess); 270-290cm 10YR6/4 silty clay loam with 20% 10YR 5/8 prominent mottles and few root channels; unconformity at 290cm; 290-330cm very mottled 10% 2.5YR 5/8, 50% 10YR 6/8, 40% 10YR 8/5, sandy clay loam grading down to sandy loam; many very soft weathered stones fragmented by the auger. These are old red weathered gravels judged to be older than Marton age (>150ka) |
| Fig. 13 | S25 115599 | p | Major crush zone of fault exposed along S bank of Makakika Stream. |
| Fig. 13 | S25 118602 | 77 | SE of Makahika Stream, near Poulton Drive, crush zone of fault exposed in a slip on the west bank of Waiti Stream. Further to NE, fault scarp passes through bedrock saddle at grid ref. S25 122605. |
| Fig. 13 | S25 122605 | 78 | Bedrock margin of small swamp is laterally offset by ca 16m. Age of swamp soil mid-early Holocene (peaty Ohakea soil), with minimum age of 4-5ka; therefore, max rate of lateral movement is 4mm/yr. |
| Figs. 13 & 16 | S25 132612 | q | Exposure of faulted course alluvial gravel (probably Ohakean in age). Fault is expressed in gravel sequence as a zone of near vertical cobble imbrication. Fault has a general strike of 50°E, a near vertical dip, and is NW-side up. |

## Table 2. Terrace and Fan Age and Soil Correlations

| Terrace or fan | Age of deposits (yrs B.P.) | Age of surface (yrs B.P.). | Terrace or fan cover | Soils | Features |
|---|---|---|---|---|---|
| **Low terraces** | | | | | |
| River flood plains | <50 | <50 | Gravel, sand, silt | Raw soils | Little vegetation |
| Rangitikei | <500 | <200 | Gravel, sand, silt | Otaki, Rangitikei, Parewanui | Floods regularly |
| Manawatu | <1850 | <1000 | Gravel, sand, silt | Manawatu, Kairanga | Floods once every 20-30 years |
| Karapoti | 1000-5000 | 1000-5000 | Gravel, sand, silt | Karapoti, Te Arakura | No longer floods |
| Early Holocene & | 5000-10 000 | 5000-10 000 | Gravel, sand, silt | Hautere, Te Horo, Paraha, Ohakea, Ashhurst | Well above flood level, but lower than Ohakean terrace |
| late Pleistocene | 10 000-15 000 | | | | |
| **Intermediate** | | | | | |
| Ohakean | 15 000-25 000 | 15 000 (10 000-15 000) | Gravel, fine alluvium, colluvium, loess | Ashhurst, Kawhatau, Hautere, Te Horo, Paraha, Ohakea | Very extensive last glacial terrace and/or fan surface |
| **High** | | | | | |
| Ratan | 30 000-50 000 | 30 000 | Ohakean loess, sands | Levin, Waitohu, Shannon, Rahui | Ohakean loess includes Kawakawa Tephra (22,500 yrs old) |
| Porewan | 65 000-75 000 | 65 000 | Ohakean loess, Ratan loess, sands | Levin, Waitohu, Shannon, Rahui | |
| Tokomaru | 80 000-125 000 | 80 000-125 000 | Ohakean loess, Ratan loess, Porewan loess, marine sands, dune sands | Levin, Waitohu, Shannon, Rahui, Koputaroa, Waitawa | Marine terrace, whereas other high terraces and fans are result of river aggradation |
| Marton | 140 000-150 000 | ca 140 000 | Ohakean loess, Ratan loess, Porewan loess, possibly dune sand and/or 4$^{th}$ loess | Levin, Waitohu, Shannon, Rahui, Koputaroa, Waitawa | Gravels weathered during Last Interglacial |
| Pre-Marton | 200 000-350 000? | >200 000 | Thick loess cover | As above | Most gravels are weathered and easily cut with spade or knife |

