

Copyright is owned by the Author of the thesis. Permission is given for a copy to be downloaded by an individual for the purpose of research and private study only. The thesis may not be reproduced elsewhere without the permission of the Author.

**THE NEOTECTONICS OF THE
WELLINGTON AND RUAHINE FAULTS
BETWEEN THE MANAWATU GORGE AND
PUKETITIRI, NORTH ISLAND,
NEW ZEALAND**

By

Judith Ann Hanson

**A thesis presented as partial fulfilment of the requirements for the degree of
Doctor of Philosophy in Earth Science**

**Massey University
Palmerston North
New Zealand
1998**

**THE NEOTECTONICS OF THE WELLINGTON
AND RUAHINE FAULTS BETWEEN THE
MANAWATU GORGE AND PUKETITIRI, NORTH
ISLAND, NEW ZEALAND**

Judith Ann Hanson

VOLUME I



Frontispiece: The Ruahine Fault from Baldy quarry (looking north) on Whittle Road, showing dextrally displaced ridges and recent eastward uplift. *Photo by Dr A S Palmer, Department Massey University.*

ABSTRACT

The Wellington and Ruahine Faults are two major faults of the North Island Dextral Fault Belt which formed approximately 2.5ma in response to the obliquely subducting Pacific Plate beneath the east coast of the North Island. Plate rotation has increased over time causing faulting patterns to change throw direction and strike-slip activity to increase within the Hawkes Bay area. Earthquakes rupturing either the Wellington or Ruahine Faults represent a serious hazard for this area.

The purpose of this study was to establish a record of paleoseismic activity on the Wellington and Ruahine Faults which would allow future estimates of likely fault behaviour to be made. Trenches were excavated across these faults in mainly swampy environments. Within these trenches are layers of earthquake debris, layers of peat and other terrestrial sediments which have been deformed by earthquake activity. The layers of peat were radiocarbon dated to give the approximate ages of underlying or overlying earthquake debris. In many areas through which the faults pass are terraces composed of gravel which has been washed down from the axial ranges composed of Torlesse greywacke. The ages of these terraces are known due to layers of dated volcanic ash preserved in cover beds and wood preserved within. Some of these terraces have been offset by the fault. Using the known age of these terraces and the distance that they are offset by the fault, it was possible to calculate rates of fault movement during late Quaternary time.

Field observations of the Wellington and Ruahine Faults reveal that the faults do not deform the areas through which they pass but rather act in response to regional deformation (within these structurally different areas). During earthquake events large blocks of land are moved both horizontally and vertically. The rate and size of these events is dependent on the regional geology where the earthquake ruptures occur. These regions are described as follows from south to north. The first region lies between Kahuki and the Ohara Depression, this is an area of prevalent strike-slip with horizontal offset rates averaging 12mm/yr for the Wellington Fault which is high by world standards. In contrast the Ruahine Fault displays little evidence of late Quaternary movement. The second region encloses the Ohara Depression which has an east-west compressional vector. Here strain is transferred from the Wellington to the Ruahine Fault thereby

lowering the horizontal offset rate for the Wellington Fault to a maximum of 4.7mm/yr. The third region lies between the Ngaruroro and Tutaekuri Rivers and is a region with a north-northeast compressional vector. Here a horizontal offset rate of 3.3mm/yr (for the Wellington Fault) was determined using offset Ohakean terrace rises. The most northern region lies between the Tutaekuri River and Napier-Taupo Highway is a zone of normal strike-slip faulting with a combined horizontal offset rate of 18mm/yr for the Wellington, Ruahine and Te Waka Faults. These regions correspond to proposed rupture segments for both Wellington and Ruahine Faults.

This study provides a record of at least 12 $M_s > 6.5$ earthquake events recorded on the Wellington Fault in the Kahuki-Dannevirke district, 9 of which occurred in the last 30,000 years. This is the longest record of earthquake events recorded within fault trenches in New Zealand. The last earthquake on the Wellington Fault took place c. 300 years ago between Kahuki and Dannevirke. The largest single offset found in the Kahuki-Dannevirke area is estimated to have been displaced by 12m horizontally and 1.8m vertically. The estimated magnitude for an earthquake occurring in this region is between M_s 7.4 and 7.8. An earthquake of this magnitude would cause major destruction to all nearby engineering structures and to buildings in the nearby cities of Palmerston North, Napier and Hastings. Earthquakes of this size are estimated to occur every c. 300 years for the Kahuki-Dannevirke area, every 300 to 500 years for the Ohara Depression and every 1000 years for the region between the Tutaekuri River and the Napier-Taupo Highway.

Similar studies were conducted along the Ruahine Fault trace between the Ohara Depression and the Napier-Taupo Highway. Seismic activity in this area is estimated to produce a M_s 7.4 to 7.5 magnitude earthquake every 400 to 500 years. Horizontal offset is expected to be in the range of 3 to 5.5m. Dates for the last earthquake on the Ruahine Fault have not been determined but it is possible that there have been up to 4 earthquakes on this fault since 1850 yrs B.P.

The Wellington and Ruahine Faults pass mainly through farmland, areas of forestry and the southern Ruahine Range. When an earthquake rupture event occurs it is possible that most farmhouses will escape major damage with little loss of life, providing they are not built on the fault or in the path of any possible landslides. However major disruption is to be expected to any engineering works close to the faults. Landslides may occur on over-steep slopes in and near the

axial ranges and some major rivers may be dammed as a result. The larger magnitude earthquakes will produce severe shaking in the cities of Palmerston North, Napier and Hastings where substantial damage can be expected to occur, especially to those buildings that are built on reclaimed land or on alluvial soils prone to liquefaction.

ACKNOWLEDGMENTS

I would like to thank the following people and organisations for their assistance in various aspects related to this thesis.

Thanks are especially extended to the Earthquake and War Damage Commission. Without their financial support this thesis would not have been possible. I would also like to thank Alan Hull and Kelvin Berryman of the Institute of Geological and Nuclear Sciences, who provided advice and funds for additional radiocarbon dates and trenches. Thanks are also due to John Williams of Desert Exploration for financial assistance with photocopying, printing and binding this thesis.

Special thanks are due to Assoc Prof Vince Neall and Drs Alan Palmer and Bob Stewart of the Soil Science Department, Massey University who supervised this thesis and patiently answered a never-ending string of questions.

I am grateful to Malcolm Boag of the Soil Science Department who assisted with the surveying of fault displacements. I would also like to thank Merryl White for the loan of aerial photographs from Landcare Research N.Z. Ltd archives. Permission to reproduce topographical maps was provided by the Department of Survey and Land Information.

I would like to thank all the farmers and their wives in the Hawkes Bay area along the eastern boundary of the Ruahine Range for all the cups of tea and permission to wander over their land. I especially would like to thank Messrs Inglis, Trotter, Beagley, McCool, Syme, Wedd, and Davis for the interest they showed in this study and who allowed me to dig large trenches through the Wellington and Ruahine Faults on their land.

I would especially like to thank my sister, Joy Hargreaves for her encouragement and help and for acting as a go-between for mail between New Zealand and Australia where this thesis was finished. Thanks are also due to various colleagues for help with editing the text. I would also like to acknowledge the inspiration provided by my parents the late Bill and Ngaere Hanson, who encouraged a love for earth sciences and taught me to think independently, ask questions and look for answers.

