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Paleoseismic assessment of the active Mokonui Fault, Wairarapa

Confidential

By R.M. Langridge, D. Townsend & M. Persaud

Client Report
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CLIENT REPORT

Prepared for

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CONTENTS

EXECUTIVE SUMMARY

The Mokonui Fault has been recognised as one of the major active faults in the Wairarapa region. Because it is close to the urban centres of the Wairarapa, it represents a potential hazard that has not yet been adequately quantified. In an effort to better understand the hazard to the region, the Wairarapa Engineering Lifelines Association (WELA) commissioned the Institute of Geological & Nuclear Sciences (GNS) to undertake a paleoseismic assessment of the Mokonui Fault. This study follows a field-mapping programme that provided a useful geological context and preliminary estimates of slip rates of the fault.

The paleoseismic study this year involved trenching the Mokonui Fault to determine its structural style and provide information on past individual earthquake events. Last year's study concluded that the style of the Mokonui Fault is not well understood, but given the similarity of strike and throw to the Carterton and Masterton Faults, it is probably a dextral strike-slip fault with a vertical component of motion. Data from this study is not adequate to confirm the style of motion on the Mokonui Fault. We recognise it to be a strike-slip fault due to the juxtaposition of different units in the trench and tectonic geomorphology. We also recognise that the Mokonui Fault has a vertical component of motion that could be normal or reverse. Some of the relations observed in the trench are clearly related to reverse sense separation across faults. Additionally, fault dip direction and back-tilt of geomorphic surfaces is indicative to a reverse sense of slip on this fault. However, we cannot rule out that the vertical component could be normal in sense. Thus, as a minimum we consider the components of horizontal and vertical motion to be equivalent, i.e. the fault is oblique with an H:V ratio of 1.

A trench across the c. 20 km long Mokonui Fault at Viewfield farm, north of Masterton on a south-facing scarp exposed twin, steeply northwest-dipping fault planes bounding a peat-filled fissure at the fault zone.

The bulk of the stratigraphy exposed consisted of alluvial gravel and sand, with an overlying cap of loess, peat, other organic and fine-grained sediments and soil, giving a rich abundance of datable materials. We recognised several Holocene surface-rupturing earthquake events in the trench, with apparent strike-slip, reverse, and normal separations. Three late Holocene events are constrained by four radiocarbon dates sampled from the units covering the gravels in the trench.

While data available for this fault is inadequate to complete a comprehensive paleoseismic assessment, comparison of available information with empirical relations developed from historical worldwide ruptures has helped establish a likely perspective on the hazard they represent. A revised estimate of the slip rate for the Mokonui Fault of >0.3- 0.7 mm/yr, when combined with a likely single event displacement, allows us to calculate a recurrence interval of about 1300-2000 years and an earthquake magnitude of M_w 6.7-6.9 earthquake. The values for a single event displacement range between 0.5-0.7 metres. It is unlikely that there has been a surface-rupturing earthquake event in the last c. 1000 years or more.

No new data concerning the Masterton and Carterton faults has been produced by this work. However, we do recognise that the results from the Mokonui Fault are similar to those documented for these two faults. We recommend that further research work be undertaken on all three of these central Wairarapa "splay" faults.

KEYWORDS

Mokonui Fault, Masterton, engineering lifelines, paleoseismology, active fault, S26, T26, single event displacement, slip rate, recurrence interval, earthquake magnitude, trenching, Masterton Fault, Carterton Fault.

1. INTRODUCTION

The Wairarapa has been one of New Zealand's most seismically active regions during historical times, with major events in 1855, 1934, and 1942 A.D. (e.g. Eiby 1968; Schermer et al., 1998). A longer record of large earthquakes is clearly identifiable by the presence of several active fault traces in the landscape and from within trenches dug across fault scarps (e.g. Ongley 1943; Lensen 1969; Grapes & Wellman 1988; Grapes & Downes 1997; Schermer et al., 1998; Downes et al., 1999; Begg et al., 2001; Townsend et al., 2002).

The Wellington and Wairarapa faults are thought to be the most active of these faults with long term average slip rates of 6-10 mm/yr (e.g. Van Dissen 1992; Van Dissen & Berryman 1996; Berryman et al., 1998; Van Dissen et al., 1998; Stirling et al., 2000). Recent studies conclude that the Mokonui, Masterton and Carterton faults (Fig. 1a), also have the potential to generate large (c. M_w 7) earthquakes (e.g., Begg et al., 2001). The Mokonui Fault, like the Masterton and Carterton faults, splays from the NE-striking Wairarapa Fault on the western side of the Wairarapa basin to ENE to east-striking segments (Lensen, 1969; Begg & Johnston, 2000; Lee & Begg, 2003; Zachariasen et al., 2000; Townsend et al., 2002).

A summary of the known active faults, earthquake history and hazard, and tectonic setting of the Wairarapa region can be found in Berryman et al.(1998) and Zachariasen et al. (2000), and for the Mokonui Fault in particular in Townsend et al. (2002). Between Carterton and Alfredton the Wairarapa Fault changes in nature. A series of active fault splays strike ENE away from it. These include the Carterton, Masterton, Mokonui and Dreyers Rock faults, and ultimately the Alfredton Fault which is the northern equivalent of the Wairarapa Fault. The northern termination of the 1855 rupture of the Wairarapa Fault is near Alfredton (Schermer et al., 1998). The structural relationship between the Wairarapa Fault and the Carterton, Masterton and Mokonui faults is not clearly established, although the latter three appear to transfer slip from the Wairarapa Fault across the region, towards the coast. These three subsidiary faults are sometimes referred to in this report as the central Wairarapa “family” of splay faults.

The active trace of the Mokonui Fault lies mainly to the northwest of Masterton, coming within c. 5 km of the urban area (Townsend et al., 2002; Fig. 1b). The fault has late Quaternary traces for a distance of at least 20 km, and clearly displaces gravel deposits that are 14,000 years old or younger. These characteristics indicate that it is an active structure, has generated moderate to large earthquakes in the past, and is capable of generating such earthquakes in the future.

Work commissioned by the Wairarapa Engineering Lifelines Association during the past two years has aimed at mapping and characterising the Mokonui Fault. The previous work of

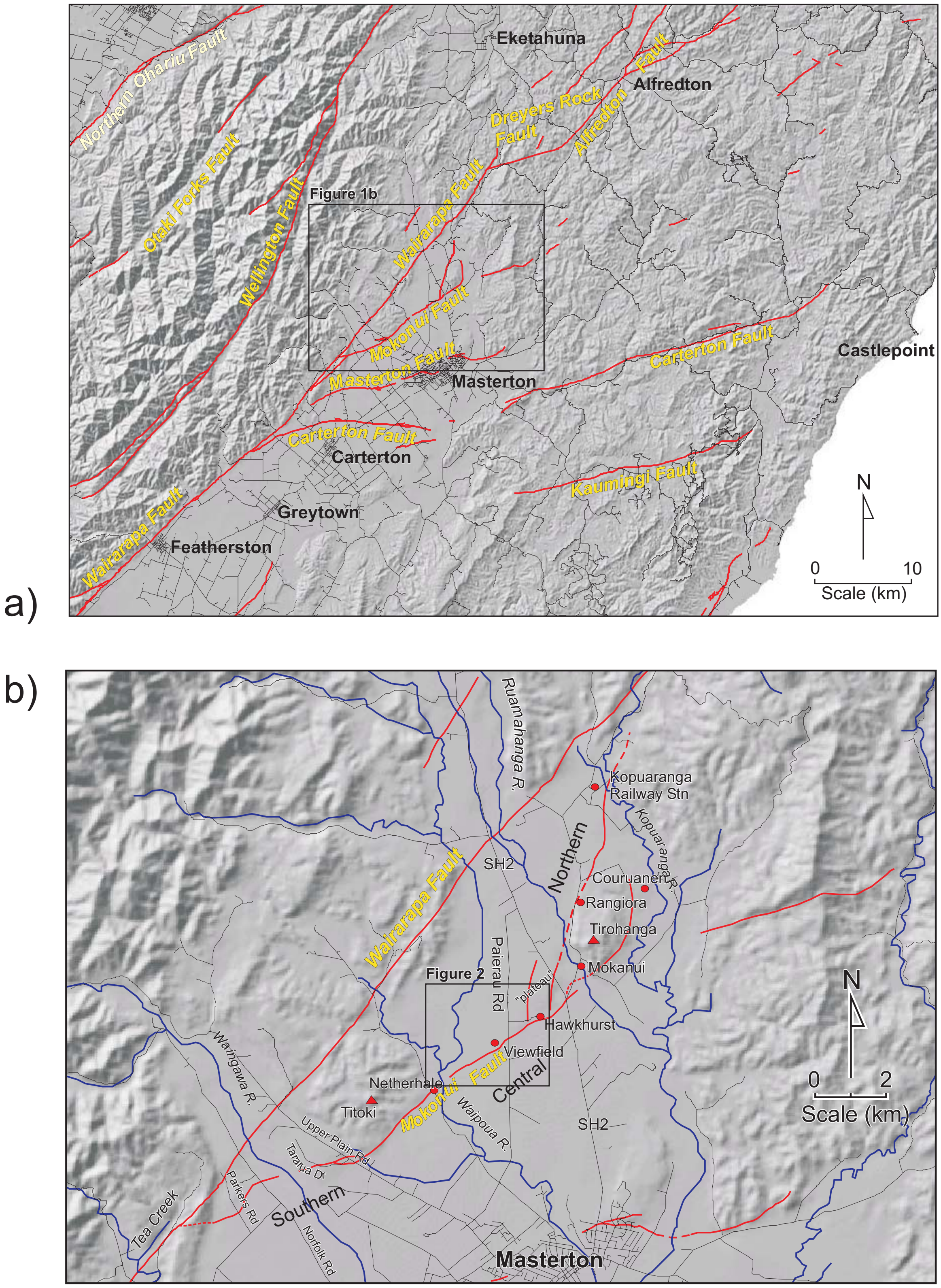


Figure 1. a) Active faults in the Wairarapa area. Active faults are shown in red; roads in black. b) Location of place names mentioned in the text. Southern, Central and Northern are sections of the Mokonui Fault referred to in the text (after Townsend et al., 2002). Area of Figure 2 shown by box.

Townsend et al. (2002) provides a geological context and location for active fault traces northwest of the Masterton area, as well as some constraints on long term slip rates for the Mokonui Fault (Table 1). The present report follows on from the recommendations of Townsend et al. (2002) which were to provide a paleoseismic assessment of the Mokonui Fault by way of a fault trench.

Table 1 Previous estimates of characteristics of the Mokonui Fault from Berryman et al. (1998), and the Masterton and Carterton faults as a comparison, from Zachariasen et al. (2000) and Begg et al. (2001).

	Segment length (km)	**Average single event displ. (m)**	**Average slip rate (mm/yr)**	**Average R.I. (yr)**	**Moment magnitude (M_w)**
Mokonui	25	2	1	2000	7.0
Masterton	22	0.3-0.7	>0.3-0.7	1000	6.7
Carterton	44	2000	2-4	700-2000	7.0

2. SCOPE OF THE PROJECT

2.1 Objectives

The objectives of the current work, defined in the contract document are to:

- Obtain information on the magnitude, style, and timing of past surface rupturing earthquake events on the Mokonui Fault;
- Assist the long-term goal of improving the knowledge of hazard and risk posed to the Wairarapa region by large earthquakes on the Mokonui Fault.