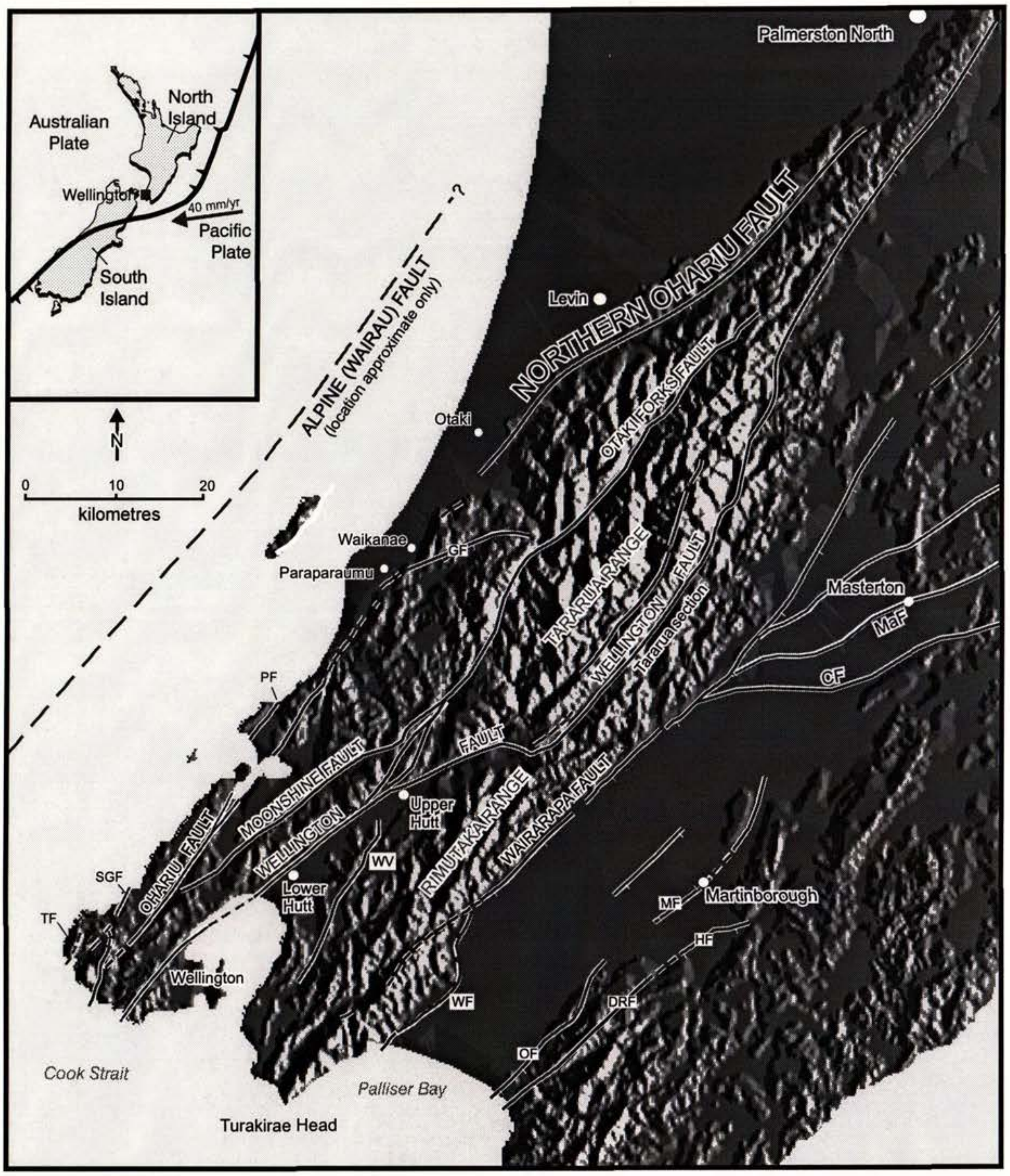


**Fig. 1.** Northern Ohariu fault and other on-land active faults in the Wellington region. Abbreviations of fault names are as follows: TF = Terawhiti fault; SGF = Shepherds Gully fault; PF = Pukerua fault: GF = Gibbs fault; OF = Otaraia fault; MaF = Masterton fault; CF = Carterton fault; MF = Martinborough fault; HF = Huangarua fault; DRF = Dry River fault; WF = Wharekauhau fault; WV = Whitemans Valley fault. Figure 2 shows the location of the Northern Ohariu fault in greater detail, as well as the locations of key sites and figures discussed in text.


Figure 2. Location of Northern Ohariu fault. Arrows show locations of figures (photographs) discussed in text, and point in the direction that the photographs were taken. NZMS 260 map sheet boundaries are also shown for reference. Other active faults and folds are not shown.

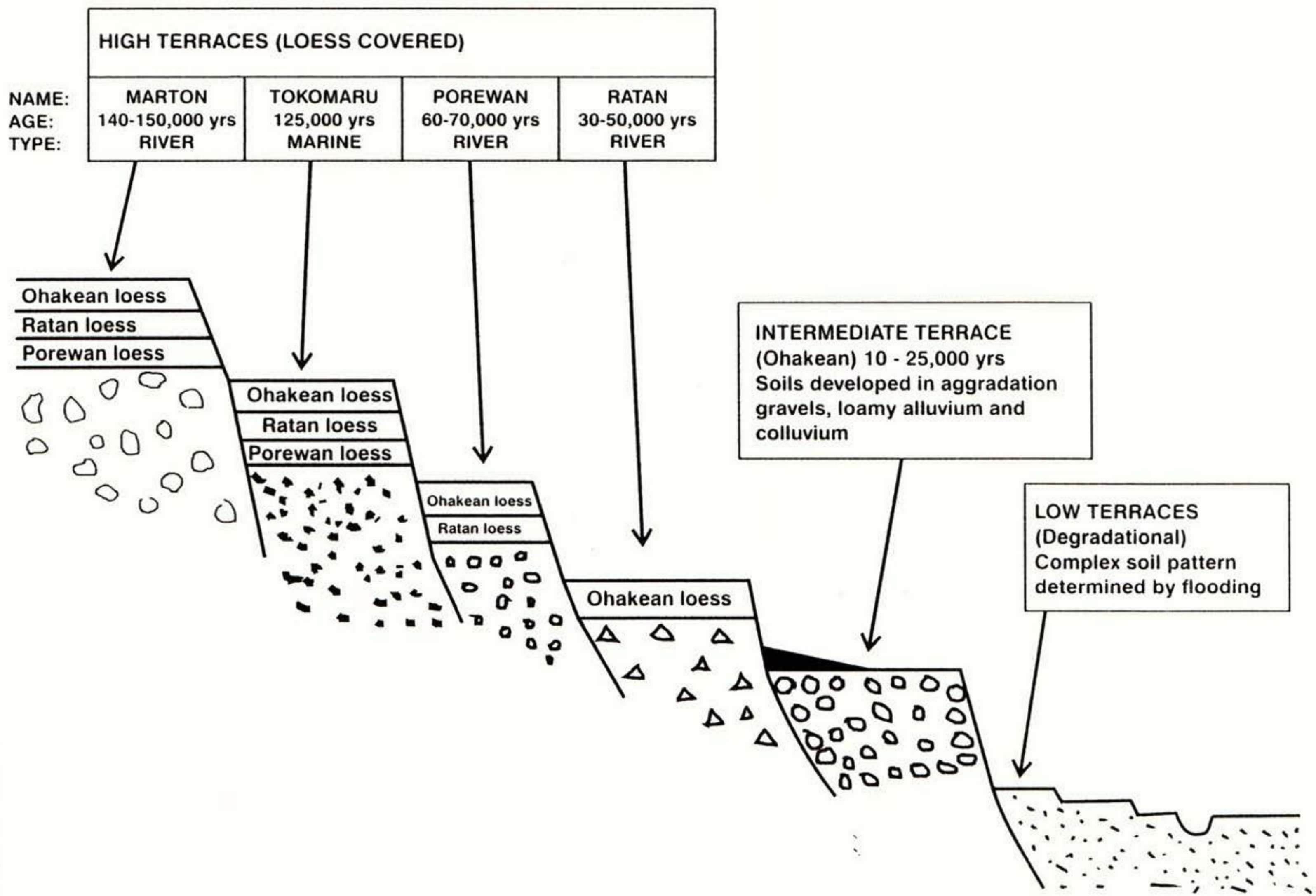


Figure 3. Relationships between, and nomenclature of , alluvial terrace and fan deposits, surfaces, and overlying loess sheets in the study area.