TABLE OF CONTENTS, VOLUME 1

Title page.....	i
Frontispiece.....	ii
Abstract.....	iii
Acknowledgments.....	iv
 CHAPTER 1 INTRODUCTION.....	 1
 CHAPTER 2 REGIONAL GEOLOGY.....	 9
 CHAPTER 3 THE WELLINGTON FAULT BETWEEN THE MANAWATU GORGE AND KUMETI ROAD.....	 20
<i>Inglis Farm Trenches.....</i>	<i>22</i>
<i>Trenching on Beagley Farm.....</i>	<i>41</i>
<i>The Paper Road Site.....</i>	<i>45</i>
<i>Trotter Farm Trenches.....</i>	<i>47</i>
<i>Summary of Paleoseismic data for the Wellington Fault between the Manawatu Gorge and Kumeti Road.....</i>	<i>62</i>
 CHAPTER 4 THE WELLINGTON FAULT FROM KUMETI ROAD TO THE NGARURORO RIVER.....	 65
<i>Trenching on McCool Farm.....</i>	<i>71</i>
<i>Discussion and Proposed Offset Rates for the Ohara Depression.....</i>	<i>81</i>
 CHAPTER 5 THE WELLINGTON FAULT FROM THE NGARURORO RIVER THROUGH THE PUKETITIRI AREA TO THE NAPIER- TAUPO HIGHWAY.....	 83
<i>Trenching on Hawkstone Station.....</i>	<i>87</i>
<i>Discussion of offset rates for the Hawkstone area of the Wellington Fault.....</i>	<i>91</i>
<i>The Te Waka Splinter Fault.....</i>	<i>92</i>
<i>Trenching on Wedd Farm.....</i>	<i>93</i>
<i>Offset rates for the Wellington and Te Waka Faults.....</i>	<i>98</i>
 CHAPTER 6 THE RUAHINE FAULT FROM THE MANAWATU GORGE TO THE KAWEKA FOREST.....	 100
 CHAPTER 7 THE RUAHINE FAULT BETWEEN THE KAWEKA FOREST AND THE NAPIER-TAUPO HIGHWAY.....	 108
<i>Trenching on Davis Farm.....</i>	<i>108</i>
<i>Summary of recent offset features and offset rates for the Ruahine Fault.....</i>	<i>122</i>

CHAPTER 8 SUMMARY OF PALEOSEISMIC DATA FOUND IN EXCAVATED TRENCHES AND ALONG FAULT TRACES.....	124
<i>Common Structural features indicative of faulting events and sedimentation rates seen in the excavated trenches.....</i>	<i>124</i>
<i>Fault scarp morphology.....</i>	<i>127</i>
CHAPTER 9 PALEOSEISMIC HAZARDS FOR THE WELLINGTON AND RUAHINE FAULTS.....	131
<i>Fault structure, segmentation and surface rupture.....</i>	<i>131</i>
<i>Earthquake magnitude and intensity models.....</i>	<i>137</i>
<i>Summary of timing and earthquake events for the Wellington and Ruahine Faults.....</i>	<i>140</i>
<i>Ground shaking and landslides.....</i>	<i>142</i>
CHAPTER 10 DISCUSSIONS AND CONCLUSIONS.....	147
<i>Subduction zone tectonics and predictions for future earthquake events.....</i>	<i>147</i>
<i>Horizontal offset rates and the history of strike-slip faulting for the Wellington and Ruahine faults.....</i>	<i>153</i>
<i>Summary of paleoseismic activity for the Wellington and Ruahine Faults.....</i>	<i>155</i>
<i>Future work.....</i>	<i>156</i>
 Appendix 1, Seddigraph and XRD analysis of Tertiary Mudstone, Unctuous Clay and Unknown Shelf Material.....	 160
Appendix 2, Tephra Descriptions and ages.....	162
Appendix 3, Descriptions and ages of Ohakean, Ratan and Porewan River Terraces.....	164
Appendix 4, Modified Mercalli Scale and associated hazards.....	166
Appendix 5, Summary of Radiocarbon and AMS dates.....	168
References.....	169

LIST OF FIGURES :VOLUME 1

	<i>page no</i>
FIGURE 1 Field Area Locality.....	8
FIGURE 2 The Ohara Depression.....	14
FIGURE 3 Locality Map from NZMS SHEET 24.....	21
FIGURE 4 Wellington Fault and Trench location on Inglis Farm.....	23
FIGURE 5 Inglis 3 trench.....	26
FIGURE 6 Inglis 4 trench.....	28
FIGURE 7 Duplex models.....	30
FIGURE 8 Sequence of events Inglis 3 trench.....	32
FIGURE 9 Sequence of events Inglis 4 trench.....	36
FIGURE 10 Surface faulting events, Inglis Farm.....	38
FIGURE 11 Displacements, Inglis Farm.....	39
FIGURE 12 Offset Streams, Beagley Farm.....	42
FIGURE 13 Beagley Farm trench.....	43
FIGURE 14 Locality Map NZMS T23.....	46
FIGURE 14A Paper Road site.....	47
FIGURE 15 Trotter 1 trench.....	52
FIGURE 16 Trotter 2 trench, north wall.....	53
FIGURE 17 Trotter 2 trench, south wall.....	54
FIGURE 18 Duplex at Fairbrother Road.....	60
FIGURE 19 Duplex, sequence of events.....	61
FIGURE 20 Kashmir to Alder roads NZMS U22.....	66
FIGURE 21 Southern Ohara Depression NZMS U22.....	69
FIGURE 22 Northern Ohara Depression NZMS U21.....	70
FIGURE 23 McCool 1 trench north wall.....	73
FIGURE 24 McCool 1 trench south wall.....	74
FIGURE 25 McCool 3 trench north wall.....	77
FIGURE 26 The Wellington and Ruahine Faults, NZMS U21.....	84
FIGURE 27 Offset Ohakean terraces, north bank Ngaruroro River.....	85
FIGURE 28 Wellington and Te Waka Splinter Faults.....	86
FIGURE 29 Syme trench Hawkstone Station.....	89
FIGURE 30 Wedd trench, Te Waka Splinter Fault.....	96
FIGURE 31 Ruahine Fault NZMS U22.....	102
FIGURE 31a Ruahine Fault NZMS U20.....	105
FIGURE 32 Ruahine Fault NZMS U20+V20.....	110
FIGURE 33 Ruahine Fault NZMS V20.....	111
FIGURE 34 Davis 1 trench north wall.....	114
FIGURE 35 Davis 1 trench south wall.....	115
FIGURE 36 Davis 2 trench north wall.....	116
FIGURE 37 Davis 2 trench south wall.....	117
FIGURE 38 Fault Scarp Morphology.....	128
FIGURE 39 Cartoon of eastward uplift.....	151

LIST OF TABLES VOLUME 1

Wellington Fault

page

Table 1, Summary of paleoseismic events.....	63
Table 2, Vertical offset rates; Manawatu Gorge to Kumeti Road.....	63
Table 3, Horizontal offset rates, Manawatu Gorge to Kumeti Road.....	64

Ruahine fault

Table 4, Faulting events for Davis 1 and 2 trenches.....	123
Table 5, Summary of paleoseismic events for the Kahuki-Dannevirke segment of the Wellington Fault.....	141
Table 6, Summary of events for the Ohara Depression of the Wellington Fault..	141
Table 7, Summary of events for the Tutaekuri to Napier-Taupo Highway segment of the Wellington Fault.....	141
Table 8, Summary of events for the Tutaekuri-Napier-Taupo Highway segment of the Ruahine Fault.....	142
Table 9, Cities and Towns in close proximity to the Wellington and Ruahine Faults.....	143
Table 10, Summary of timing for eastward uplift.....	152
Table 11, Horizontal and vertical offset, Wellington Fault.....	154
Table 12, Horizontal and vertical offset, Ruahine Fault.....	154
Table 13, Paleoseismic activity, Wellington Fault.....	156
Table 14, Paleoseismic activity, Ruahine Fault.....	156