Because of its proximity to Masterton, the Mokonui Fault has the potential to produce a hazard of strong shaking to this urban centre.

2.2 Goals

The goals of the work are to:

- Assess the magnitude of past, and possibly future, earthquakes resulting from rupture of the Mokonui Fault;
- Assess the timing and size of past surface faulting events on the fault;
- Determine the recurrence interval for rupture of the Mokonui Fault;
- Provide further detail on fault geometry; and
- Determine return period and exceedance probability of rupture for the fault.

The contract recognises that the last goal is a long-term one, beyond the scope of this project.

2.3 Tasks

Two tasks have addressed the first four goals:

2.3.1 Task 1 -Site location and augering

Potential paleoseismic trenching sites, identified on the basis of geomorphic relations and their likelihood to yield useful faulting relationships and/or deposits suitable for dating, were to be augered to assess the suitability of sediments for trenching. These site investigations were designed to prioritise them for trenching.

Augering is the most efficient method for investigating the suitability of soil/ coverbed types for paleoseismic studies at these potential trench sites. It is a fast and cheap method, providing the basic information on soil conditions beneath the surface. Sediments that are ideal for trenching include sequences that are well stratified and represent a significant period of time, and those that contain datable geologic materials. In general terms, this involves sediments with at least some fine-grained component for stratification and wood or carbonaceous components for dating. Sequences that are not well suited for trenching include coarse, poorly stratified alluvial gravel and sequences that have extended periods lacking deposition.

2.3.2 Task 2 -Paleoseismic trenching

Following agreement of both parties, a trench was to be excavated across the Mokonui Fault, and once open, assessed for its likelihood to yield useful faulting information and dateable material. If considered appropriate for a paleoseismic investigation, GNS was to undertake a complete investigation of the site and trench. This would involve logging the trench walls and collecting and submitting material for geologic dating. If it was considered unsuitable after opening, the trench was to be filled and the next most suitable site selected and assessed in the same way. Any data characterising the fault was to be collected from any trench excavated before it was refilled.

In the event that all the sites identified in Task 1 were unsuitable, following the agreement of both parties, GNS was to undertake a third task as laid out in the contract.

3. TRENCH SITE LOCATION AND AUGERING

During 2002, the Mokonui Fault was mapped using aerial photographs with some ground investigation. Results were reported in Townsend et al. (2002). Their report identified several possible trenching sites on the Mokonui Fault (Fig. 2). In March 2003, we undertook a one day reconnaissance and some augering at these sites.

Along most of the length of the Mokonui Fault the active trace is found across abandoned

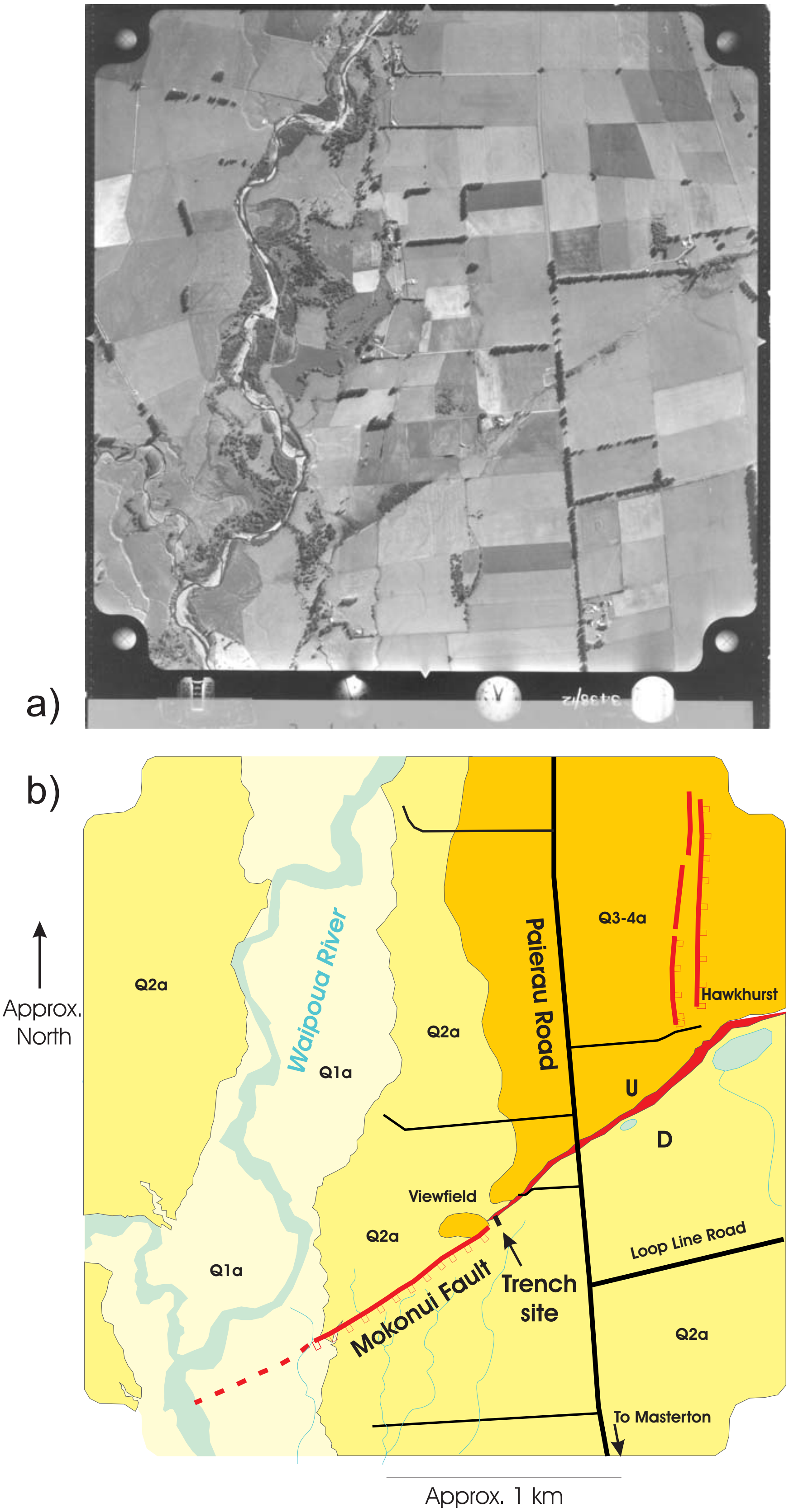


Figure 2. a) Aerial photograph 3834/12 covering the area of the Mokonui Fault shown in (b). b) Geomorphic map of the Mokonui Fault and surrounding area from the Waipoua River to Hawkhust Station. The trench site at Viewfield farm is labelled. Waiohine fluvial (Q2a; 10-14 ka) surfaces are mapped on either side of the fault trace at the site.

alluvial surfaces (e.g., the Waiohine Surface, c. 10-14 ka) that are underlain by gravel (Townsend et al., 2002). The key to learning more about the characteristics of the fault is to find suitable sites with sedimentation (preferably including fine-grained sediments) post-dating 10-14 ka and containing datable carbonaceous material. Materials deposited subsequent to the last surface faulting event will be undeformed, but can constrain the timing of the last rupture. Young material pre-dating the last rupture may record the timing of a single event or a few earthquakes. Old materials are not suitable for paleoseismic studies, because they may have been deformed by so many events that individual events cannot be distinguished or dated.

In March 2003, D. Townsend and R. Langridge visited likely trenching sites on the Mokonui Fault and augered the upthrown and downthrown surfaces, where necessary, to confirm sites most likely to provide information on its Holocene (≤10 ka) faulting history.

Sites visited included:

- Hawkhurst farm pond site (Figs. 1b & 2 NZMS 260 T26/330339), where augering proved the presence of gravel close to the surface on the downthrown side of the fault in the middle of the large ephemeral pond adjacent to the fault scarp. We expected to encounter peaty, fine-grained deposits in this pond but, even the soil cover on this pond was poorly-developed. This site may have been deflated due to drying and wind erosion.
- Viewfield farm scarp (Figs. 2-4; T26/320312) was examined in detail. There are several factors which give this site potential to preserve a late Holocene faulting history. First, the scarp is small, varying from 1.4 to 4.2 metres on this station. Second, there is a lot of swampy ground near the fault scarp, suggesting that organic material would be preserved close to the fault. We focused on a location west of the Wyeth farmhouse next to a small pumping shed where the scarp height was measured to be ~3.2 metres (Townsend et al., 2002). At this location, the scarp is quite boggy and churned up by animal tracks and slope process in weak, peaty materials. This indicates a high probability of encountering datable organic materials at this site. Interestingly the break in slope representing the scarp was the swampiest part of the profile across the fault. This allows that water draining from the gravels in the scarp on the upthrown side of the fault could drain across the scarp providing an environment for the formation of peat. We augered four holes in a transect perpendicular to the scarp. The auger holes showed that a useful cover stratigraphy including peat, silt and wood fragments of up to 80 cm thickness overlies gravels that could not be penetrated by the auger bit (Fig. 3).
- Two other sites were considered but were not viewed during the reconnaissance, nor considered as trench sites. These are near Netherhale (Fig. 1) where the fault trace cut young fan deposits and at Tirohanga, where an apparent reverse scarp was observed (see Townsend et al., 2002).

Figure 3. a) The fault scarp of the Mokonui Fault at the Viewfield site prior to trenching (NZMS 260 T26/320312). Four auger holes were drilled across the scarp to assess the subsurface stratigraphy. The total scarp height here is c. 3.2 metres. Water pumphouse occurs in the midground and farmhouse in the background.
b) Auger hole and sediments retrieved adjacent to the Viewfield site. Gravels underlie c. 80 cm of fine-grained cover deposits.

The Viewfield site offered the best potential for trenching the Mokonui Fault. This information was conveyed to WELA (Langridge/Barrow) and discussion quickly concluded that the Viewfield site should be the preferred primary trench site. It was thought to be the most likely to record a history of Holocene sedimentation and faulting. Following this decision, we constructed a GPS-RTK topographic map of the surrounding field and scarp to show the geomorphology of the scarp and the location of the trench .

4. TRENCH DESCRIPTION

4.1 The Viewfield trench site

Viewfield 1 trench is located in the central (northeast-striking) section of the Mokonui Fault (NZMS 260 T26/320312) as defined by Townsend et al. (2002). The Mokonui Fault has a trend of 061° at Viewfield (Fig. 4). The scarp at this site is small (~3.2 metres) enabling excavation across the scarp. Along its length it is consistently downthrown to the southeast. The main gravel units underlie a widespread surface considered to be of Q2a (last Glacial) or Waiohine age (c. 10-14 ka), and are considered to be outwash materials deposited during and toward the end of the last glacial cycle. From its geomorphic expression, the Mokonui Fault seems to have equivalent sedimentary units on each side of the fault, which is an important criteria for paleoseismic studies.