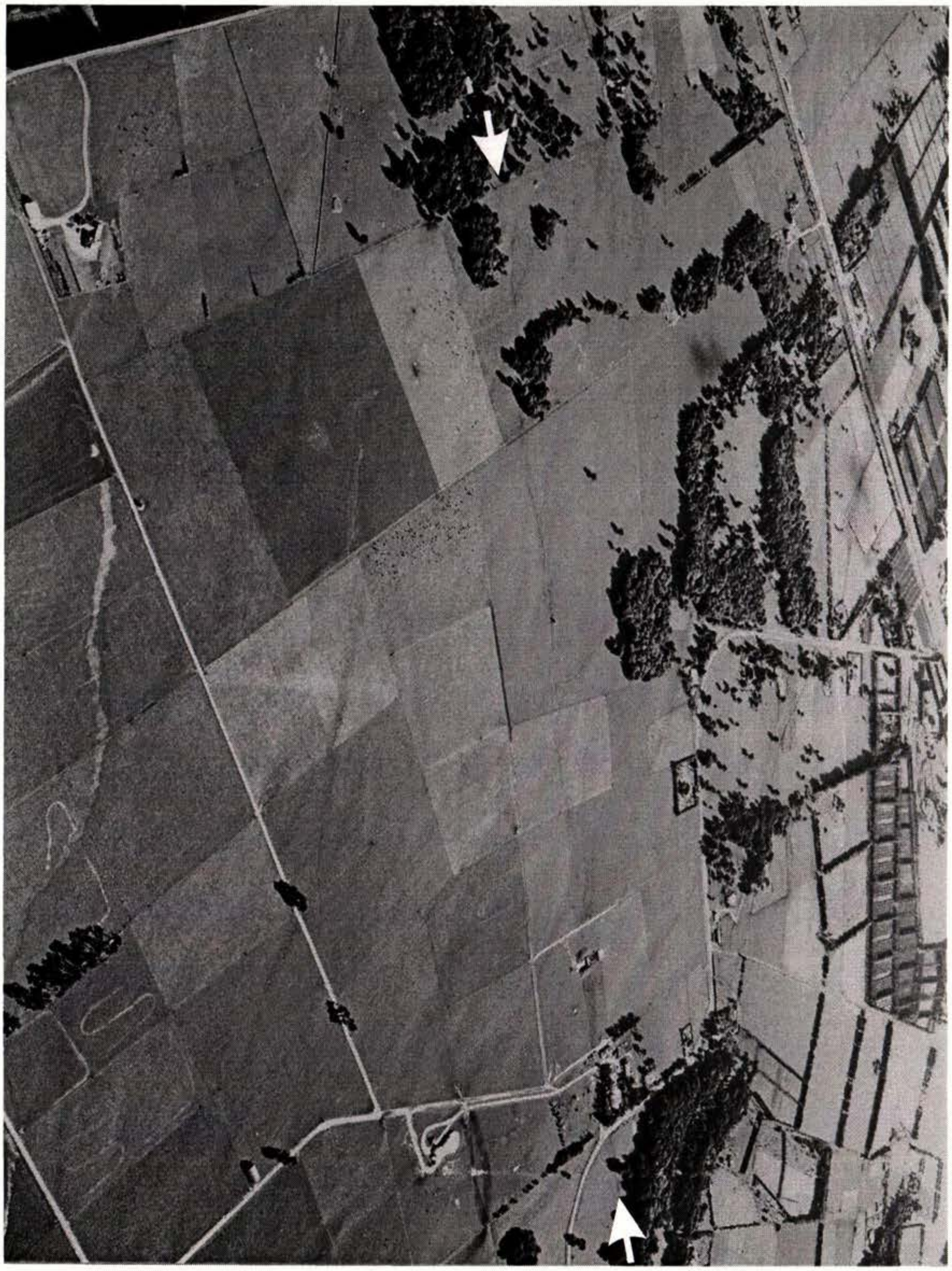

**Fig. 4**. Aerial photograph looking northwest across the northeast-trending scarp, 1-2 m high, of the Northern Ohariu fault, Te Horo/Old Hautere Road area. Bold arrows show the location of the fault which extends left to right across middle of photo. State Highway 1 runs diagonally across upper-left of photo, and Old Hautere Road is at upper-middle left. The extensive alluvial terrace in the photo that is displaced by the fault is predominantly Ohakean in age (about 10 000-15 000 years old).
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39571 24).*

A)