VOLUME 2, LIST OF PLATES

<i>Plate No</i>	<i>Page No</i>
1, The Wellington and Ruahine Faults south of the Manawatu Gorge.....	1
2, Engineering structures in the Manawatu Gorge.....	2
3, Steeply dipping Nukumaruan Limestone.....	2
4, Aerial photograph of the Manawatu Gorge and Limestone.....	3
5, Aerial photograph of the Nukumaruan Limestone Block.....	4
6, Slump feature in limestone.....	5
7, Silty unit underlying the limestone.....	5
8, Limestone/silty unit contact	6
9, Wellington fault duplex at Inglis' Farm.....	7
10, Main fault plane Inglis 3 trench.....	8
11, Horizontal fault Inglis 3 trench.....	9
12, Mini graben northeast trench wall, Inglis 3 trench.....	10
13, Mini graben south trench wall, Inglis 3 trench.....	11
14, Drag structures in unctuous clay unit (Inglis 3 trench).....	12
15, Inglis 4 trench north wall.....	13
16, Inglis 4 southwest trench wall.....	14
17, Inglis 4 horse in south trench wall.....	15
18, Inglis 4 footwall horse.....	16
19, Wellington Fault at Beagley Road.....	17
20, Fault scarp at Beagley Road.....	18
21, Beagley trench.....	18
22, Offset streams at Beagley Road (aerial view).....	19
23, Paper Road, Wellington Fault.....	20
24, Offset stream at Coppermine Road.....	21
25, Fault scarp at Trotter 2.....	21
26, Duplex at Fairbrother Road.....	22
27, Trotter 1 trench.....	23
28, Offset stream (Trotter Farm).....	23
29, Trotter 2 trench south wall.....	24
30, Trotter 2 trench north wall.....	24
30a, Offset ridges just north of Apiti Saddle.....	25
31, Wellington Fault, offset spurs at Moorcock Stream.....	26
32, Wellington Fault scarp at Gull Road.....	27
33, Pipe repairs at Gull Road (evidence of fault creep ?).....	27
34, McCool 1 trench north wall.....	28
35, McCool 1 trench south wall.....	28
36, Wellington Fault scarp at Big Hill.....	29
37, McCool 3 trench site.....	29
38, Offset overflow streams McCool Farm.....	30

39, McCool 3 trench, north wall.....	31
40, Wellington Fault scarps, south bank Ngaruroro River.....	32
41, Offset Ohakean Terraces north bank Ngaruroro River.....	33
42, Fault scarps crossing Ohakean terraces.....	33
43, Wellington Fault crossing Hawkstone Station.....	34
44, Wellington Fault, eastern edge Maniaroa Range.....	34
45, Syme trench Hawkstone Station.....	35
46, Wellington Fault, Potter Road.....	36
47, Wellington Fault north of the Napier-Taupo Highway.....	36
48, Wellington and Te Waka Splinter Faults south of Puketitiri Road.....	37
49, Te Waka Splinter Fault.....	38
50, Small scarps, Te Waka Splinter Fault.....	38
51, Wedd trench, Te Waka Splinter Fault.....	39
52, U-shaped valley, Te Waka Splinter Fault.....	40
53, Te Waka and Titiokura Limestone.....	40
54, Offset Te Waka Limestone.....	41
55, Te Waka Splinter Fault, termination splays.....	42
56, Ruahine Fault between North Block and Glenlynn Roads.....	43
57, Ruahine Fault north of Whittle Road.....	44
58, Davis 1 trench, Ruahine Fault.....	45
59, Davis 1 trench, Ruahine Fault.....	46
60, Ruahine Fault south of Whittle Road.....	47
61, Davis 2 trench, Ruahine Fault.....	48
62, Ruahine Fault, Kaweka Range.....	49
63, Ruahine Fault? Hot Springs Road.....	50
63, Ruahine Fault, south of the Mohaka-Ripia junction.....	51
64, Nukumaruan Limestone, Napier-Taupo Highway.....	52

MAP POCKET CONTENTS : VOLUME 2

WELLINGTON FAULT TRENCHES

INGLIS 3 TRENCH, SCALE 1:20, *South wall*

INGLIS 4 TRENCH, SCALE 1:20, *North wall*

BEAGLEY ROAD TRENCH, SCALE 1:20, *West wall*

TROTTER 1 TRENCH, SCALE 1:20, *North, south and east walls plus
correlated sequence of events for Trotter 1 and 2 trenches*

TROTTER 2 TRENCH, SCALE 1:20, *North, south, east and west walls*

MC COOL 1 TRENCH, SCALE 1:20, *North and south walls*

MC COOL 2 TRENCH, SCALE 1:40, *East Wall*

MC COOL 3 TRENCH, SCALE 1:20, *North, east and south walls*

SYME TRENCH, SCALE 1:20, *North wall*

TE WAKA SPLINTER FAULT TRENCH

WEDD TRENCH, SCALE 1:20, *South wall*

RUAHINE FAULT TRENCHES

DAVIS 1 TRENCH, SCALE 1:20, *North wall*

DAVIS 2 TRENCH, SCALE 1:20, *North and south walls*

CHAPTER 1

INTRODUCTION

New Zealand's active geological landscape is governed by its position astride a plate boundary where the Pacific plate is being obliquely subducted under the North Island (Australian plate). The surface boundary contact between the two plates lies off the east coast of the North Island along the Hikurangi Trough (Figure 1a). Movement between the two plates is manifest in the North Island by both volcanic activity and frequent earthquakes. The magnitude of relative plate convergence varies from 41 mm/yr (at Cook Strait) to 44mm/yr in central Hawkes Bay and 47mm/yr north of East Cape. Based on the new global modelling system NUVEL-1 (DeMets et al. 1990). This convergent vector has been resolved into 25km/my of dextral strike-slip parallel to the Hikurangi margin and 35km/my of convergence perpendicular to the plate margin (Cashman et al. 1992).

The east coast of the North Island forms the emergent part of the plate boundary deformation zone on the Australian Plate (Lamb and Vella, 1987). This emergent zone of deformation is referred to as the Axial Tectonic Belt (Walcott 1978b) which consists of two main structural domains. The eastern domain is a contractional fold and fault zone defined by the east coast ranges (Lamb and Vella 1987) and referred to as the East Coast Deformed Belt (Van der Lingen and Pettinga 1980). The western domain, adjacent to and including the axial ranges, consists of a shear zone of dextral strike-slip faults with early Quaternary uplift to the west. This domain is referred to as the North Island Dextral Fault Belt (Beanland 1995) and is considered to be a continuation of the dextral South Island Alpine Fault Zone (Walcott 1978a). Studies of Cretaceous-Cainozoic stratigraphy suggest that the North Island Dextral Fault Belt has been active from mid-Tertiary times when the current plate boundary began to evolve (Cole and Lewis 1981, Ballance et al., 1982, Cutten 1994). Deformation rates in both these domains and their accompanying earthquake hazards are approximately ten times higher than areas outside the North Island Dextral Fault Belt (Berryman and Beanland 1988). The eastern domain and the North Island Dextral Fault Belt lie within the area designated by Ballance

(1975) as the Hawkes Bay Microplate which is bounded to the east by the subduction zone and the west by the westernmost faults of the North Island Shear Belt.

The plate boundary zone through New Zealand is marked by a broad band of shallow seismicity. This activity occurs at depths of between 20 and 40km and has been interpreted to mark the boundary with uppermost layer of the subducting Pacific plate (Arabasz and Lowry 1980). These shallow earthquakes however, lack a clear association with major late Quaternary surface fault traces in the western zone of the North Island Dextral Fault Belt. This is of significance when compared to seismic studies of other similar fault zones overseas especially those in California, which have demonstrated that small to moderate size events concentrate only on a fault zone when the fault is creeping. Creep is considered to be a factor which inhibits the generation of large earthquakes (Wallace 1970). So far strain measurements from the Te Marua strainmeter near Wellington have only recorded 3.2 ± 0.2 ppm/yr of displacement. This very small displacement rate remains three orders of magnitude lower than the rates referred to as fault creep (Darby 1993).