Viewfield 1 trench was opened on the morning of Wednesday 3rd April, 2003 using a backhoe excavator (contractor: Master Roads, Masterton). Both trench walls were cleaned, examined and logged from Wednesday through Friday of that week. The trench was reviewed by P. Villamor and J. Begg (GNS) on Thursday 4th of April. The trench confirmed the observations concerning the scarp and fault location, cover deposits, peaty deposits and gravel substrate that were identified during the reconnaissance and augering phases.

The trench was c. 15 metres in length, with a maximum depth of 2.8 metres. It was sited c. 80 metres southwest of Noel Wyeth's farmhouse, which sits on the upthrown side of the fault. It was oriented at a bearing of 158° (almost perpendicular to the fault) so that it crossed the fault but positioned to avoid pre-existing farm drains, a power line and a pumphouse (Fig. 4). It was benched for safety reasons, such that each face was not higher than ~1.4 m. On the trench logs the bench appears as a thin band with cross-hatch pattern fill (e.g., Fig. 6).be recoverable from the trench data.

4.2 Stratigraphy of the Viewfield trench

The stratigraphy of the west and east walls of Viewfield 1 trench are summarised in Figs. 5-7. As suspected from the augering, the sediments exposed in the lower parts of the trench on both sides of the fault were predominantly indistinctly- to thick-bedded, matrix- and clast-

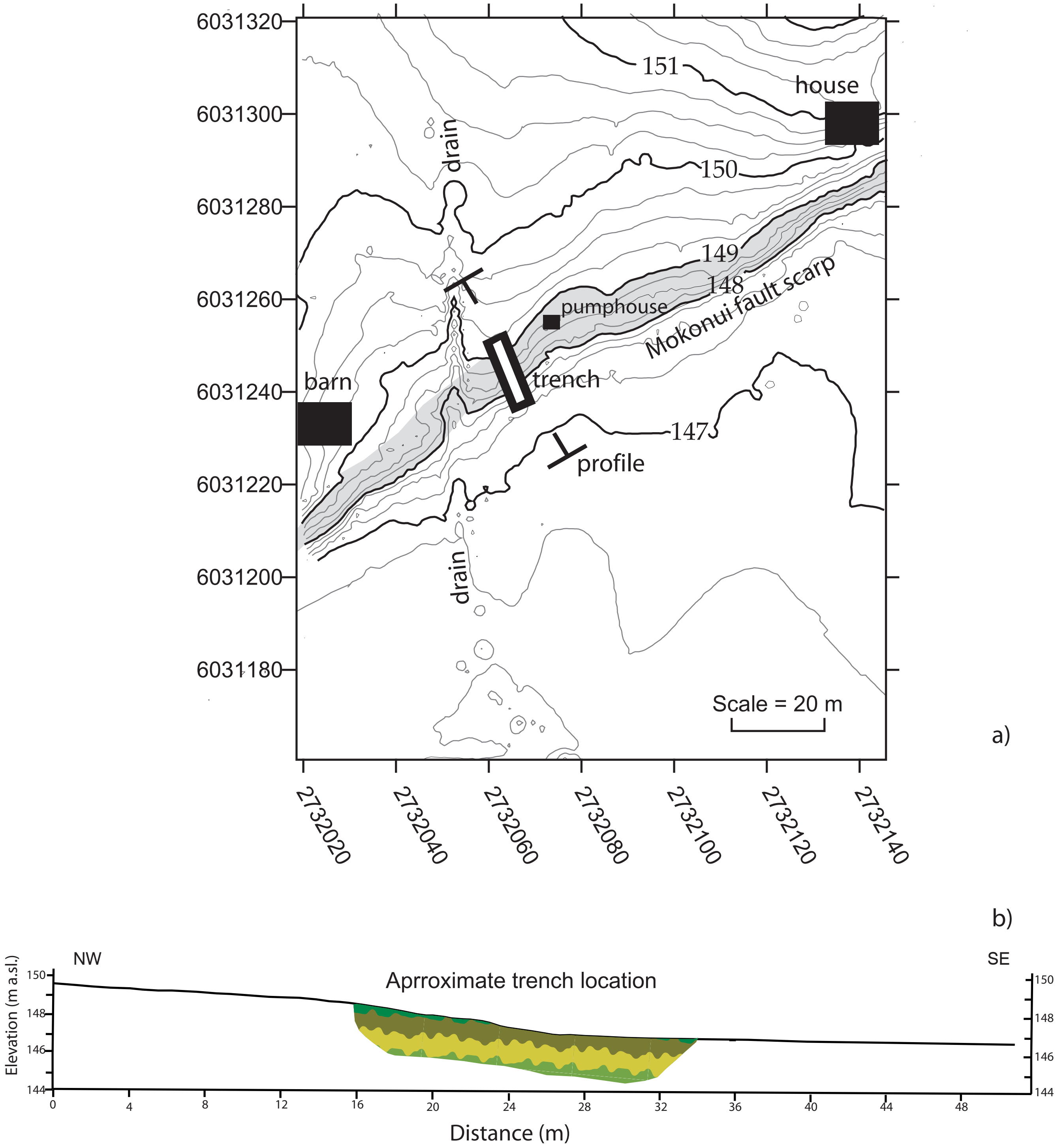


Figure 4. a) Topographic map of the Viewfield site constructed using a GPS-RTK system. Contour interval is 25 cm. The fault scarp (grey shading), trench location, and profile are located on the site map for reference.

b) Profile created from topographic data in a) with the approximate extent of the trench excavation (coloured shading) placed on it. trench. The SURFER contouring program has not accentuated the scarp as effectively as appears at the site. The far-field scarp height is c. 3 metres.

supported, well-rounded greywacke gravel, with sparse finer interbeds. The gravels are generally orange-brown on the upthrown (northwest) side of the fault, and blue-grey on the downthrown side of the fault. This reflects the differing groundwater conditions that exist adjacent to the Mokonui Fault itself, i.e., reducing conditions in a water-logged environment on the downthrown side and oxidising conditions in a dryer environment on the upthrown block. The gravel units (>2.2.m thick) were overlain by <1 metre of finer-grained cover deposits consisting of layered silt, sand, peat, and fine gravels, all capped by a modern soil. One of the most obvious features of the logs is the cross-cutting fissure or fault zone at metre-9 on both walls of the trench (Figs. 6,7), where the earthquake-related deformation is focused.

The sediments in the Viewfield trench (described below) have been split into four major sequences (Fig. 5) that relate to the timing of sedimentation throughout the late Holocene. These are from youngest to oldest:

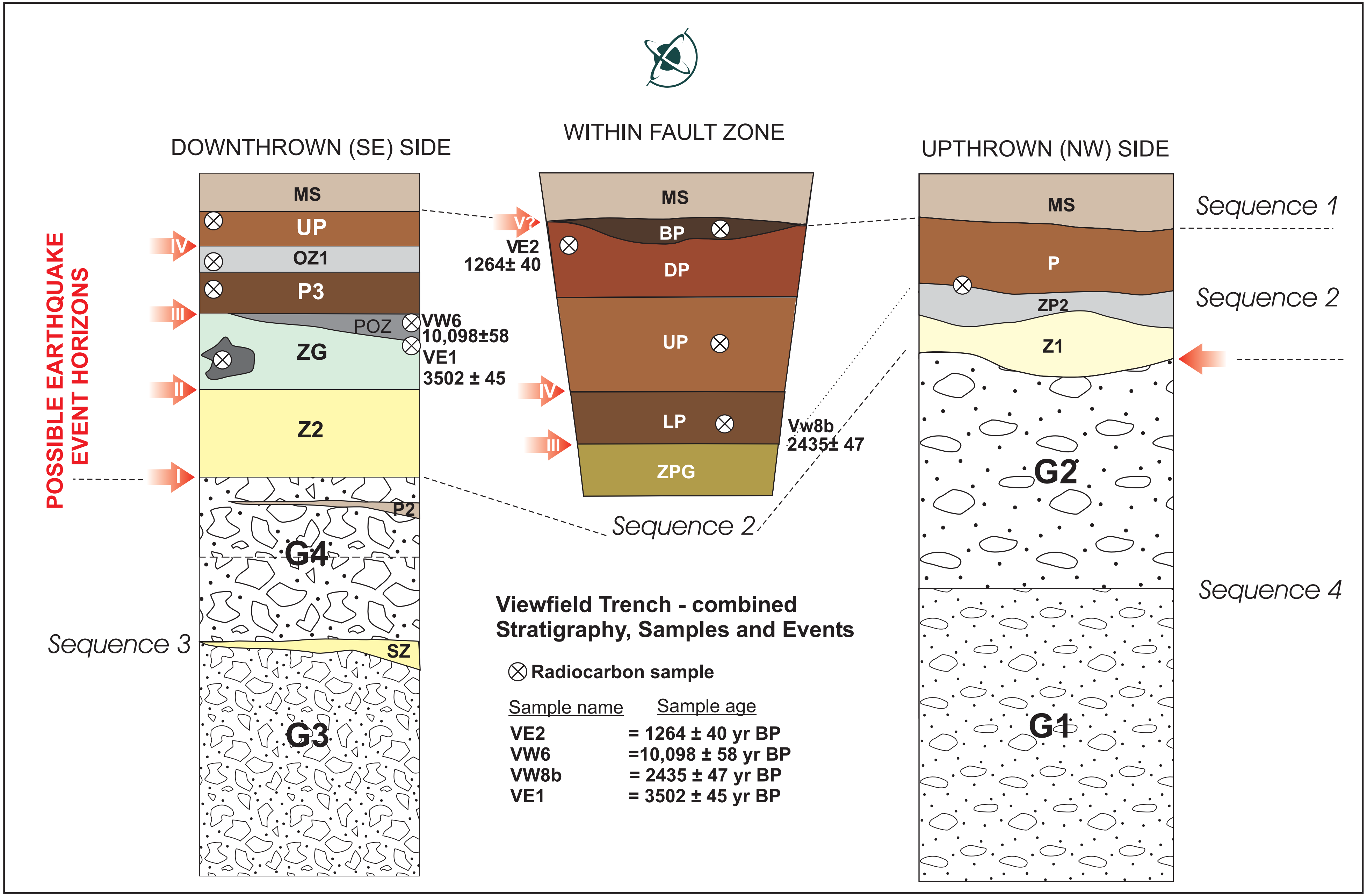
- The uppermost sequence consists of the topsoil or modern soil (MS) only - ***Sequence 1***.
- The next oldest sequence - ***Sequence 2*** - consists of fine-grained clastic to organic deposits overlying the thick gravel units, draped over the fault scarp and within the fissure itself, including Units Z2 through BP on the downthrown side and in the fault zone, and Units Z1 through P on the upthrown block.
- The third sequence consists of those gravels (G3 & G4) and fine-grained deposits (SZ) found only on the downthrown (southeast) side of the fault - ***Sequence 3***.
- The fourth sequence is also alluvial in origin and consists of gravel deposits exposed only on the upthrown side of the fault, e.g., G1 & G2 - ***Sequence 4***.

The units themselves are described in detail in Appendix II.