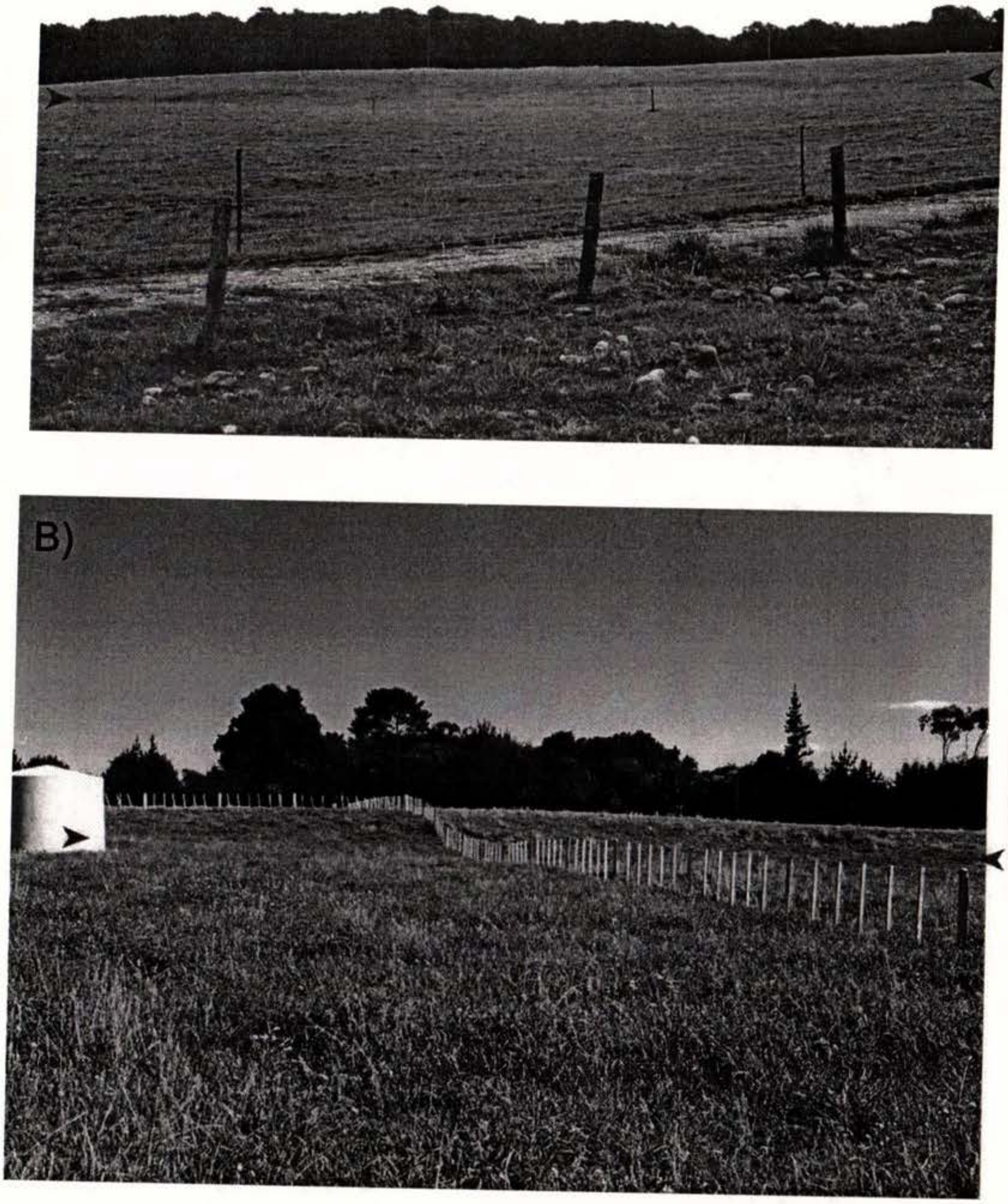


**Fig. 5**. Photographs looking northwest across the 1-2 m high, southeast-facing, scarp of the Northern Ohariu fault, Old Hautere Road area. Bold arrows show fault's location. Displaced alluvial terrace in photographs is Ohakean in age (about 10 000-15 000 years old). A) Photo taken about 300 m west-southwest of Old Hautere Road (grid ref. S25 909 437). Area shown in this photo is encompassed by that in Fig. 4. B) Photo taken about 200 m northeast of Otaki Gorge Road, between Otaki Gorge Road and the Otaki River (grid ref. S25 925 446). *Photo: R. Van Dissen, Institute of Geological & Nuclear Sciences.*


**Fig. 6.** Aerial photograph looking southeast across the northeast-trending Northern Ohariu fault, Corbetts Road area. Bold arrows show the fault's location. The maximum right-lateral offset of ca 450 m is denoted by the arrows labelled a & a', and the prominent loess covered alluvial terrace to the right of a' is probably Marton in age (ca 140 000 years), yeilding a maximun right-lateral slip rate at this site of about 3 mm/yr.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39580 5).*

**Fig. 7**. Aerial photograph looking northwest across the small graben along the Northern Ohariu fault near Tangimoana Road. Bold arrows show the fault's location. Tangimoana Road extends across center of photo, and is slightly oblique to the fault. Muhunoa Road runs diagonally across upper-right of photo, and the Ohau River flows right to left across top of photo.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 46625 A).*