The main subject of this thesis is the study of two of the most prominent and important faults in the western domain of the Axial Tectonic Belt (Sporli 1988). These are the Wellington and Ruahine Faults. The Wellington Fault trace has been mapped from Cook Strait in the south to Whakatane in the Bay of Plenty (figure 1b). Just south of the Manawatu Gorge the fault bifurcates, the major westward splinter being named the Ruahine Fault. The Ruahine Fault continues north where it ends at the edge of the Whakatane Graben. Both of these faults have been mapped in the study area as having active late Quaternary traces (Officers of the Geological Survey 1979). Historical earthquakes in the vicinity of the Ruahine and Wellington Faults of magnitude ≥ 6 in 1940, 1951 and 1963 are considered to be the result of an extensional phase in the overlying Hawkes Bay Microplate following the Hawkes Bay (1931) and Wairoa (1932) earthquakes (Walcott 1978a). Between 1964 and 1987, earthquake studies suggest a change from extensional, to a compressional phase of activity where the faults are now locked and the region is deforming as a whole (Walcott 1978a and Reyners 1989). It is worthy of note that there have been no reported surface ruptures on either the Wellington or Ruahine Faults in the last 150 years since European settlement.

OUTLINE OF STUDY

The area studied in this thesis is limited to the Wellington and Ruahine Fault traces from the Manawatu Gorge in the south to the Napier-Taupo Highway just north of Puketitiri (figure 1b). This covers a significant length of faulting (145km) which lies within 10 to 40km of three major North Island cities, Palmerston North, Napier and Hastings.

This study aims to produce a detailed record of late Quaternary earthquake events, their magnitudes and their frequencies through dating of displaced surfaces and deposits where appropriate along the Wellington and Ruahine Faults. Identification of these paleoseismic events were used to predict the magnitude, rupture length and timing of future earthquake hazards for the Wellington and Ruahine Faults.

To achieve these objectives the following methods were employed:

- Analysis of sedimentary records revealed within deposits exposed in trenches excavated across recent fault traces. Deposits within these excavations consist mainly of freshly eroded materials from newly exposed adjacent fault scarps which were rapidly deposited into adjoining fault traces during or immediately after rupture events. The deposits recorded within excavated trenches provide an estimate of displacement and timing of individual surface-faulting events which then relate to late Quaternary offset rates determined from adjacent dated gravel terraces offset by the fault. From these offsets estimates of individual earthquake events can be determined.
- A general reconnaissance of the regional geology and fault trace structure was used to delineate the length, throw and type of possible segment rupture boundaries.
- A study of fault scarps with known dates was compared with undated scarp morphology and overseas studies to give ages for untrenched areas of the faults

Maps of both faults containing new unpublished information and their neotectonic geological environs are provided together with large scale cross-sections of all trenches excavated.

PREVIOUS REGIONAL WORK ON THE WELLINGTON FAULT SYSTEM

Since the Wellington Fault represents a significant seismic hazard to the greater Wellington region, there have been intensive studies along the fault trace between Cook Strait and the Hutt Valley. The Wellington Fault was first mapped by McKay in 1892 who suggested that the fault belonged to a system of faults linking both North and South Islands. Other authors including Bell (1908), Cotton (1912, 1950), Adkin (1949, 1954), and Hall (1946) realised the recent origin of the fault scarp trace. Wellman (1953) and Stevens (1956, 1957) first described movement on the fault as being dextral strike-slip. Then in 1957, Lensen described the fault and associated structures in detail from Cook Strait to the Manawatu Gorge.

Due to the large number of earthquakes experienced in Wellington between 1840 and 1968 (20 of magnitudes 5-7) the DSIR published an earthquake microzoning study in 1974 to predict future earthquake damage. In 1981 the New Zealand Geological Survey produced a late Quaternary tectonic map of the Wellington region. Other detailed studies include marine studies in Evans Bay (Wellington Harbour) where deformation of late Holocene sediments were interpreted as compaction and slumping due to earthquake shaking (Lewis and Mildenhall 1985). Further research in Wellington Harbour (Lewis 1989) showed that the fault behaviour pattern was not simple and that changes in throw and trend occur. For example the recent trace in the harbour is upthrown to the south-east whereas long-term movement has been to the north-west. More recent research by Berryman (1990) and Van Dissen et al. (1992) suggests the Wellington-Hutt Valley segment of the Wellington Fault ruptures as a single fault segment and that the last rupture occurred between 340-490 years ago. The next oldest rupture occurred between 710-870 years ago, giving a horizontal slip rate of 6-7.6mm/yr. Work on displaced Holocene beach ridges agrees with this amount of horizontal movement (Stirling 1992).

Detailed research farther north of the Wellington-Hutt Valley segment has been less intensive. The Wellington and Ruahine Fault traces were originally mapped by Lillie (1953) and Kingma (1962). Between Wellington and the Manawatu Gorge information of recent displacements on the Wellington Fault were provided by Lensen (1958). In more recent

times three trenches have been excavated across the Wellington Fault adjacent to the study area near Pahiatua. Exposed within these trenches were deposits that represented earthquake events with radiocarbon ages of c. 300, 1000 and 3800 years B.P. (Beanland and Berryman 1990).

PREVIOUS RESEARCH WITHIN THE STUDY AREA

The Wellington and Ruahine Faults were first mapped in detail by Marden (1984), who documented a maximum horizontal offset of 150m on a Porewan terrace cut by the Wellington Fault. Marden concluded that the latest phase of vertical fault movement is up to the east of the Wellington Fault trace although there are exceptions. In the south of the study area at Ballantrae, Marden and Neall (1990) established a maximum westward vertical uplift rate for the Wellington Fault of 1.23mm/yr from offset Ohakean river terraces. A reconstruction of late Quaternary erosional events for the West Tamaki catchment that lies along the fault was not directly correlated with paleoseismic events (Hubbard and Neall 1980).

To the north the area between the Upper Pohangina catchment and Kashmir Road has not been studied in any detail. The basement geology of the Kashmir Road area was mapped by Sporli and Bell (1976) but no detailed work on the active faults was published.

Farther north Erdman and Kelsey (1992) mapped the Wellington and Ruahine Faults in the Wakarara Range and the Ohara Depression. A seismic hazard analysis of the Wellington Fault in this area gave a return period for magnitude 7 earthquakes of 1000 years (Raub 1985, Raub et al. 1987). Wood fragments from an offset deposit located in the Wakarara area indicate that a surface rupture has occurred since 1165 yrs B.P. giving horizontal offset rates of 3mm/yr for the last 30,000 years. The Ruahine Fault was not included in their study.

From the Ohara Depression through the Puketitiri area to the Napier-Taupo Highway, only one reconnaissance study has been conducted. This was part of a seismotectonic hazard evaluation for a proposed Mohaka power development which suggested a tentative average horizontal slip rate of 1 to 2mm/yr for the Ruahine Fault (Beanland and Berryman 1987).

METHODS OF DATA COLLECTION AND ANALYSIS

Field Studies

Due to the size of the field area, approximately 145km in length with a combined fault trace length of some 315km and the nature of the terrain within the Ruahine Range only the more accessible areas of fault trace were studied in detail.

Active faulting visible on aerial photographs of the study area has been interpreted and used to search for suitable excavation sites. These sites were then selected after field examinations of the area. The main criteria for the location of the trench sites were as follows;

- (1) Sites were chosen in areas where scarps from faulting activity appeared to be of recent origin.
- (2) The best sites were located in accumulating environments where colluvium would fall from scarps during faulting events and become entrapped. The environments were usually wet where wood and peat were preserved between the layers of colluvium and could then be radiocarbon dated.
- (3) The most suitable sites were also located in close proximity to what were judged to be Holocene offsets so that vertical and horizontal faulting rates could be measured.