4.2.1 Geological units in the west wall

Upthrown side: On the upthrown (northwest) side of the fault the cover bed sequence is underlain by two gravel units, named G1 and G2, that form *Sequence 4* (Fig. 5). G2 is distinguished from G1 on the basis of a slight imbrication of clasts and its finer grainsize. No material was found within these two units suitable for geologic dating. G2 is overlain by a blue-grey fine clastic unit (Z1), which is the basal unit of *Sequence 2* on the upthrown side of the fault. Z1 has a grey-brown, slightly organic top (paleosol?) and is overlain by ZP2, which consists of a discontinuous, mixed zone at the base of the peat, P. Unit P grades into peats that fill the fissure and can be differentiated into distinct units there based on their colour, texture and deformation. P is overlain by the modern soil, MS.

Downthrown side: On the downthrown (southeast) side of the fault two main gravel units, G3 and G4 (*Sequence 3*) have been defined. G3 is a moderately-sorted, weakly-stratified cobble gravel with clasts of up to 20 cm in diameter, occur in a sandy matrix. G4 is an unstratified cobble gravel with fewer large clasts than G3. On the east wall, these gravels have been differentiated by the presence of a sandy to sandy-silt bed that occurs at the base of G4



Viewfield Trench - combined Stratigraphy, Samples and Events

⊗ Radiocarbon sample

Sample name	Sample age
VE2	= 1264 ± 40 yr BP
VW6	=10,098 ± 58 yr BP
VW8b	= 2435 ± 47 yr BP
VE1	= 3502 ± 45 yr BP

Figure 5. Composite stratigraphic, age, and event relationships from the fissure, upthrown and downthrown sides of the Mokonui Fault. The red arrows represent the possible stratigraphic positions of a number of earthquake-related event horizons. Radiocarbon ages and stratigraphic tie lines are shown. Refer to text for full explanations.

(Fig. 7). Despite their close proximity, we consider that the gravel units on either side of the fault zone may not correlate with each other. That is, *Sequence 4* gravels need not match with *Sequence 3* gravels, if the latter were deposited up against a scarp, or if *Sequence 4* gravels are a remnant of older Q3 gravels (Fig. 2). However, we have no datable material from any of these gravels that could be used to confirm these observations, and base this statement mainly on the obvious differences in thickness (G4 is considerably thinner than G2), colour, overall texture, and displacement sense (discussed below).

Overlying and abutting G4 on the west wall is unit Z2. Z2 is probably the equivalent of unit Z1 on the upthrown side. Z1 and Z2 are both fine-grained and are either overbank flood deposits or loess that overlie the terrace-forming gravels. Stratigraphically above Z2, but only on the downthrown side of the fault, is a silty gravel unit, ZG. ZG is a poorly sorted gravel with a matrix of fine sand to silt. ZG thins and fines to the southeast away from the fault becoming a gravely silt (Figs. 6,7). Above ZG is a peaty organic silt (POZ) and a peat (P3). POZ is distinguished from P3 on the basis of a higher silt content and lighter brown colour, while P3 is a true peat. It is overlain by a light brown, slightly organic massive silt, OZ1. OZ1 is in turn overlain by the upper peat UP, which extends from the fault zone across the downthrown block UP is a medium brown slightly sheared woody peat. Near the fault zone, UP is overlain by a seedy peat (DP) and black peat (BP). A dark brown, friable, organic soil (MS) also overlies deposits on both sides of the fault (*Sequence 1*). This soil contains occasional stones, wood fragments, charcoal, and farm litter.

Fault zone: The stratigraphic sequence is complicated within the fissure zone by faulting (Fig. 6). The fissure is mostly filled with peat (LP = lower peat), but other units, including a silty peaty gravel (ZPG) occur within the fissure on the west wall. On both sides of the fissure are infaulted or smeared slivers of units mapped outside of the fault zone, i.e., slivers of OZ2 (metre-9.3; Fig. 6) probably correspond to the unit ZP2 above it. Peat LP has a disorganised or sheared appearance, whereas, peat UP is more coherent and intact compared to the units about it. UP corresponds to peat P on the upthrown block. Above peat UP a distinct peat containing tree seeds (peat DP), could be mapped on both sides of the fault and within the fissure. Overlying DP within the fault zone on the west wall is a black peat (BP).

Due to the complex nature of the deformation in the middle part of the trench (fissure zone) it was decided that both walls of the trench should be logged in detail. The strategy adopted to constrain the timing of the last rupture of the Mokonui Fault was to establish a minimum age for that event by dating unfaulted Holocene deposits exposed in the trench. A maximum age could be provided by carbonaceous materials if found in faulted horizons within the trench. It was hoped that some information on rupture events prior to the most recent event might also

4.2.2 Geological units in the east wall

Some subtle differences occur between the stratigraphic and structural features of the east wall (Fig. 7) and the west wall. We recognise the same gravels G1 and G2 on the east wall (upthrown block). Another gravel unit, however, has been recognised in this area of the east wall, named G5. G5 is a wedge-shaped and occurs on the upthrown block adjacent to the fissure zone. On the east wall, *Sequence 4* also includes silt and clay beds overlying the gravels, which corresponds to Z1 on the west wall. On the downthrown (southeast) side, G3 and G4 have been recognised, and are separated in part on the basis of a sandy to sandy-silt bed that occurs between them (Fig. 7). Although the thickness and geometry of units can change considerably across the 2-4 m space between the trench walls, we infer that this bed corresponds to the sandy base of G4 on the west wall.

Sequence 2 on the east wall again consists of a series of fine clastic to peaty units that thicken above the fault zone and fill the fault-related fissure. The texture and organic content of the *Sequence 2* units vary from wall to wall. However, we are able to match units across the two walls, e.g. ZG = ZG, PZ (east) = P3, ZP (east) = OZ1 (Fig. 7). Several of the unit contacts within *Sequence 2* pinch out at metre-6, suggesting that they may have formed by filling a small depression related to deformation (Fig. 7). On the east wall the peat unit DP contained tree seed cases and a flattened mat of swamp grass. The black peat, BP is far more prominent on the east wall than seen on the west wall, draping across both sides of the faults zone. The topsoil (MS) comprising *Sequence 1* overlies *Sequence 2*.

On the east wall the fissure appears to have several pockets of in-sheared peat and gravel and a block of intact stratigraphy that occurs as an untilted package in the fault zone. This structural pattern is similar to the west wall and implies opening across the fault zone, with blocks that fall into the fissure or are sheared along the fault zone. We were not able to discern any further structural detail within the peat. Consequently, we were unable to measure any fault plane orientations in these materials, e.g. fault strike and dip using a compass.

4.2.3 Radiocarbon dating strategy for trench sediments

According to the GNS/WELA contract, geological materials were to be sampled for radiometric dating of the geologic events recognised in the trench. The Viewfield trench has an abundance of carbonaceous materials suitable for dating geologic strata. Radiocarbon samples that we collected were deemed adequate to characterise the timing of the geologic events in the trench. Consequently no other samples were collected for dating by other techniques, e.g., luminescence dating (OSL, TL).

We collected 14 carbonaceous samples from the two walls of the Viewfield trench with the bulk of these (11) taken from the west wall (Appendix 1). These samples include wood, seeds, peat, reed grass, and organic sediment, all of which came from *Sequence 2*. Due to budget constraints only four samples could be considered for dating. Of these four, two were selected from each wall for dating. These are VE1 (metre-4; Fig. 7) and VE2 (metre-8.2; Fig. 7) from the east wall, and VW6 (metre-8; Fig. 6) and VW8b (metre-9.2; Fig.

6). Samples were prioritised according to their quality, ability to constrain the age of the uppermost and lowermost deposits in the trench, and their position relative to horizons that are involved in deformation, e.g., above and below earthquake event horizons. Sample quality, as mentioned above, refers to the nature of the materials and likelihood of a “correct” stratigraphic age, e.g., seed cases that were deposited *in situ* versus roots that later grew through the section. Three of the four samples gave ages of <4000 years for the section above the coarse gravels (VE1, VE2, VW8b). The fourth sample (VW6) was significantly older (>10,000 years) and apparently out of place relative to the other three. After considering all four dates we believe that the best explanation for an age of >10,000 years for VW6 is that the wood sampled has been reworked from an older unit into the layer POZ on the west wall. We consider that it may have existed within or just above the level of the gravels on the upthrown block (G2), prior to reworking, and therefore provides a reasonable minimum age for the gravels on the upthrown side of the fault, i.e., a “Waiohine” gravels age.

4.3 The Record of Faulting

With a clear understanding of the stratigraphic sequence we can attempt to address the record of faulting and deformation related to these units in the trench. The sediments in the Viewfield trench were split into four major sequences (Fig. 5) that relate to their position and composition rather than their timing related to earthquake displacements during the Holocene.

The main zone of recent faulting is expressed by the peat-filled fissure at metre-9 on both walls. Faults in this area have been labelled W1-W3 on the west wall and E3-E6 on the east wall (Figs. 6,7). Another major zone of displacement is shown by faults W4, E1 and E2. We show the faulting on the geologic logs of the trench (Figs. 6,7) along with a photo-mosaic of the west wall to illustrate the units and deformation.

It is also important to understand the stratigraphic level to which each deformation event penetrates. Large, surface-rupturing earthquakes naturally break the fault to the ground surface and thereby leave evidence of that event at the ground surface of that particular time. This earthquake deformation event and its surface are called an Event Horizon. Earthquake deformation can also be recognised from dragging or folding modes of deformation. We need to determine the number and position of event horizons in the stratigraphic sequence of the trench, and then in time, using the radiocarbon dates. For example, more than one event horizon has been recognised from *Sequence 2,* and the uppermost Sequence (topsoil) is not deformed by any earthquake events.

We observe evidence for four clear earthquake events and perhaps one further young event in Viewfield trench. All of these events are constrained by stratigraphic relationships in the trench and somewhat constrained by the radiocarbon samples that we have had dated.