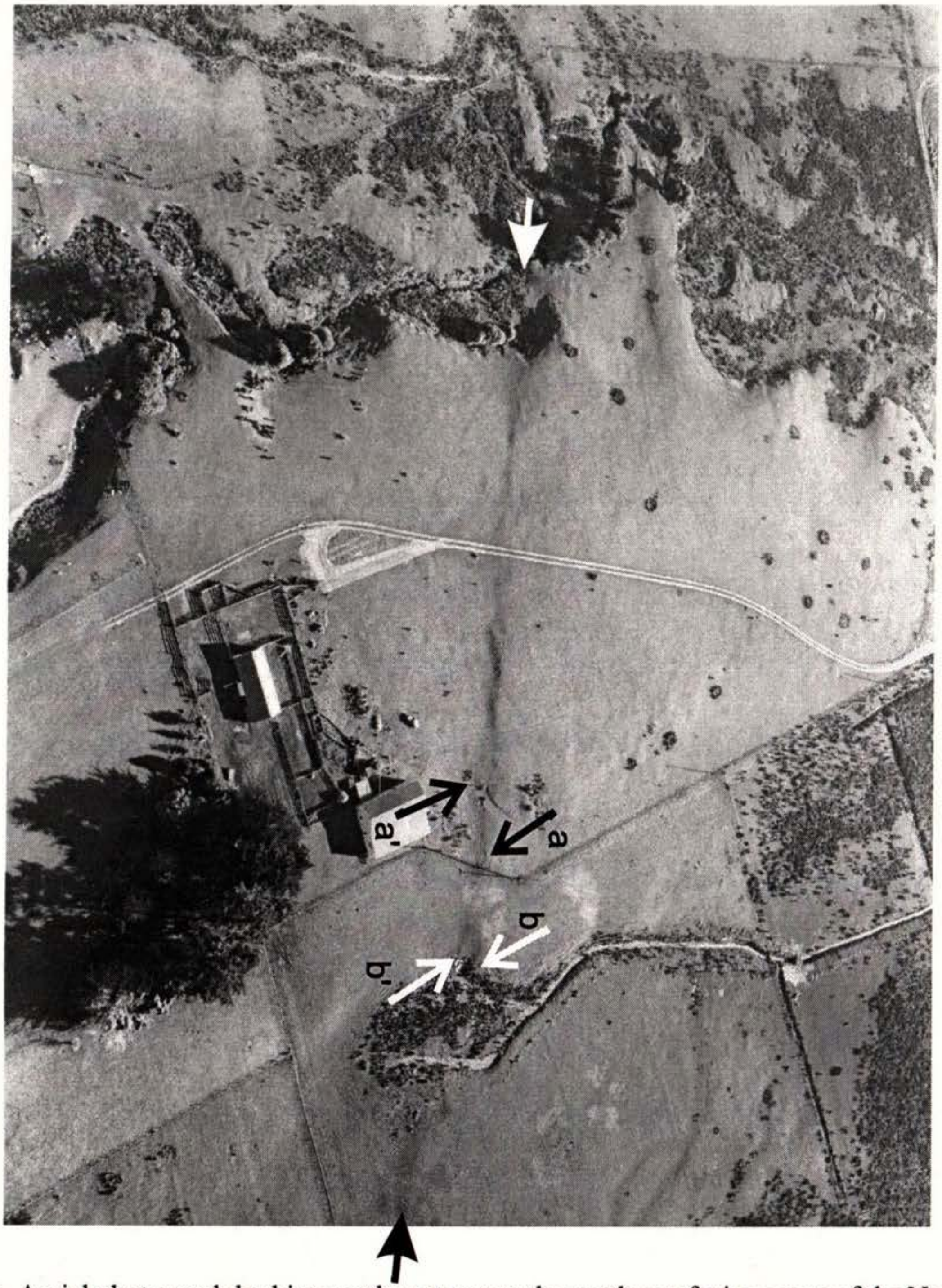


**Fig. 8**. Aerial photograph looking northwest across the southeast-facing scarp of the Northern Ohariu fault (grid ref. S25 039 555). Bold arrows show the fault's location. The faulted terrace in the centre of the photo is Ratan in age (ca 30 000-40 000 years), and the road in the upper left-hand corner of the photo is Tangimoana Road. The ca 10-20 m right-lateral displacement of an Ohakean age terrace riser (10 000-15 000 years) is denoted by a-a', yielding a lateral slip rate of ca 0.7-2 mm/yr. This, however, is a minimum rate for the fault as a whole because about 300 m to the northwest, off the photograph, there is the sub-parallel western strand of the fault for which a slip rate has yet to be determined. The ca 3 m right-lateral offset of the channel-wall of a small spring is denoted by b-b'. This may represent the amount of lateral displacement resulting from the most resent surface rupture displacement on this strand of the fault.

*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39578 23).*

**Fig. 9.** Aerial photograph looking north-northwest across the northeast-trending Northern Ohariu fault (grid ref. S25 050564). Bold arrows show the fault's location. The main road in the photo is Florida Road. The displaced terraces in the photograph are Marton in age and younger (less than ca 140 000 years).
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39618 10).*


**Fig. 10.** Aerial photograph looking north-northwest across northeast-trending Northern Ohariu fault, Florida Road/Ohau River area. Bold arrows show fault's location. The 3.0-3.5 m net displacement of the young terrace riser is denoted by the arrows labelled a-a', and is interpreted to represent the amount of surface rupture displacement that occurred at this site during the most recent earthquake. "s" is location of silage pit discussed in text.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39576 17).*

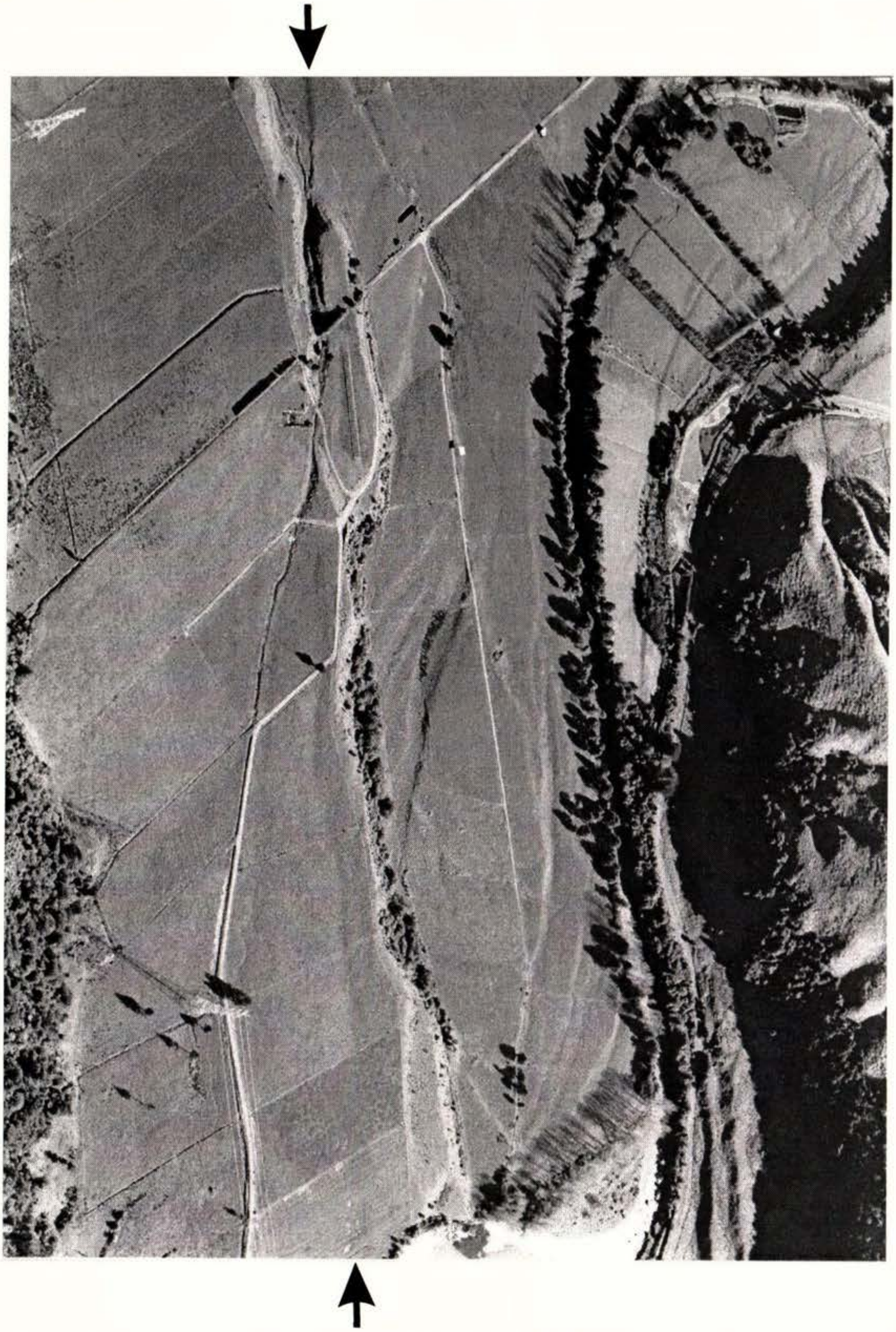

**Fig. 11**. Aerial photograph looking north-northwest across the ENE-trending Northern Ohariu fault (grid ref. S25 073 574). The bold arrows show the location of the fault. The river and road in the upper part of the photo are the Ohau River and Gladstone Road, respectively. The displaced alluvial terraces in the photograph are Ohakean age (10 000-15 000 years old) and younger. The photograph shown in Fig. 10 was taken just to the left (southwest) of this photo.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39616 5).*