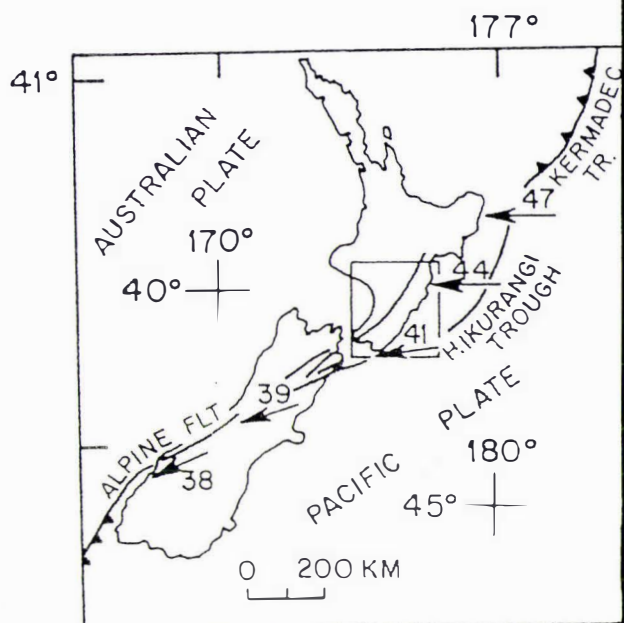
Excavations were made across both Wellington and Ruahine main fault traces over a broad spectrum of environments and localities. A splinter fault trace and abandoned river channels adjacent to the Wellington Fault were also trenched. Information obtained from these different environments allows for cross-referencing of faulting activity. It is usual to view geological cross-sections looking northward. This convention has not always been followed here because the light on the southern walls was often better and showed the more subtle features to advantage. Such cross-sections of excavated trench sites are clearly labelled in the text and named after the farm owner or manager. Data from these excavations has provided the first detailed information on Quaternary faulting events along these sections of the faults. The techniques used in resolving paleoseismic events are based on the application of classical stratigraphic cross-cutting relationships and superposition of materials deposited in a fault trench immediately after a surface rupture from an adjacent fault scarp. These

events were then dated, wherever datable material was available, using either tephrochronology or radiocarbon dating techniques. All radiocarbon dates given in this thesis are presented using the old half life in yrs B P. Fault trace segments have been mapped and both vertical and horizontal offsets have been determined where possible. This information has been used to make predictions on expected future faulting activity. This includes possible fault magnitudes, offsets and their associated hazards. All strike directions in this thesis relate to grid north.

FAULT NOMENCLATURE

In 1912a Cotton identified the west shore of Wellington Harbour as a fault scarp of recent origin. In a later paper (1912b) he named it the Wellington Fault. This nomenclature was extended farther north by Wellman (1948) who saw the fault as being a continuous trace from Wellington to the Manawatu River. Many localised studies subsequently have resulted in various segments of the fault being given the name of the area in which it occurs. North of the Manawatu Gorge it is sometimes referred to as the Mohaka Fault (Kingma 1962) or the Mohaka-Wellington Fault (Grapes et al., 1984 and Raub, 1985). However Marden (1984) preferred to refer to the segment adjacent to the southern Ruahine Range as the Wellington Fault for two reasons. Firstly, the fault had a continuous trace from Wellington to Lake Waikaremoana (Lensen, 1957) and secondly because the trace has a regional tectonic significance. In this thesis the name Wellington Fault has been retained in preference to Mohaka Fault for the same reasons. Localised splinters of the Wellington Fault are named as they were first mapped. New trace splinters have been assigned names derived from local areas. Both the Wellington Fault and the Ruahine Fault plus all splinter faults are here referred to conjointly as the Wellington Fault Zone.

Figure 1a



60km

Figure 1b



**Figure 1a, Map of New Zealand showing the Australian - Pacific Plate boundary. The arrows represent motion of the a Pacific Plate relative to the Australian Plate. the rates of motion are from DeMets et al. (1990).
Figure 1b, This map shows the study area locality (enclosed Box) the Axial Ranges (coloured grey) and the Wellington and Ruahine Faults (heavy lines) with arrows for indicators of horizontal movement.**

CHAPTER 2

REGIONAL GEOLOGY

This chapter presents a literature review and general outline of the studied field area from the Manawatu Gorge to the Napier-Taupo Highway. It discusses the relationship between the Wellington and Ruahine Faults and the effects these faults have on the regional geology and geomorphology. The field area has been divided into four main areas which have similar structural geology and faulting characteristics.

MANAWATU GORGE TO OHARA DEPRESSION

The southern boundary of the study area begins at the northeastern end of the Manawatu Gorge. Here there is a pronounced structural sag in the axial mountain ranges of the North Island, geographically separating the Tararua Range to the south and Ruahine Range to the north (Lillie, 1953). In this area the Wellington and Ruahine Faults are only 1km apart, having bifurcated some 5km to the south of the Manawatu Gorge (Plate 1). The Wellington and Ruahine Faults with their different deformational styles (upthrow on the Wellington Fault is mainly toward the southeast and the Ruahine Fault up to northwest) and different levels of faulting activity, exhibit the same dextral strike-slip behaviour throughout their separate lengths.

Wellington Fault

The Wellington Fault is one of the major active dextral strike-slip faults of the North Island Dextral Fault Belt. Within the field area the trace of this fault shows many signs of late Quaternary faulting throughout most of its length. Near Woodville in the south of the study area the Wellington Fault (Marden 1984) separates marine sediments of the Ruahine Anticline (Lillie, 1953) and younger overlying Ohakean 1 and 2 river terraces to the west (Appendix 3) from Holocene and Ohakean 3 terraces, to the east (Marden and Neall, 1990). Farther north the Wellington Fault is bounded to the

west by the Ruahine Range which is an upthrown block of Torlesse greywacke tilted to the northwest (Kamp 1988). In this area the Range rises to a height of 920m where its crest is jagged and uneven. The incline of the eastern range slopes are often up to 30° and over, being incised by steep valleys filled with eroding greywacke rubble which during flood events is transported to the farmland below (Marden 1984).

East of the Wellington Fault is the downthrown Dannevirke Basin which is about 80km long and between 19 and 24km wide. Within it are greywacke conglomerates which are considered to be early alluvial fan deposits from an uplifting Ruahine Range (Lillie, 1953, Beu et al., 1981 and Krieger, 1992). As the oldest conglomerates are around 1ma in age, the Range is inferred to have been uplifted rapidly since then (Beu et al., 1981). This period of rapid westward uplift and tilt of this portion of the Range would have been largely controlled by the Wellington Fault. Within the Dannevirke Basin Castlecliffian deposits of the Mangatarata Formation have been folded and at the northern end of the basin thrust faulted. These thrust faults and folds, lie parallel to the Wellington Fault and were considered by Lillie (1953) to have formed in response to uplift of the Ruahine Range during Castlecliffian times. However this overall Quaternary deformation style appears to have changed in the Holocene and recent movement on the fault appears to have become dextral strike-slip with an oblique (vertical) component. Late Quaternary uplift rates at Ballantrae are in the region of 0.76 to 1.23mm/yr with uplift being to the west (Marden and Neall 1990).

The major deformation visible along the present fault trace is associated with late Quaternary-Holocene strike-slip faulting and predominantly eastward uplift. Locally, early Quaternary marine sediments dip inward towards the fault (at Beagley Road, Figure 3) while the dips of the latest Ohakean terraces adjacent to the fault appear to be unchanged since their formation. These terraces dip eastward between 3° and 6° however vertical and horizontal offsets are common (Marden 1984). Larger deformational features seen along the Wellington Fault trace between the Manawatu Gorge and Kumeti Road include two strike-slip duplexes. The larger of these duplexes is no more than 2km in length (see chapter 3). Duplexes are complex zones of deformation which often, but not necessarily, form at compressional or extensional fault bends and are zones of high fracture

density with smaller en-echelon faults defining the duplex structure. The area around the duplex appears to be unstrained and the volume balance is maintained by localised uplift or subsidence within the duplex itself. However some vertical accommodation takes place by uplift around a contractional duplex or subsidence around an extensional duplex (Woodcock and Fischer 1986). These two duplexes are found on Inglis' Farm at the end of Foleys Road and between Loveday and Fairbrother Roads (Figures 14 and 18, Plate 26).