In the Viewfield trench the 70 cm wide fault-related fissure forms the major zone of

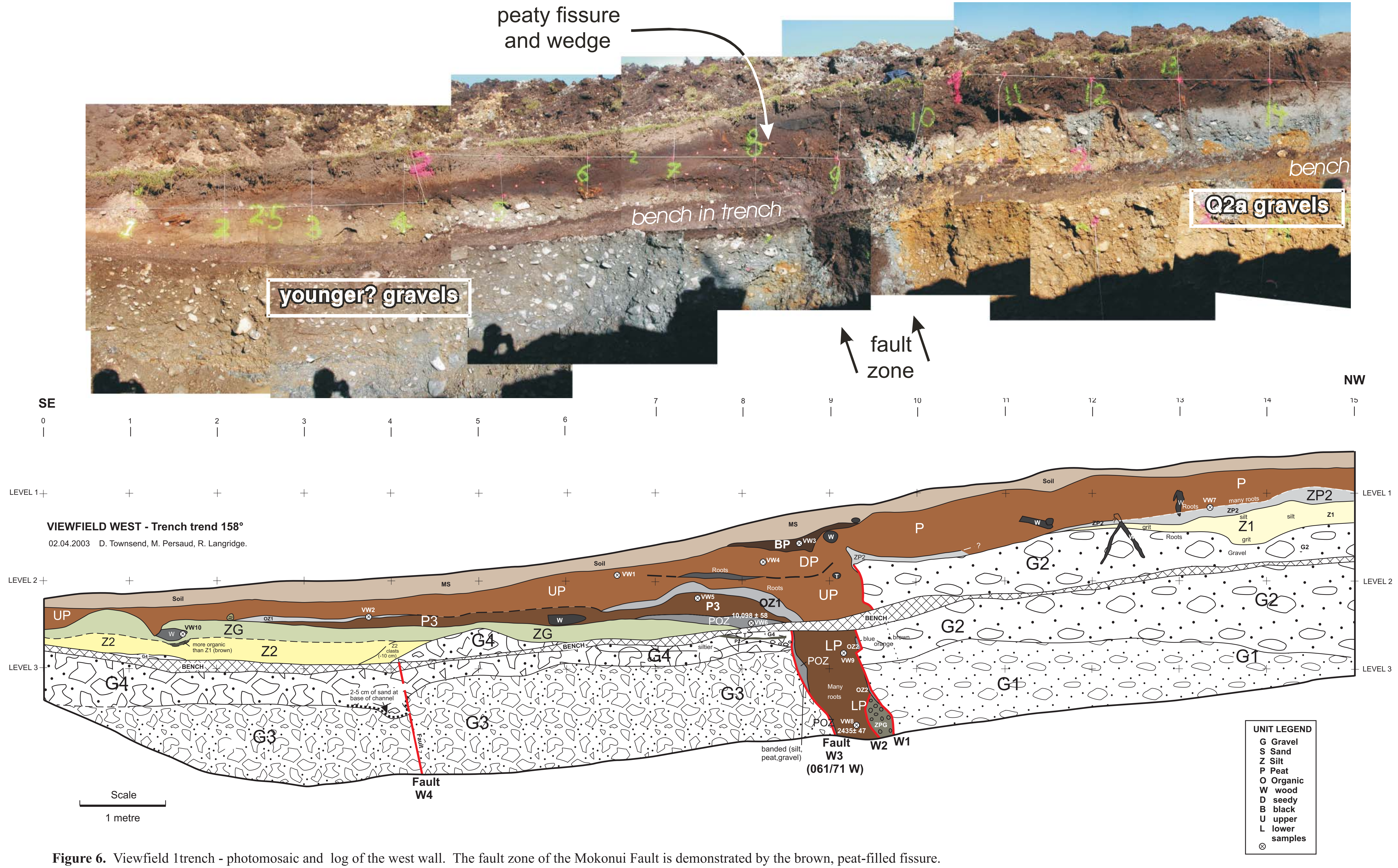


Figure 6. Viewfield 1trench - photomosaic and log of the west wall. The fault zone of the Mokonui Fault is demonstrated by the brown, peat-filled fissure. Near the base of the trench this fissure contains material dated at 2435 ± 47 radiocarbon years B.P. Distinct surface-rupturing earthquake events can be extracted from the geological history of the trench, documented here.

deformation. The two walls of the fissure are themselves faults, as they juxtapose and shear different units across them. It appears that a third fault bisects the fissure-filling peat and deposits on the east wall (metre-7.5, Fig. 7). *Sequences 3* and *4* are separated across the width of the fissure. Units of *Sequence 2* fill the fissure but are also dragged into it. However, the record of faulting (offset of strata) in units above the fissure is difficult to determine as no clear fault breaks are observed in the upper half of *Sequence 2*. In these cases we have relied on stratigraphic evidence for defining deformation events, e.g., deformed (warped or dragged) units, thickening of units and the presence of unconformities in the section. This relies on an assumption that faulting events have occurred but they are masked due to the ductile nature of the peats within and overlying the fissure.

4.3.1 Evidence for Earthquake Event Horizons

The oldest deformation events in the trench are contained within *Sequence 4*. These units are clearly faulted as they abut the fault-related fissure. It is difficult to assess the timing of faulting during or after the deposition of these gravels as no offsets are observed across the G1-G2 contact on either wall. Additionally, we have little age control within these deposits. We suspect that the wedge-shaped G5 gravel package, which occurs only on the upthrown block (metre-10.5; Fig. 7), is fault-related in origin. This deposit has a steep uphill facing contact against G2, and may have developed as a colluvial wedge deposit as gravels of unit G2 were eroded from the fault scarp (fault E7) following a faulting event (Fig. 7). This is perhaps the oldest recognised deformation event in the trench.

On both walls the contact between gravels G3 and G4 in *Sequence 3* is faulted. On the west wall a fault (fault W4; metre-4) is identified penetrating up to, and probably higher than, the G3-G4 contact based on the disruption to unit G4. We recognise that G4 is warped up to the northwest of fault W4 in the same style as the unit contact below it. This warping has a reverse style of drag on the unit G4. Unit Z2 overlies the top of gravel G4 in an onlapping fashion. Some clasts are included in the northern end of Z2 where it laps against G4. ZG is the first unit to completely drape over the deformed top of G4 (Fig. 6). On the east wall, two faults (E1 and E2; metre-7.5) were mapped cutting gravel G3. One of these faults (at metre-7.7) terminates on the base of bed SZ, while the second fault (at metre-7.3) truncates this same bed (Fig. 7). It is not certain whether these two faults represent the same faulting event, or even if the bed on either side of the second fault is the same one. There is a strong possibility that they were active during the same faulting event (here called Event I) due to their proximity within the section. If we correlate the beds on either side of the second fault, then we infer a small (up to 40 cm) vertical separation across this bed at the fault (near-field).

The far-field separation on this bed is closer to 20 cm because the beds flatten out with distance from the faults. This offset has a reverse sense of separation across it, as it does on the west wall. It also seems likely that there is a component of strike-slip separation across fault E1. This will be discussed further below.

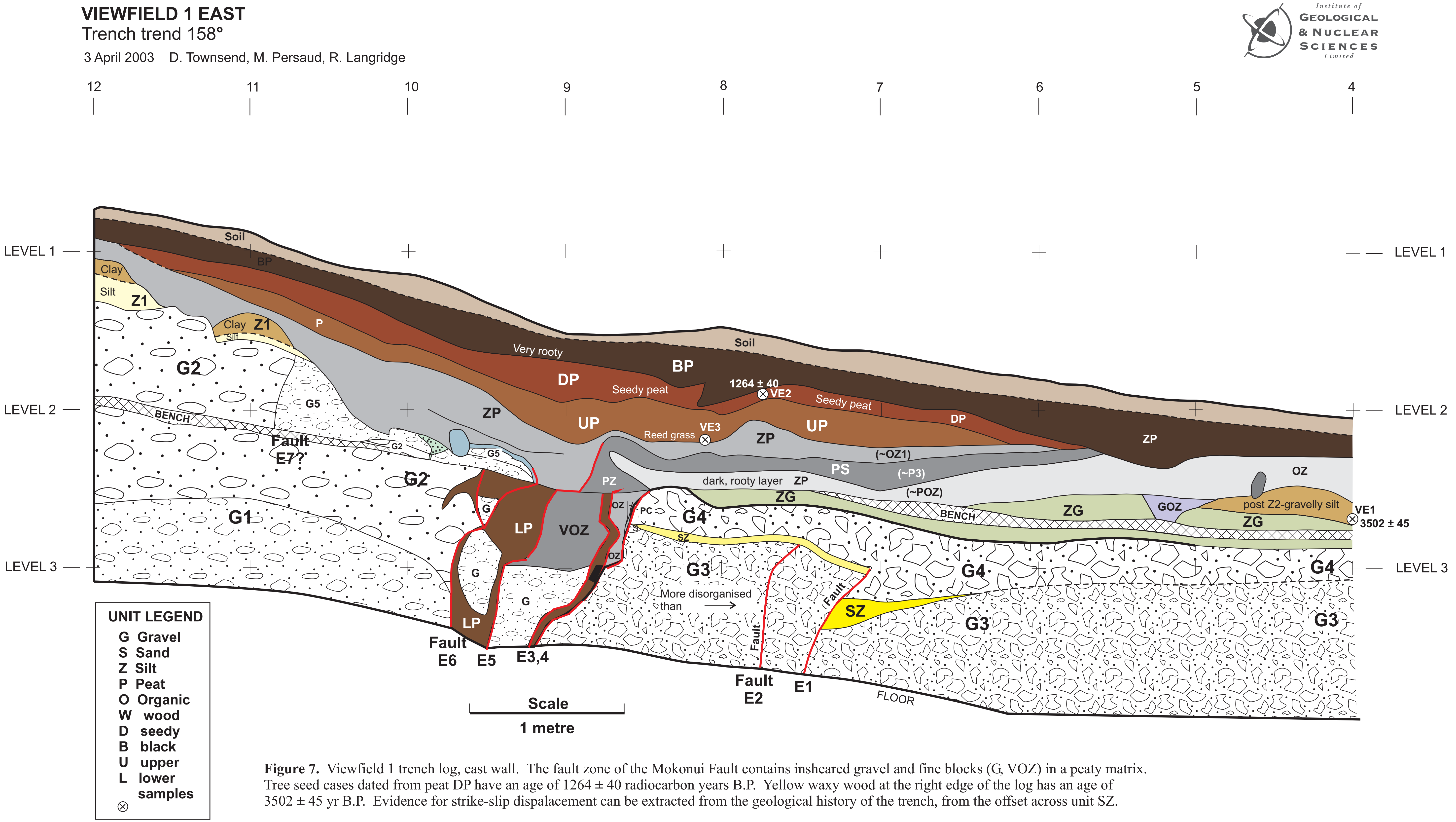


Figure 7. Viewfield 1 trench log, east wall. The fault zone of the Mokonui Fault contains insheared gravel and fine blocks (G, VOZ) in a peaty matrix. Tree seed cases dated from peat DP have an age of 1264 ± 40 radiocarbon years B.P. Yellow waxy wood at the right edge of the log has an age of 3502 ± 45 yr B.P. Evidence for strike-slip dispalacement can be extracted from the geological history of the trench, from the offset across unit SZ.

At least three potential earthquake-related deformation events have occurred within the *Sequence 2* units. This is evident from the deformation within the units and the re-sheared nature of the peat-filled fissure. The complete event story is more clearly shown on the west wall of the trench (Fig. 6), though supporting and additional insights come from the log of the east wall (Fig. 7). Because G2 and Z1 are partially stripped from the upthrown side of the fault zone, and gravel ZG occurs only on the downthrown side of the fault, we infer that the deposition of ZG post-dates a rupture event, Event II. ZG has the appearance of a colluvial unit. This stratigraphic evidence is the only basis for this event.

The next event (Event III) is placed at the top of units POZ and ZP2 (west wall) and at the top of the equivalent unit (OZ) on the east wall. Event III caused the draping of POZ into the fault zone (fissure). This implies that the fissure began to open at or before the time of this deformation event. Unit ZP2, on the upthrown block, was generally dragged upward rather than downward. Remnants of sheared ZP2-equivalent material (OZ2) are smeared along the sides of the fissure below ZP2 on the downthrown block. At a lower level in the fissure there is an isolated occurrence of silty peaty gravel (ZPG) near the floor of the trench. This is also interpreted as a fault-bounded sliver, and the timing of its emplacement in the fissure must be related to this event. Pods of gravel surrounded by peat are also observed within the fissure on the east wall, and are probably equivalent to ZPG. On the east wall the exact relations of this displacement event are unclear, though it appears that Unit OZ was warped up and also dragged into the fissure (Fig. 6). Following Event III there was probably a large open fissure that then began to accumulate peat. This type of fissure was common in the 1999 Izmit earthquake surface rupture, especially where the surface rupture passed through soft surficial materials (USGS, 2000; Langridge et al., 2002). The opening of this fissure, and therefore Event III, is constrained by the radiocarbon date on sample VW8b (Appendix I). The wood dated from this peat (LP) is 2435 ± 47 yrs B.P. and thus Event III occurred prior to the opening and filling of the fissure. The fabric of the peat in the lower part of the fissure (peat LP) is more disturbed than the uppermost peaty units, implying that it has been sheared by at least one faulting event.