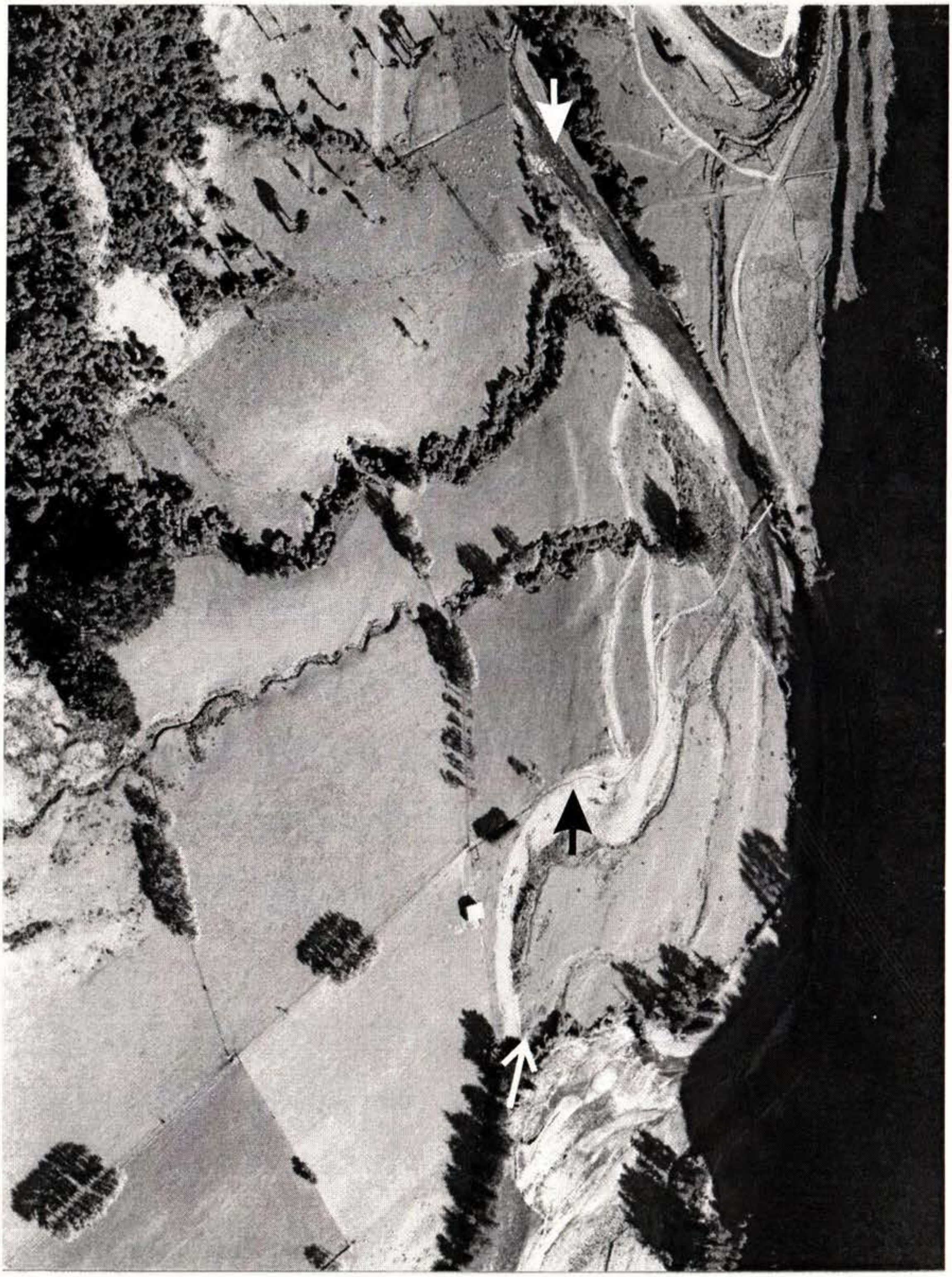

**Fig. 12.** Aerial photograph looking northwest across the scarp of the Northern Ohariu fault, Poads Road, Ohau River area (grid ref. S25 081 579). Bold arrows show the fault's location across Ohakean age terrace, and finer arrow shows location of possible scarp on Holocene degradational terrace. The photograph shown in Fig. 11 was taken just to the left (southwest) of this photo.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39615).*


**Fig. 13**. Aerial photograph looking east-northeast along the Northern Ohariu fault, Makahika Stream area. Bold arrows show the locations of the fault traces. Makahika Stream flows top to bottom along left side of photo, and Makahika Station is located near the center. "cz" and "s" are locations discussed in text. The area shown in this photograph encompasses that shown in Figs. 14-16.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 46645 13).*

**Fig. 14.** Aerial photograph looking northwest across the ENE-trending mole-track scarp of the Northern Ohariu fault, Makahika Stream area (grid ref. S25 127 609). Bold arrows show the fault's location. The prominent displaced alluvial terrace in the photograph is Ohakean in age (10 000-15 000 years old). The area shown in this photograph is encompassed by that shown in Figs. 13 & 16.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39628 9).*