Other deformational features close to the Wellington Fault trace are three parallel splay or splinter faults mapped by Marden (1984). These are found between Oxford and Coppermine Roads and due to their proximity to the Wellington Fault are likely to be part of the fault system. However there is no surface expression where they join the main fault plane (Marden 1984). Very little deformation was visible between these splay faults and the main fault plane but this may have been due to the lack of geomorphic expression.

The third kind of deformation is confined to the fault trace itself in the form of tectonic and geomorphic landforms. The tectonic landforms are sagponds, upthrown or downdropped scarps (Plate 25) and breaks in slopes seen on steep hillsides. Geomorphic landforms are offset streams (Plate 24), springs, ridges (Plate 23) and river terraces. Offsets of older Holocene streams and terraces are in the order of 90 to 150m (Marden, 1984). Other landforms indirectly related to tectonic deformation are landslides, rock and earth slumps and debris flows.

From Kumeti Road northward the fault traverses through Torlesse greywacke of the Ruahine Range. It is interesting to note that the frontal range crest still retains its original peneplain surface north of Kumeti Road. While the frontal range spine controlled by the Wellington Fault south of Kumeti Road is very irregular. Parallel to Cattle Creek are truncated spurs which have been offset dextrally up to 100m. Aerial photographs show the fault trace crossing what appears to be an extensive slump feature diverting the upper reaches of the Makaretu River eastward, indicating movement since the slumping occurred. It is possible that the above offsets are the same age as those seen south of Kumeti Road in younger Tertiary and Quaternary sediments. At Moorcock Stream the fault scarp along the

west bank has a fresh trace with 100m offsets recorded in dextrally displaced spurs (Plate 31). Here a number of folding episodes recorded are within the Torlesse basement rocks but these are highly ductile features which could only have formed early in the rocks history. Quaternary faulting deformation (from outcrops near to the fault) is brittle and the greywacke highly fractured (see chapter 4). It is thought (Sporli and Bell 1976) that the main faults in this area have been persistent since late Mesozoic times and that Torlesse rocks have changed their mechanical response to faulting from ductile to brittle as they were uplifted.

Ruahine Fault

The Ruahine Fault is a major splinter of the Wellington Fault, that diverges from it 5km south of the Manawatu Gorge (Figure 3 Plate 1). In contrast to the Wellington Fault, the Ruahine Fault seems to have been less active between the Manawatu Gorge and Ohara Depression during Holocene time. In the south the fault scarp is the contact fault between upthrown Torlesse basement to the northwest and downthrown (southeast) Tertiary sediments (Marden 1984) and therefore must have been active during the Tertiary period. Seismic cross-sections of the Range by the Superior Oil Company (1943) and a similar cross-section in Melhuish (1990) do not show the Ruahine Fault profile. It is possible that this is largely due to the inaccessibility of the area through which it passes. However for most of the fault length only multiple crush zones (sometimes tens of metres wide) show the locality of the fault (Marden 1984). There are a few offset streams and some minor influence on drainage patterns but little else. Marden (1984) reports that there are only two sharply defined fault scarps of 50 and 75m lengths where a walking track crosses the main range east of Maharahara Trig. The height of these scarps is between 6 and 8m with uplift being to the northwest. The scarps are the only evidence of probable Holocene faulting through the length of the area mapped by Marden. Northwest of Takapari peak the Pohangina River flows parallel to and within the fault trace. Here aerial photos show no signs of recent faulting activity. Fault scarps appear rounded and heavily eroded. Between the Pohangina Saddle and the Tukituki River the fault was mapped by Sporli and Bell (1976) but they reported no signs of recent faulting activity. North of the Tukituki River the fault trace was not found on aerial photographs.

It is possible that this may be due to the rejuvenating steep landscape rather than a lack of faulting activity.

OHARA DEPRESSION

In this area both faults display evidence of having been active during the Holocene (Plates 36 and 37). The Ohara Depression (Figure 2) consists of two basement blocks, one having subsided between the Wellington and Ruahine Faults and now covered with Tertiary and Quaternary sediments. The other is the Big Hill block located in the northern end of the depression. The overlying Tertiary sediments are folded close to the major faults (Erdman and Kelsey 1992) but elsewhere maintain their gentle, regional southeasterly dip (Figure 2). In this area the behaviour and deformational style of both faults are seen to be similar with the most recent uplift being toward the east. Due to the compressional nature of this area both faults have compressional left steps (Figures 2 and 21) and parallel or semi-parallel folds in Tertiary sediments close to the fault trace strikes. Structural development and conglomerate units within late Tertiary and early Quaternary rocks show that the Wellington and Ruahine Faults have been active from Tertiary times to the present within the Ohara Depression (Erdman and Kelsey 1992).

Wellington Fault

From the top of Alder Road (Figure 20) where the fault enters the Ohara Depression and northward, the trace is straight and clear with steep scarps uplifted to the east and spurs offset between 60 to 100m. There is a prominent compressional left step of 500m (Figure 21) in the fault trace at Wakarara together with a 4km offset in the basement Torlesse greywacke mapped by Raub (1985). Between the limbs of this sidestep is a compressional zone containing one small anticlinal and two synclinal folds (Raub 1985). The vergence of these folds is consistent with the dextral of movement on the fault. River terraces in the Wakarara area indicate that upthrow on the Wellington Fault has reversed during the late Quaternary. Along the Mangataura Stream, Porewan (Appendix 3) river terraces with estimated ages of c. 60,000 to 80,000 years are upthrown to the northwest

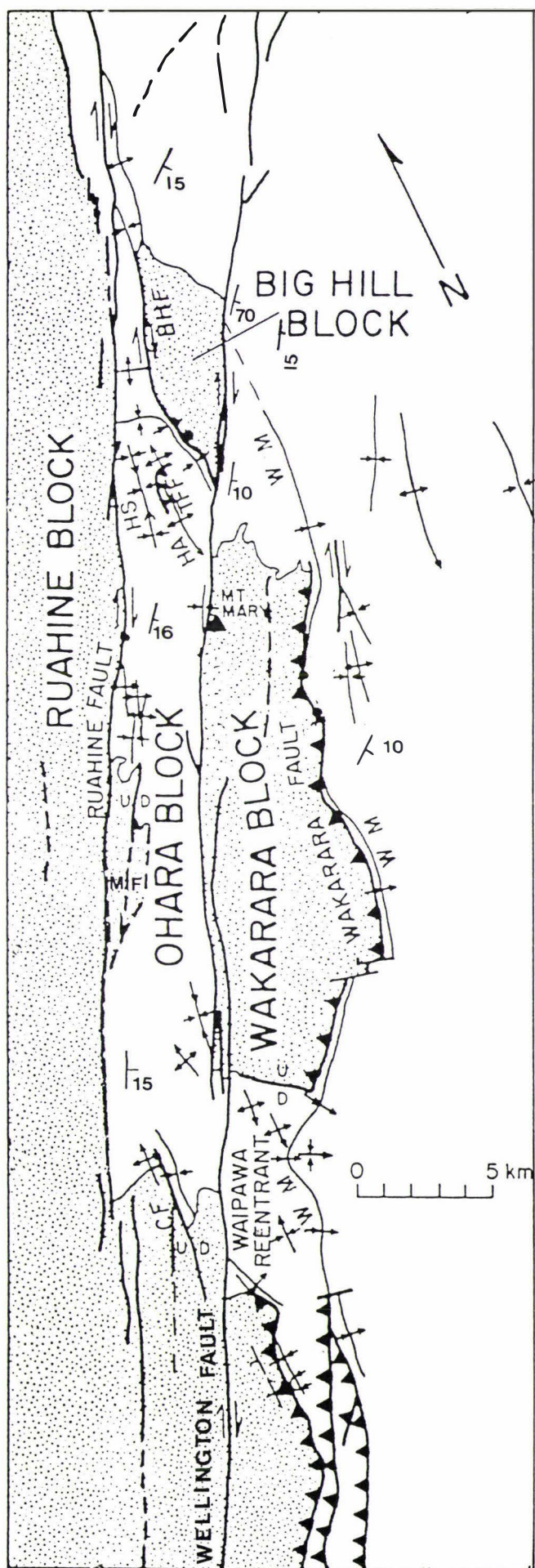


Figure 2. The Ohara Depression showing uplifted and down-thrown faulted blocks, after Erdman and Kelsey (1992). Stippled pattern is Torlesse greywacke, W M is the Wakarara Monocline, BHF is the Big Hill Fault, MF is the Matapuna Fault, TFF is the Thorn Flat Fault, CF is Cullens Fault and HA, HS is the Herricks monocline and syncline. The white areas are Tertiary strata with regional dips that are not greatly changed by block uplift and downthrow.