The next displacement event (Event IV) postdates units P3 and OZ1 (west wall) and their equivalents on the east wall (PZ and ZP). Beginning with the west wall, after the lower part of the fissure was filled by peat LP, another peat P3 accumulated and was overlain by OZ1. The latter two units were deformed on the downthrown block and dragged into the fissure during Event IV (Fig. 6). Shearing occurred in unit LP. On the east wall buckling or folding of units ZP and PZ occurred near the fissure zone (Fig. 7). Faulting arguably occurred up to the level of these units. A new fissure was opened that was filled by the upper peat UP after Event IV. The units above this horizon, i.e. UP, DP, BP and MS, are generally trough-filling and appear to be undeformed (unfaulted). Event III occurred after the dated material VW8b was deposited.

On the east wall (Fig. 7), the top of the seedy peat (DP) may be warped by another deformation event (Event V?). Evidence in support of an event this high in the section are the pinching unconformity relations mapped near metre-6 on the east wall and the trough-filling nature of the black peat (BP) over the top of DP. Two lines of evidence against an event at this level include the lack of faults or shearing deformation in the units deposited after the previous event, i.e., UP and DP. The second reason that this may not be earthquake-related is its proximity to the surface and recent processes, e.g., natural compaction in soft, waterlogged sediments or deformation related to animal treading, or from the weight of the backhoe as the trench was excavated.

There is no evidence for disruption (faulting) of the modern topsoil (*Sequence 1*). It drapes the scarp in a continuous, undisturbed fashion (Figs. 6,7).

4.3.2 The Style of Faulting Events

The style of faulting, or the relationship between horizontal and vertical movement is important for assessing the total displacement, and thereby hazard and magnitude posed by surface-rupturing earthquakes on the Mokonui Fault. We can assess this in two ways: (i) using the data available from the trench exposure and geomorphic analysis of the fault, and (ii) comparison with the style of faulting on the other central Wairarapa splay faults, i.e. the Masterton and Carterton faults.

In addition to the topography, i.e., offset, created by the Mokonui Fault, there is further evidence for vertical separations giving dip-slip motion across faults in Viewfield trench that will be discussed in this section. Displacements on the Mokonui Fault clearly have a net down-to-the-southeast style, i.e. the downthrown block of the fault is to the southeast or east, over the entire mapped length of the fault (Townsend et al., 2002). The fault dip observed in the trench is steep and to the northwest, from 61-72° on the west wall and from 55-85° on faults exposed on the east wall (Fig. 6, 7). This dip projects the fault plane back toward the Wairarapa Fault at depth.

This kind of dip direction in association with dip-slip motion would usually be associated with reverse faulting. In such cases the hangingwall block, in this example the side to the northwest of the fault, is uplifted over the footwall block, bringing older units over younger ones. This may be the case as we have asserted from stratigraphic and geomorphic arguments that *Sequence 4* gravels may be older than *Sequence 3* gravels in the trench. However, the same relationship could be developed by normal faulting. In some cases such steep faults could be associated with normal motion if those faults have rolled over (changed their direction of dip) at the surface of the earth, as seen in trench exposures. Another line of reasoning would suggest that normal faulting is more likely to produce local thickening on the downthrown block adjacent to the fault, producing a wedge-shaped profile in the deposits that drape across the fault zone.

From the mapping of geomorphic surfaces it is clear that older terrace gravels exposed on the northwest side of the fault are “back-tilted” to the northwest toward the Wairarapa Fault (Townsend et al., 2002). This relationship is more typically associated with a normal component of motion, but could also be related to a reverse sense of motion if a warping, or fault-bend-fold type of deformation is occurring in the hangingwall of the fault.

Can we determine whether there has been strike-slip, or horizontal displacement on the Mokonui Fault from the Viewfield 1 trench? No horizontally-offset surficial geomorphic features that would provide unequivocal confirmation of strike-slip movement, such as river terrace risers, have been recognised along any part of the Mokonui Fault. However, compressional and extensional fault jogs recognised by Townsend et al. (2002) indicate dextral strike-slip motion along the fault. Some features in the trench, such as the juxtaposition of units in the trench wall, slivered units in the fault zone, the style of the fissure, and the steep fault dip are consistent with strike-slip behaviour. The exposure of the faults in Viewfield trench is typical of many New Zealand strike-slip faults observed in trenches, e.g. the Wellington Fault (Van Dissen & Berryman, 1996; Berryman et al., 2002) Strike-slip faults will often fan out (splay) or roll-over to angles of <90º dip as the fault approaches the ground surface from depth. Conversely, true reverse faults (>60º dip) are not often observed in trenches, and thrust faults (low-angle reverse faults) are expressed as faults with low dips of 0-30º in trench exposures. The faults in this trench are therefore, not thrust faults. This argument is not conclusive, but in association with mismatched and slivered fault zone units is strongly suggestive of an important component of strike-slip motion.

We have demonstrated in Section 4.3.1 that there are significant mismatches (juxtaposition) of units across faults. For example, the fine clastic bed SZ, between G3 and G4 changes thickness and texture across fault E1 (Fig. 7). In addition, within the fissure on both walls are isolated, vertical slivers of gravel units and blocks of clastic units. We argue that these have occupied the fissure and have been re-sheared by horizontal fault movement. A third line of reasoning follows that the fissure is the product of local extension along the fault zone. Would this be possible under a contractional (reverse) regime, or does this favour a normal mode of dip-slip separation? We argue that the opening that created the fissure is the product of strike-slip faulting, with an additional component of dip-slip movement, of which the style is not clear. In cases where strike-slip faulting is the dominant style, small changes in the strike or dip of the fault at a given point will yield transtensional or transpressional features at the ground surface. We suspect that this is the case along this portion of the Mokonui Fault. The sense of strike-slip motion cannot be determined from the trench, but it is likely to be dextral. This was also the conclusion from the observation of fault jogs along the fault trace (Townsend et al., 2002).

The second means of testing the style of movement is to compare the Mokonui Fault with the nearby Masterton and Carterton Faults (Zachariasen et al., 2000; Begg et al., 2001). These authors showed that the Carterton Fault is a dextral-slip fault with a normal component of vertical motion. This was observed both from geomorphic offsets, such as laterally-displaced terrace risers across a scarp, and also from faulting evidence in a trench and in outcrop. A normal component of motion is consistent with the local stress field related to plate boundary convergence across southern North Island (Beanland, 1995).

Like the Mokonui Fault, the Masterton Fault yielded no geomorphic evidence of lateral displacement, e.g., offset stream channels. A trench that was dug across the Masterton Fault showed that a normal component of deformation was present for that fault (Begg et al., 2001). Therefore, with a similar strike and length, and its position adjacent to the Carterton Fault, it has been assumed that the Masterton Fault is also a dextral strike-slip fault with a normal component of dip-slip motion (Zachariasen et al., 2000; Begg et al., 2001). Therefore, if we follow the concept of a “family” of central Wairarapa splay faults, i.e. the Carterton, Masterton, and Mokonui Faults, then the Mokonui Fault should also be a dextral-slip fault with a normal component of vertical motion. However, the style of vertical motion may have more to do with the local strike along the fault, and the tendency for fault dip back toward the Wairarapa Fault producing reverse dip-slip motion.

In summary, it appears likely that the Mokonui Fault has both strike-slip and dip-slip motion. The lateral component of motion is likely to be dextral in sense, while it is unclear if the vertical component of motion, is normal or reverse in sense.

4.3.3 Magnitude of fault displacement

The amount of displacement on geomorphic features near to and in the trench is difficult to accurately assess for several reasons: (i) we have not found a correlation between the lower gravels (*Sequence 3* and *4*) across the fissure zone in the trench; (ii) this creates uncertainty regarding the displacement of units higher up that drape the scarp; (iii) the exact style of faulting is not known; and (iv) the component of horizontal motion is difficult to assess.

To estimate the amount of vertical separation we can use a number of techniques. First, if we create a profile along a bearing of 150° from the GPS-RTK topographic map of the Viewfield trench site shown in Fig. 4 we observe a total vertical separation across the scarp of c. 2.5 metres over a distance of 25 metres on either side of the fault scarp (Fig. 4). This is comparable to the 3.2 metre scarp height shown in Townsend et al. (2002). Across the length of the trench (15 metres on the west wall = “mid-field”) the total change in height of the two surfaces is 1.7 metres, while the total far-field displacement across the scarp (scarp height) is c. 3 metres. The cover sequences (*Sequences 1 and 2*) appear to be of a relatively constant thickness (60-80 cm) outside of the fault zone, therefore we can make the assumption that the total displacement between *Sequence 3* and *4* gravels is also c. 3 metres. The apparent offset at the fault, 0.9-1.1 m, is considerably less than observed in the far-field (Fig. 6). The apparent displacement at the fault itself is lessened by the bending of units, erosion of units from the upthrown block, and the effects of secondary deformation near the fault zone, which could account for c. 10% of the total deformation (Rockwell et al., 2002).

In addition, if we accept that *Sequence 3* and *4* gravels consist of different units of different age, then there is at least 2.2 m of near-field displacement across the fault from the upper contact of G2 to below the exposed base of G3 at the floor of the trench.

4.4 Discussion and interpretation

On faults that are predominantly strike-slip in character, trenching cannot usually constrain displacement measurements, but through juxtaposition of stratigraphic units the timing of events can usually be evaluated. In this section we present an interpretation of our observed data on the Mokonui Fault. Although we found abundant datable material in the trench, the faulting relationships and event designations are not ideal for paleoseismic interpretation. We also discuss our interpretation of the vertical and horizontal slip rates, the single event displacement, and average recurrence interval.