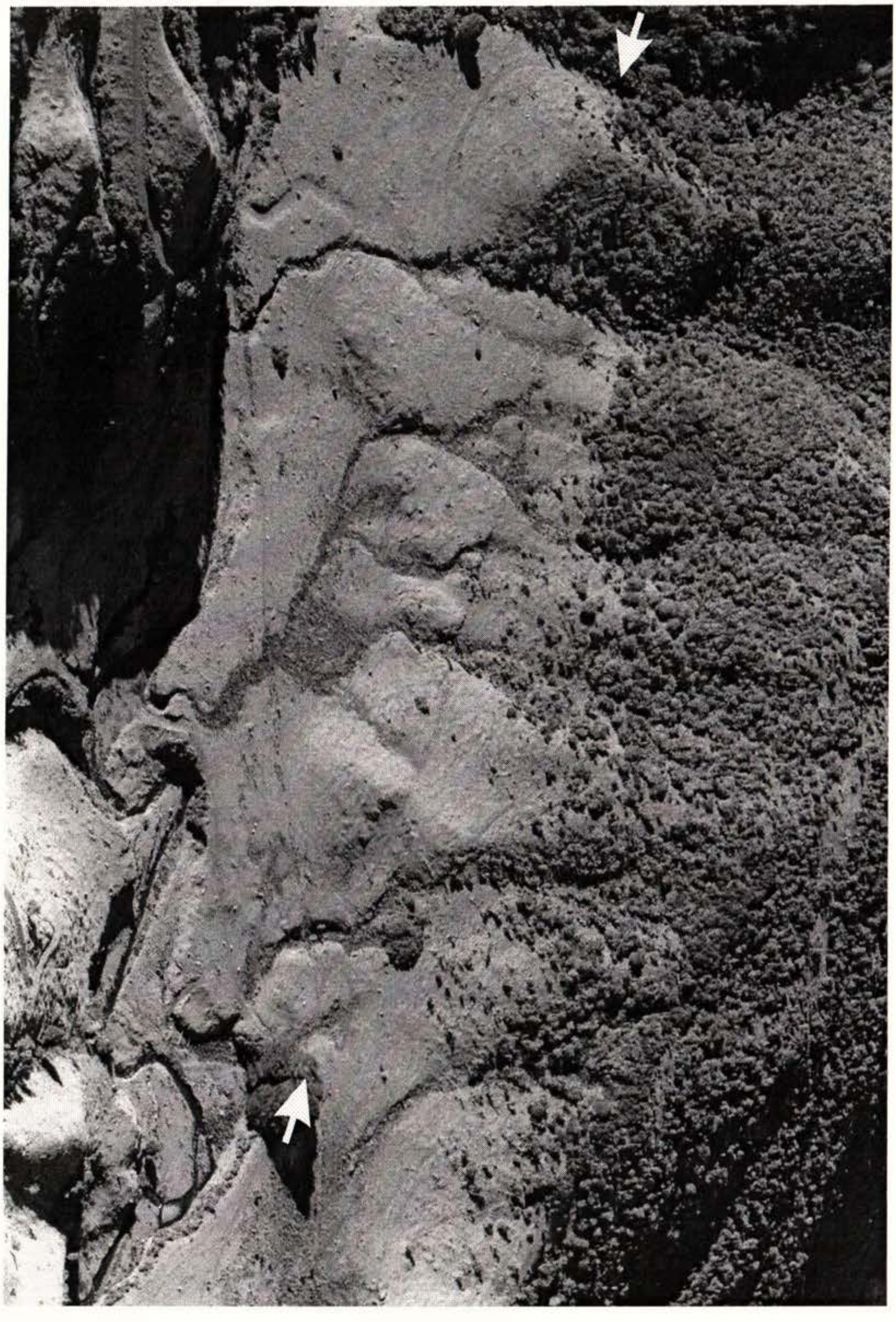

**Fig. 15**. Aerial photograph looking east-southeast across uphill-facing, bedrock scarp of the Northern Ohariu fault, Makahika Stream area (grid ref. S25 135 614). Bold arrows show the fault's location. Makahika Stream winds its way left to right across the bottom of the photo. *Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39624 13).*