whereas younger Ohakean terraces of c. 11,000 years are upthrown to the southeast (Raub, Cutten and Hull 1987). From Wakarara north the trace is straight and forms the western boundary of the Wakarara Range. Farther north on the west flank of Mt Mary is another syncline close to the fault which is probably associated with uplift of the Wakarara basement block to the east. Close to the Ngaruroro River on the east side of the fault plane, the dips of Tertiary sediments steepen from 15° 200m south of the Wellington Fault to 70° , close to the fault. It is possible that the Wakarara Monocline located 1km to the southeast (Erdman and Kelsey, 1991) may merge with the Wellington Fault in this area (Figure 2). A single natural exposure at Smith Stream in the Wakarara area revealed offset units that indicated a surface rupture had occurred since 1165 ± 50 yrs B.P. (Raub et al. 1987).

Ruahine Fault

The Ruahine Fault lies between the younger downthrown late Tertiary sediments to the east and the uplifted Ruahine Range (Torlesse Supergroup greywacke basement) to the west showing that most of the uplift in the past was toward the west. However, the most recent uplift on this fault especially in the northern section of the Depression is toward the east as confirmed by striations on the fault surface in Tarapeke Stream (Erdman and Kelsey 1992). Where the Ruahine Fault enters the Ohara Depression between Cullens Trig and the Airstrip (Figure 21) there is a large 1.5km compressional sidestep in the fault trace. Other deformation along the Ruahine Fault occurs in the Sentry Box area. The Matapuna Fault is a possible splay of the Ruahine Fault whose presence is inferred from a small block of upthrown greywacke basement to the east of the Ruahine Fault (Figure 2). This fault has the same strike as fold axes in the Sentry Box limestone (located to the north) which are likely to have formed as a response to movement on the fault and may be a northern extension of the Matapuna Fault structure. South of Gwavas Forest there are some moderately eroded (older) offset spurs, ridges and streams between North Block Road and Glenlynn Road (Figure 21) with horizontal offsets between 50 to 100m and uplift being predominantly to the west (Plate 56). North of the Forest (Figure 22) uplift is predominantly to the east and the fault trace is fresh with steeper younger scarps $\geq 30^{\circ}$. Farther north on McIndoe Flat

(south bank of the Ngaruroro River) the Ruahine Fault splits into two traces (Figure 26).

NGARURORO RIVER TO TUTAEKURI RIVER

This area is dominated by compression with a north northeast vector (Brown 1980) which translates into thrusting action rather than folding as seen in the Ohara Depression. The Wellington Fault has a single trace and the Ruahine 2 traces. Fault scarps are generally rounded and are sometimes difficult to follow both in the field and on aerial photographs.

Wellington Fault

North of the Ngaruroro River Ohakean-aged terraces are offset by the fault but they are not internally deformed except within the fault trace itself, where there are rent, bridge and sag features (Figure 27, Plate 42). Farther north near the Fort (Figure 26), and to the east of the fault trace, the regional east to southeast dips of the limestone (10° to 20°) remain unchanged by faulting activity. Likewise Te Waka and truncated Whanawhana limestone (Beu 1995) between the Ruahine and Wellington Fault dips at 15° to the southeast. The major deformation seen, is in the difference in the height or horizontal offset of the limestone blocks. Here the Te Waka Limestone is offset dextrally 3km but this may not represent the total offset (Beu 1995). To the north of these limestone blocks (in the Omahaki Road area) the fault traverses softer marine siliclastic rocks of Tertiary age and the fault trace becomes less pronounced. In the upper reaches of Otamauri Stream the fault trace is marked by offset streams, the largest offset being approximately 150m. The trace then crosses Glenora Road at Willowford where only poorly defined offset ridges are preserved. On the Napier-Taihape Road, Mohaka (Ohakean aged?) gravel terraces (Grindly 1960) dip at 3° to the southeast which may have been their original depositional dip. It is possible that these terrace surfaces have been displaced vertically approximately 2 to 3m. Tertiary sediments underlying the gravels close to and east of the fault trace have bedding planes tilted or dragged down westward toward the fault between 3° and 5° . These same bedding planes resume their regional south easterly dips of

10° to 15° some 500m east of the fault plane. Other features seen in this area are widespread slumping and landslides which may be fault related. Off Willowford Road the Wellington Fault trace is barely discernible (see chapter 5). Aerial photographs show that there are multiple slumps and landslides which obscure the fault trace here. On Willowford Station a linear structure crosses the Tutaekuri River to the headscarp of a large landslide some 4km on the north-east side of the river. While this linear feature is not seen to be in direct contact with the Wellington Fault (due to slumping) it may be an extensional (east stepping) splinter fault diverging from the main fault plane.

Ruahine Fault

On the south bank of the Ngaruroro River (McIndoe Flat) the Ruahine Fault is seen to splinter into two traces. The eastern Ruahine trace can be followed north across the west flank of The Lizard (Figure 31a). The western Ruahine trace can be followed north to Omahaki and beyond until it becomes untraceable in the Kaweka Forest Park. In the area around Mt Miroroa the regional faulting pattern is complex. Here cross-cutting relationships between faults becomes ambiguous and relative chronologies difficult to establish (Brown 1980). The Ruahine Fault traces appears to be mainly upthrown to the east, whereas the parallel Kaweka Fault is upthrown to the west. On the northeasterly slopes of Mt Miroroa Torlesse greywacke basement has been thrust over Nukumaruan siltstone. This thrust has developed due to dextral shear from the western splinter of the Ruahine Fault (Brown 1980, Figure 31a). Bedding on The Lizard (eastern splinter of the Ruahine Fault) has been overturned (Beu 1995). It is possible that the Ruahine Fault has a third poorly defined trace which can be followed across the Omahaki Basin to the Miroroa thrust fault (Figure 31a).

TUTAEKURI RIVER TO THE NAPIER-TAUPO HIGHWAY

In this area similar deformation is caused by both the Wellington and Ruahine Faults within Tertiary and Quaternary sediments. The geology is dominated by block faulting so that the major deformation occurs between

blocks rather than within them. The fault traces which serve as boundaries to these blocks are offset both vertically and horizontally. Trenching studies have shown that the Ruahine Fault has been more active in Holocene times than the Wellington Fault (see chapters 5 and 7).

Wellington fault

North of the Tutaekuri River the fault trace becomes much more pronounced as it passes through harder Te Waka limestone. This limestone formation has intraformational and interformational unconformities with large along-strike (100m to over 5km) and across-strike (300m to over 1km) variations in limestone thicknesses. There are also giant tabular cross-beds with sets 10 to 40m thick (Kamp et al., 1988). These features formed in response to the prevailing sedimentary processes at the time of deposition. The differing dips and bed thicknesses make measuring accurate offsets and differentiating between natural and fault deformation difficult and unreliable. At Mangatutu Station the limestone to the east of the fault dips southeast between 6° and 14°; west of the fault there is poor exposure, but one outcrop almost right on top of the fault trace appears horizontal. This change in dip may not necessarily be due to fault activity but may be one of the giant cross beds within the formation. Farther north of Hawkstone Station there are several landslides on the west side of the steeply uplifted Maniaroa Range (Plates 44 and 46). Some of these landslides may have been triggered due to earthquake shaking.