4.4.1 Timing of rupture events

The main information about fault timing that can be extracted from field data is discussed below and presented in Figure 8. The size of the age range for each event is determined by the number and spacing of radiocarbon ages that we have at our disposal. The ranges are broad and show us as much information about earthquake recurrence as they do the actual event timing. The main results are:

1. The oldest event in the trench that can be dated, i.e. in *Sequence 2*, we call Event II. Faulting relations are not observed, but would have occurred at the main fissure zone. This event produced the colluvial deposit ZG, and is constrained only by the radiocarbon date on wood from the east wall, i.e. sample VE1; radiocarbon age of 3502 ± 45 yrs B.P. The age of VE1 is calendar–calibrated to the range 3639-3893 years B.P. at the 2σ level. This provides a minimum age for the Event II rupture of >3639 calendar-calibrated yr B.P. We have no definitive age control before this event, though we can say that Event I faulted *Sequence 3* gravels, but not ZG, and those gravels are younger than 10,098 ± 58 yrs B.P., if the wood dated in POZ was re-deposited from older gravels
2. Event III is younger than the radiocarbon date on VE1, but older than the age on VW8b (2435 ± 47 yrs B.P), which marks the accumulation of peat in the fault-related

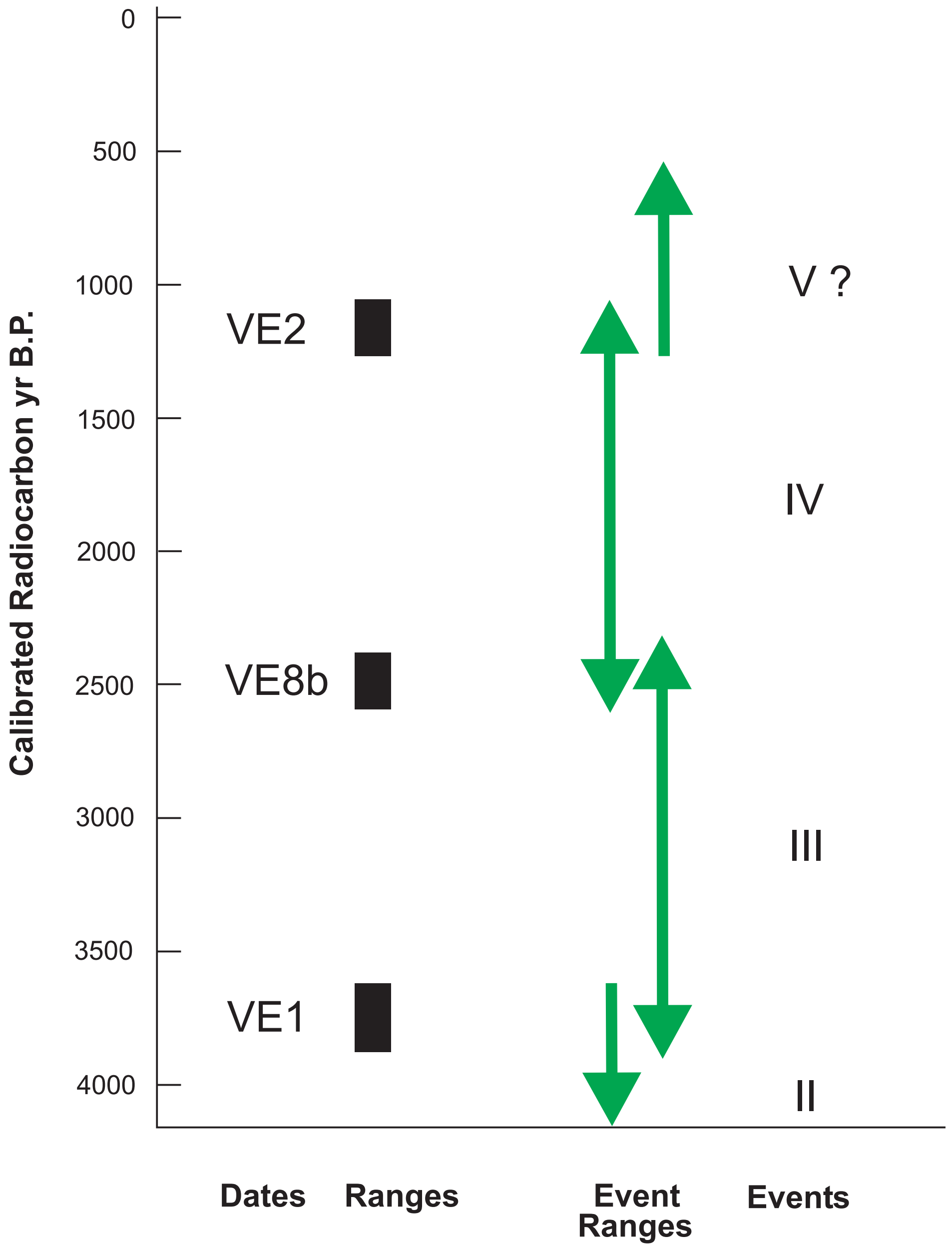


Figure 8. Radiocarbon dates and earthquake event ranges for the Mokonui Fault from the Viewfield trench. The green arrows represent the possible 2-sigma age ranges of each of 4 potential earthquake events that have occurred since deposition of Sequence 2 units began.

fissure. The age range for Event III covers the whole range of these two dates and is therefore from 2356-3837 calibrated yr B.P.

3. Event IV occurred between the dated samples, VW8b and VE2 (1264 ± 40 yrs B.P) and therefore falls in the 2σ calibrated range (1068-2707 yr B.P.). However, we suspect that this was not an earthquake-related deformation event.

4. If Event V? did occur then it post-dates sample VE2 and therefore we can constrain the maximum age of such an event to <1283 calendar-calibrated years B.P. We consider such a young event to be unlikely.

4.4.2 Vertical Slip Rate

The vertical component of motion across the fault scarp and offset in the gravels is ~3 metres. If we use the age of the young Waiohine gravels (Q2a) that probably underlie the upthrown side of the fault scarp (i.e. *Sequence 4*), and in particular the date on VW6, we can develop a vertical slip rate for the fault. These data produce a vertical slip rate of ~0.2-0.3 mm/yr (rounded) for the period since Q2a gravels were deposited at this site, i.e. since VW6.

The vertical displacement recognised in *Sequence 2* units is considerably less than that interpreted from the gravels. The Event III horizon has a vertical separation across the fault in the trench of ~50 cm, while the Event IV horizon appears to have ~40 cm of separation. The vertical slip rate across the former event horizon equates to <0.2 mm/yr, while Event horizon III yields an even lower rate. Conservatively, these data together indicate that the vertical slip rate is 0.1-0.3 mm/yr.

If we use the largest scarp height near the Viewfield trench (4.2 m; Townsend et al., 2002) and also the separation across a Q2a cut surface at the fault at Hawkhurst (10.7 m; Lensen, 1969), a vertical slip rate of 0.3-0.5 mm/yr is derived. Additionally, if we use the scarp heights from the older Q3a to Q4 surfaces on Hawkhurst Station (15.2-17.8 m), minimum vertical slip rates of 0.2-0.7 mm/yr are calculated across surfaces ranging from 24-71 ka old, to the current surface on the downthrown side there (Lensen, 1969; Townsend et al., 2002). All of these rates are dependent on the correct designation of the ages of terrace and gravel packages with particular climatic stages, which themselves have broad age ranges.

Overall, from this dataset we deduce a vertical slip rate ranging between 0.2-0.5 mm/yr. The slip rate values appear to generally increase for larger scarp heights, which suggests there is some question about ages of the surfaces we are dealing with, or that the depth to the equivalent surface on the downthrown side is not well understood. The value of 0.2-0.5 mm/yr is comparable to the calculation of 0.3-0.7 mm/yr derived for the nearby Masterton Fault (Begg et al., 2001).

4.4.3 Horizontal Slip Rate

We recognise that there is a lateral component to displacement on the Mokonui Fault. This displacement is unknown, and no guide to its magnitude was determined from the trenching study. However, there is physical evidence in the trench that implies that lateral motion occurs.

How then do we best address its importance? Due to the lack of dextrally-displaced late Holocene geomorphic features we consider it unlikely that the Mokonui Fault ruptures in multi-metre horizontal events. If it did, we would see the evidence for Waiohine (Q2a) age features with many metres of displacement, or evidence for at least 3 late Holocene events, as observed in the trench record, with significant horizontal motion and offset post-Waiohine channels. As modern channels between Hawkhurst and Mokanui (Fig. 1) do not yield significant displacements or stream deflections, we prefer to consider the Mokonui Fault as a pure oblique fault, i.e., with a ratio of horizontal to vertical motion (H:V) of 1.

Alternatively, we recognise that most faults tend to have a dominant mode of displacement (reverse, normal or strike-slip) while a secondary mode is significantly sub-ordinate. Thus, we also recognise that if the Mokonui Fault is a strike-slip similar to other New Zealand strike-slip faults, e.g., the Wellington Fault (Van Dissen and Berryman, 1996) or the nearby Carterton Fault (Zachariasen et al., 2000; Begg et al., 2001), then the H:V ratio may be considerably higher, (closer to 8:1).

Without more adequate data on the style of faulting, we prefer to consider, as a minimum, that the Mokonui Fault is a pure oblique fault with H:V =1. Therefore, this yields a horizontal slip rate of 0.2-0.5 mm/yr and a total slip rate of >0.3-0.7 mm/yr.

4.4.4 Single event displacement

Our data suggest that c. 50 cm of vertical movement has occurred since the formation of OZ1 (west wall), the top of which corresponds to the Event III horizon. Considering the real possibility of strike-slip juxtaposition of units, and the doubt over Event V?, the 50 cm vertical separation is attributed to only one displacement event (IV). If the c. 50 cm of vertical separation per event is combined with the H:V ratio of 1:1, then the dextral single event displacement would amount to c. 0.5 metres, and indeed, the total single event displacement (SED) would total c. 0.7 m (due to rounding). For older units such as the footwall gravels (*Sequence 4*; Q2a) with a vertical separation of c. 3 m, the total dextral displacement of these deposits since 10-14 ka would amount to only c. 3 metres, and may not be visible in the geomorphology.

If we return to our slip rate argument, a higher H:V ratio of c. 8 would yield a SED of up to.

5.6 metres. While this is possible, we re-iterate that no such horizontal offsets have been identified. In addition, this amount of lateral motion would generate displacements of post-Waiohine age geomorphic features of up to 25 metres, and these also have not been recognised.

4.4.5 Earthquake recurrence interval

A slip rate of 0.3-0.7 mm/yr combined with a single event displacement of 0.5-0.7 m implies a recurrence interval (RI) of c. 715-2333 years. Results from the trench show that there have been 2-3 events in the last c. 4000 yr, or probably 2 events (II, III) over c. 2800 yr (1068-3893 yr B.P.). This result implies an average recurrence interval of 1300-2000 yr from this study (preferred), which, given the levels of uncertainty in our results, is similar to the calculated value above. If we consider the event window ranges of Event III and IV as an independent test of RI, i.e., materials available to date are buried and preserved by earthquake events, then that range is 1500-1600 yr (Fig. 8). As we consider the evidence for Event V? to be weak, then it is likely that the most recent event on the Mokonui Fault occurred more than 1000 years ago.

5. COMPARISON WITH INTERNATIONAL HISTORIC FAULT RUPTURE DATA

In this section, the fault characteristics of the Mokonui Fault derived from the trenching and geomorphic studies are compared with information compiled for faults internationally and a new analysis of global fault parameters from New Zealand (Wells and Coppersmith, 1994; Stirling et al., 2002). From these comparisons, reasonable and logical limits on the characteristics of the Mokonui fault can be established. Due to limitations in the field data derived for the Mokonui Fault, this step is critical in assessing its hazard.