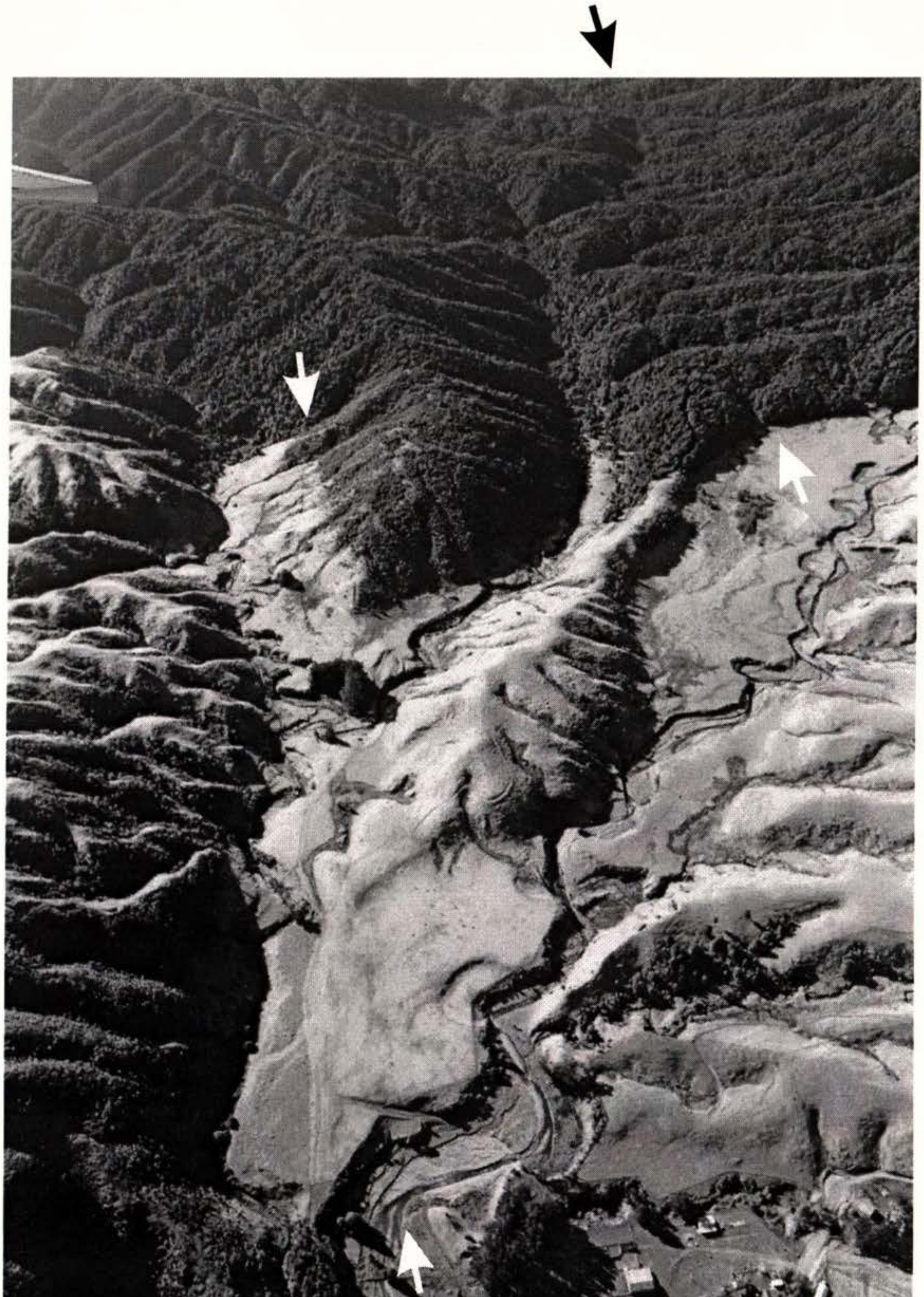

**Fig. 16**. Aerial photograph looking east-northeast along traces of the Northern Ohariu fault, Makahika Stream area. The bold arrows show the locations of fault traces. The prominent displaced alluvial terrace in the foreground is Ohakean in age, and is the same as that shown in Fig. 14. The forested ridges and valleys that are displaced by the arrowed fault trace in the upper centre-right of the photo comprise a dissected alluvial fan of Marton age (ca 140 000 years) or greater.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39590 8).*

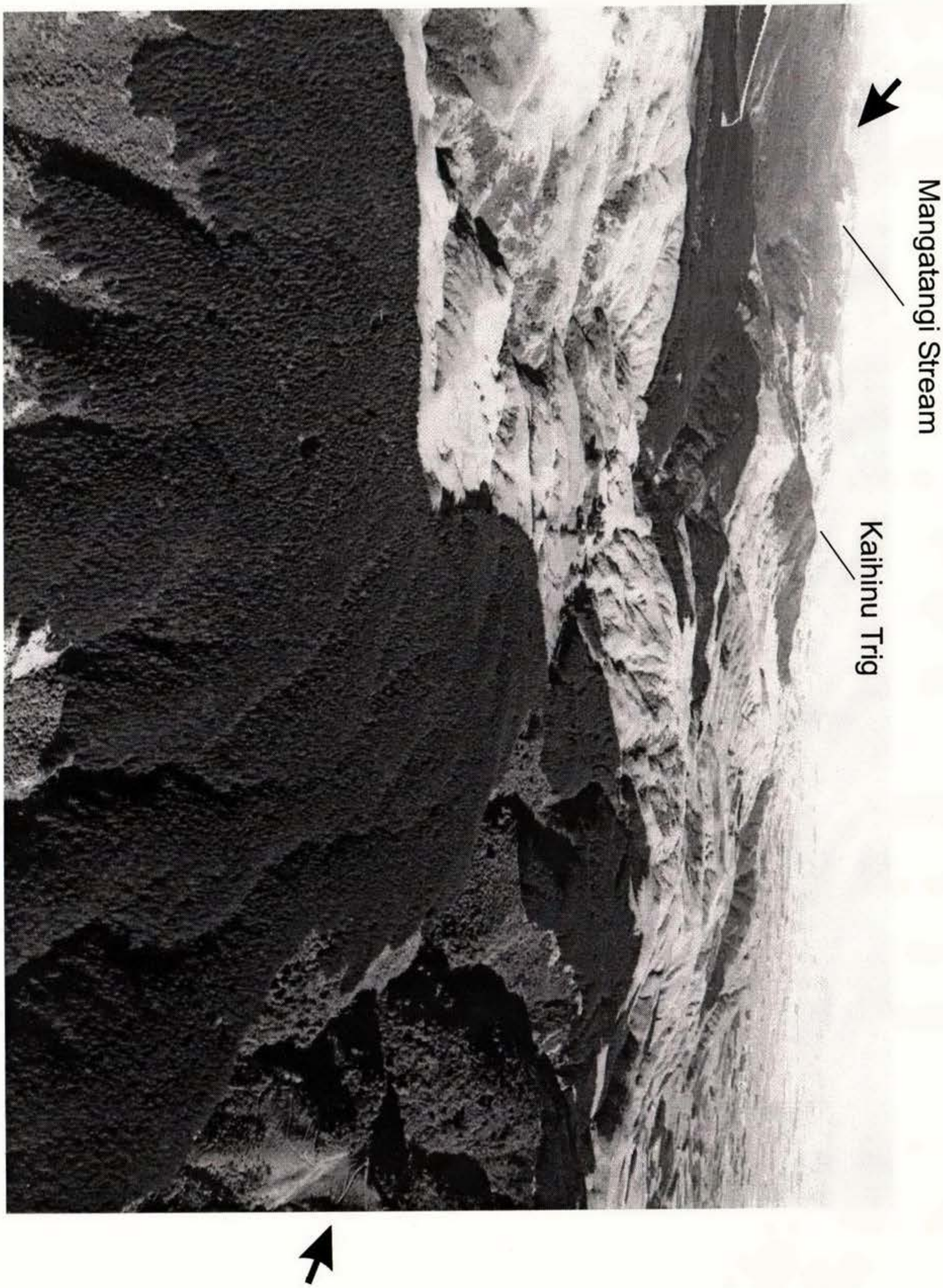


**Fig. 17**. Aerial photograph looking west-southwest across the northeast-trending Northern Ohariu fault, from above the Kahuterawa Stream area (approximate grid ref. S24 300 770). The bold arrows show the general location of the fault.
*Photo: D.L. Homer, Institute of Geological & Nuclear Sciences (photo ref. CN 39593 19).*