Trenching of the Mokonui Fault has revealed that the vertical component of the fault movement is on the order of c. 50 cm per event at the Viewfield trench. The vertical slip rate is in the range 0.2-0.5 mm/yr in the area adjacent to Paeirau Rd. Strike-slip faults can have sections with a normal or reverse vertical component. The fault scarp can therefore have opposite facing scarps along different sections of the fault. The Mokonui Fault scarp is entirely downthrown to the south, but has local north-facing secondary scarps at extensional jogs, e.g., Hawkhurst pond. The Viewfield trench is located on a south-facing scarp. We consider that the fault plane geometry at Viewfield locality is representative of almost the entire fault, so the Mokonui Fault is a strike slip fault with a vertical component of motion that is difficult to assess. If the Mokonui Fault is like its adjacent neighbours - the Masterton and Carterton Faults - then that vertical component would have a normal sense.

Fieldwork has not provided unequivocal data on the characteristics of the Mokonui Fault.

Therefore, we apply worldwide information to assess single event displacement (SED) and maximum earthquake magnitudes. During the last decade the global dataset of historic surface-rupturing earthquakes of Wells & Coppersmith (1994) has been used by the geological community to calculate parameters for faults yet to rupture in the historic period. However, in this report we use the most up-to-date version of this dataset published by Stirling et al. (2002) which considers surface rupturing earthquakes, and heavily weights data from New Zealand surface faulting events. Stirling et al. (2002) have re-compiled statistics on a large number of historical fault ruptures from which they deduce new relationships between fault length and single event displacement (SED) and between fault length and earthquake magnitude. The new relationships they deduce for faults are:

$$\log (D) = 0.06 + 0.18*\log (L)$$

$$M_w = 5.88 + 0.8*\log (L)$$

where D = average surface displacement; L = surface rupture length; and M_w is earthquake moment magnitude. Based on these relationships, the 20 km length of the Mokonui Fault yields an average SED of 2 m and an M_w of 6.9. The equivalent results using the equations of Wells and Coppersmith (1994) are also presented in Table 3 as a comparison only. They tend to give SED values closer to those expected for the Mokonui Fault if it is considered an oblique fault. The data produced from this study yield smaller SED and magnitude results to those of Berryman et al. (1998) and Stirling et al. (2002), e.g., single event displacement of up to 0.7 m (minimum) and Mw c. 6.7 for the Mokonui Fault. Additionally, these values are generally lower than those estimates for the Masterton and Carterton Faults, but still imply that the Mokonui Fault poses a similar hazard to those faults (Table 2).

In summary, we consider the "best estimate" value for slip rate on the Mokonui Fault to exceed the maximum value of its vertical slip rate. Although we do not unequivocally know the ratio between horizontal and vertical slip for the Mokonui Fault, we have assumed that as a minimum, it is purely oblique (H:V c. 1). Therefore, its total slip rate has to be larger than 0.5 mm/yr, and is estimated at c. 0.7 mm/yr (Table 2).

Table 2 Estimates of characteristics for the Mokonui Fault

	Horizontal – or total* - slip rate (mm/yr)	**Vertical slip rate (mm/yr)**	**SED (m)**	**RI (yrs)**	**Time of last EQ (yr BP)**	**EQ Magn. (Mw)**
Berryman et al. (1998)	1*	-	2	2000	-	7.0
W&C (1994)	-	-	0.5-0.7	-	-	6.6
this field study	**>0.3-0.7***	**0.2-0.5**	**0.5-0.7**	**1300-2000**	**1100-2600**	**6.7#**
using Stirling et al. (2002)	**-**	**-**	**2**	**-**	**-**	**6.9**

* = combination of horizontal and vertical slip rate; SED = single event displacement; RI = recurrence interval; EQ = earthquake; # using the Stirling et al., (2002) relations; W&C (1994) = Wells and Coppersmith (1994).

No new analysis of the Masterton and Carterton Faults was included in the scope or tasks of this project. We have largely considered the data from these faults in light of relationships we observe for the geomorphology and faulting on the Mokonui Fault. In addition, there is new independent data from the Mokonui Fault that helps confirm the work already published for the other two faults.

6. CONCLUSIONS

- A lateral component of slip is inferred for the Mokonui Fault, in conjunction with a vertical component of slip whose style is difficult to determine. The vertical component would be normal, if the Mokonui Fault behaves like the Masterton and Carterton Faults, but reverse if the Mokonui Fault dips back and joins the Wairarapa Fault plane.
- Our current preferred style of motion for the Mokonui Fault is oblique (H:V ratio = 1) where the horizontal and vertical components of slip are equivalent. This is a minimum as we have no way of assessing the actual amount of horizontal motion.
- The materials and faulting relations in this trench have been useful in identifying earthquake events and their timing. At least two surface-rupturing earthquake events occurred during the last 4,000 years (at least 4 in the last c. 12,000 yr) on the Mokonui Fault. The average recurrence is in the range 1300-2000 years.
- Fault characterisation relies significantly on comparison with calculations using the global dataset of historical surface-rupturing earthquakes, and comparison with the nearby Carterton Fault and Masterton faults.
- Field data and comparison with documented overseas historical earthquakes suggests that the Mokonui Fault ruptures with a SED of c. 0.7 m and is associated with an earthquake of c. M_w 6.7-6.9, probably every 1,300-2,000 years. The slip rate has been estimated at 0.5-0.7 mm/yr.
- While we have no new data for the Masterton and Carterton Faults, our results for the Mokonui Fault vindicate the previous studies of those faults, in that this “family” of faults have similar styles, rates of motion, and overall earthquake hazard.

7. RECOMMENDATIONS

- We recommend that an additional WELA project is mooted to tie together the knowledge learned from all of the GNS studies on the three central Wairarapa "splay" faults. The global earthquake parameter dataset for these faults needs to be recast according to the new results of Stirling et al. (2002), and more recent updates undertaken by Terry Webb at GNS for New Zealand faults and earthquakes (unpublished data).
- As part of this project we recommend that an additional component of field study is funded and undertaken on the Masterton Fault, which poses the most serious seismic risk to structures in the Wairarapa.
- We also propose that as part of this new study that an additional trench be dug across the Masterton Fault at a new location that is likely to yield better data for the characterisation of that fault.
- We recommend that better dating of the late Quaternary surfaces in the Wairarapa is undertaken to better constrain the faulting history. Better estimates will reduce the uncertainties, most of which (regarding the slip rate and levels of fault activity) stem from uncertainties in the ages of the offset features. For example, we have several organic samples from the Viewfield 1 trench that could still be dated to better constrain the earthquake event record there.
- We recommend studying the structural interactions between the active faults in the area to determine how they work together. Determining whether slip on the Wairarapa Fault is transferred to the Carterton, Masterton and Mokonui Faults by determining the slip rate on the Wairarapa Fault immediately south of the Carterton Fault and immediately north of the Mokonui Fault, or the sum of fault motions across faults near Alfredton.

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APPENDIX I: DATING

Radiocarbon dates

Four wood and seed samples were submitted for radiocarbon dating to help constrain timing of rupture events and the slip rate for the Mokonui Fault. The radiocarbon dating results are listed below.

Field no.	Lab. no. (R no.)	Sample type	Date no.	d13C (o/oo)	Radio-carbon age (yrs BP)	1 sigma Calibrated age	2 sigma Calibrated age
VE 2	26486/1	tree seeds	NZA-17299	-18	1264 ± 40	1265 - 1170 BP	1283 – 1068 BP
VE 1	26486/2	wood	NZA-17298	-22	3502 ± 45	3837 – 3693 BP	3893 – 3639 BP
VW 6	28187/3	organic sediment	Wk-12742	-28.1	10,098 ± 58	11,360 – 11,927 BP	11,297 – 12,258 BP
VW 8b	28187/4	wood	Wk-12743	-26.8	2435 ± 47	2356 – 2707 BP	2344 - 2723 BP

Samples VE1 and VE2 were dated using the AMS technique at Rafter Radiocarbon Laboratory, IGNS Ltd., Lower Hutt, New Zealand. VW6 and VW8b were dated by Conventional means at Waikato University Radiocarbon Facility. Location co-ordinates are from NZMS 260 T26/ 3206 3124. Ages are calibrated using INTCAL_14C of Stuiver et al. (1998).

APPENDIX II: STRATIGRPAHIC DESCRIPTIONS

Viewfield 1 unit descriptions, Mokonui Fault

North of fault:

Gravel 1 (G1): poorly sorted, densely packed cobble gravel; matrix of sand to grit; clasts sub-rounded up to 30 cm max, most 4-8 cm. Weakly stratified by slightly better sorted layers; orange-brown colour.

Gravel 2 (G2): poorly to moderately sorted gravel with sandy matrix; slight imbrication of clasts; occasional cobble to 15 cm; rounded to sub-rounded clasts; coarsens in top 30 cm; orange-brown, but blue grey at top and where affected by tree roots.

Silt 1 (Z1): Blue-grey sand to clay; graded over ~30 cm, sandy/gritty at base above gravel (G2) and finer clay at top; slightly organic at top, where finer, and brown-grey colour.

Silty peat 2 (ZP2): Mixed zone at base of peat; organic fine silt to clay; many roots from peat.

Peat (P): medium to dark brown peat with little or no silt; many roots and pieces of wood; abundance of wood varies laterally, with less to the south of the fault. On east trench wall peat contains seeds and mats of rushes.

South of fault:

Gravel 3 (G3): moderately sorted weakly stratified cobble gravel with clasts sub-rounded up to 20 cm; sandy matrix.

Gravel 4 (G4): moderately sorted gravel with sandy matrix; no stratification; clasts rounded to sub-rounded up to ~15 cm, but fewer large clasts than G3 and more sand; matrix not well consolidated; base often marked by a 2-8 cm thick, coarse sand layer. Tough silty khaki coloured gravel at top ~15 cm.

Peat 2 (P2): 2 cm thick (max) organic layer in silty gravel at top of G4.

Silty gravel (ZG): poorly sorted gravel with matrix of silt to fine sand; clasts rarely up to 15 cm, but on average 6 cm; thins away from fault to a gravely silt with a stone line at top.

Silt 2(Z2): fine to medium silt with grit towards top where in contact with colluvial gravel; top contact gradational; medium brown to olive brown colour; grades laterally towards fault zone into a silty gravel (colluvial wedge?) above Gravel 4.

Peaty organic silt (POZ): organic silt in peat; siltier horizon at top (pale brown); peatier towards base (dark brown); thins to south and merges with top of silty gravel; upper contact with peat gradational.

Peat 3 (P3): woody peat; dark brown, fibrous and friable.

Organic silt 1 (OZ1): fine, medium light brown silt; burrowed lower contact; otherwise massive.

Peat (P): as above.

Silty peat (ZP): slightly silty layer in peat; medium to dark brown; discontinuous; contacts gradational with peat.

Soil (MS): organic soil; dark brown; fine roots to ~20 cm deep; friable when dry, stony in places with occasional pieces of wood and charcoal.

Gravel 5 (G5): loosely packed, poorly sorted matrix supported gravel with sub-rounded clasts up to ~15 cm; mixed with silt at top and 1-2 silt clasts incorporated into gravel; silty to sandy matrix; blue-grey colour. Sits on slightly better sorted gravel with distinct sandy matrix (G2)

<u>Within fault zone:</u>

Silty peaty gravel (ZPG):

Lower Peat (LP):

Upper Peat (UP):

Seedy peat (DP):

Black peat (BP): dark brown to black, fine friable peat.

Very organic silt (VOZ):

Peaty Clay (PC):

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