Just north of Puketitiri Road a major splinter of the Wellington Fault, referred to here as the Te Waka Splinter Fault has been mapped (Figure 28). The fault can be traced north to the Te Waka Trig where it displaces Te Waka limestone (Grindly 1960, Plates 49, 52, 45 and 55) both vertically and horizontally. Between the Te Waka Trig and the Napier-Taupo Highway another large block landslide is found (the Te Pohue landslide) which may have moved in response to earthquakes and or movement on the Te Waka Fault (chapter 7).

The most northern deformation seen on this segment of the Wellington Fault is found on the Napier-Taupo Highway where Tertiary sediments dip up to 70° to the east, in a steep road cutting east of the Mohaka River.

West of the river the gentle regional southeasterly dip (10° to 15°) is maintained close to the fault trace.

Ruahine Fault

North of the Kaweka Forest the Ruahine Fault trace becomes a single strand. The fault trace is clear, straight and appears fresh with steep scarps (Plates 57 and 60). Local deformation in this area is recorded by offset streams, spurs, shutter ridges and upthrow to the east. Four kilometres north of Whittle Road (Figures 32 and 33) uplift changes from east to west in a scissor-type geometry (Plate 62). On the Napier-Taupo Highway the Ruahine Fault has offset an isolated Nukumaruan limestone block and a section of Taupo Pumice Alluvium. Bedding within this limestone seems relatively undisturbed by faulting activity (Plate 65). This limestone block is an outlier preserved due to faulting activity and surrounded by Torlesse greywacke outcrops. This implies early Quaternary to Recent throw on the Ruahine Fault but it is not possible to say how much (see Chapter 7). Recent activity on this fault is reported by Beanland and Berryman (1987) who proposed an average Holocene horizontal slip rate of 1 to 2mm per year with an earthquake recurrence interval between 1 and 5000 years.

CHAPTER 3

THE WELLINGTON FAULT BETWEEN THE MANAWATU GORGE AND KUMETI ROAD

The geology alongside the Wellington Fault between the Manawatu Gorge and Kumeti Road consists mainly of Tertiary and early Quaternary (marine) sediments which unconformably overlie basement greywacke. On the downthrown (eastward) side of the fault these sediments are up to 2km thick (Hicks, 1983). In some areas the Tertiary strata are covered by Pleistocene river gravel terraces and Holocene river sediments (Marden, 1984). For the most part the Pleistocene river terraces dip gently eastward away from the fault. However between Saddle and Coppermine Roads Quaternary and Tertiary strata both east and west of the fault dip towards the fault. The eastward dipping Tertiary sediments west of the fault are part of what Lillie (1953) named the Ruahine Anticline. Tertiary sediments immediately east of the fault dip to the west but these beds may have been dragged downward due to faulting deformation.

Northwards from Coppermine Road most strata on the western side of the fault dip towards the fault. Due to a general lack of outcrops it was difficult to determine dip direction of Quaternary strata to the east of the fault in this area. However Marden's (1984) maps show that Quaternary sediments in this area also dip gently to the east, most of these outcrops are now destroyed by farming activity.

The Wellington Fault trace is obscured where it emerges on the north bank of the Manawatu Gorge (Plate 4). The main causes of this are firstly coverage by recent river sediments and secondly eastward block-sliding of a Nukumaruan limestone unit. Part of the fault scarp and its associated springs are offset 200m to the east round the toe of the limestone (Marden, 1984). This offset mapped by Marden (1984) is particularly unusual. Nowhere else in the whole field area (Figure 1) is this behaviour observed. At all other localities the fault trace does not detour round obstacles but traverses uninterrupted through them. It is proposed here, that this limestone block slid 200m east during the last earthquake on the Wellington Fault.

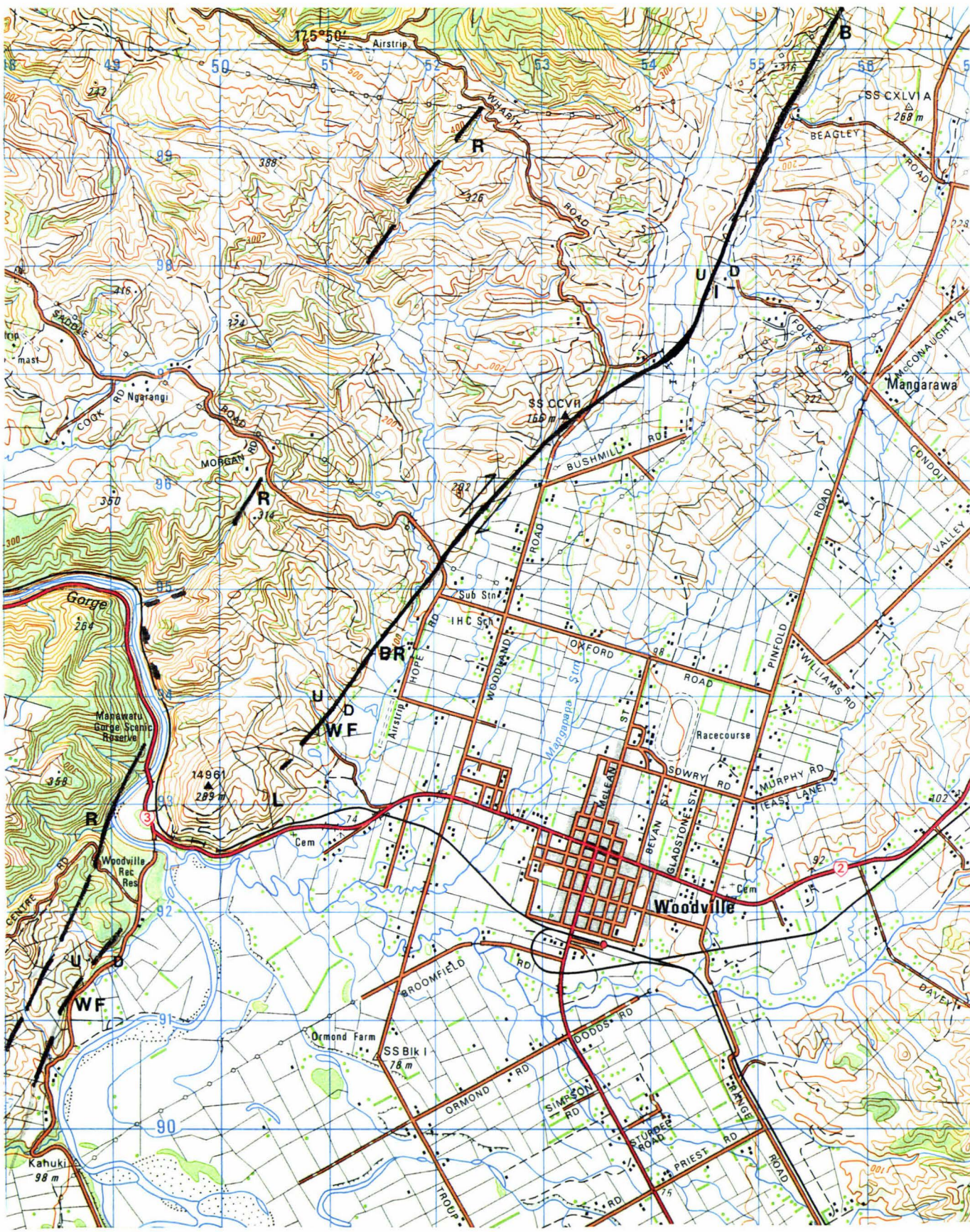


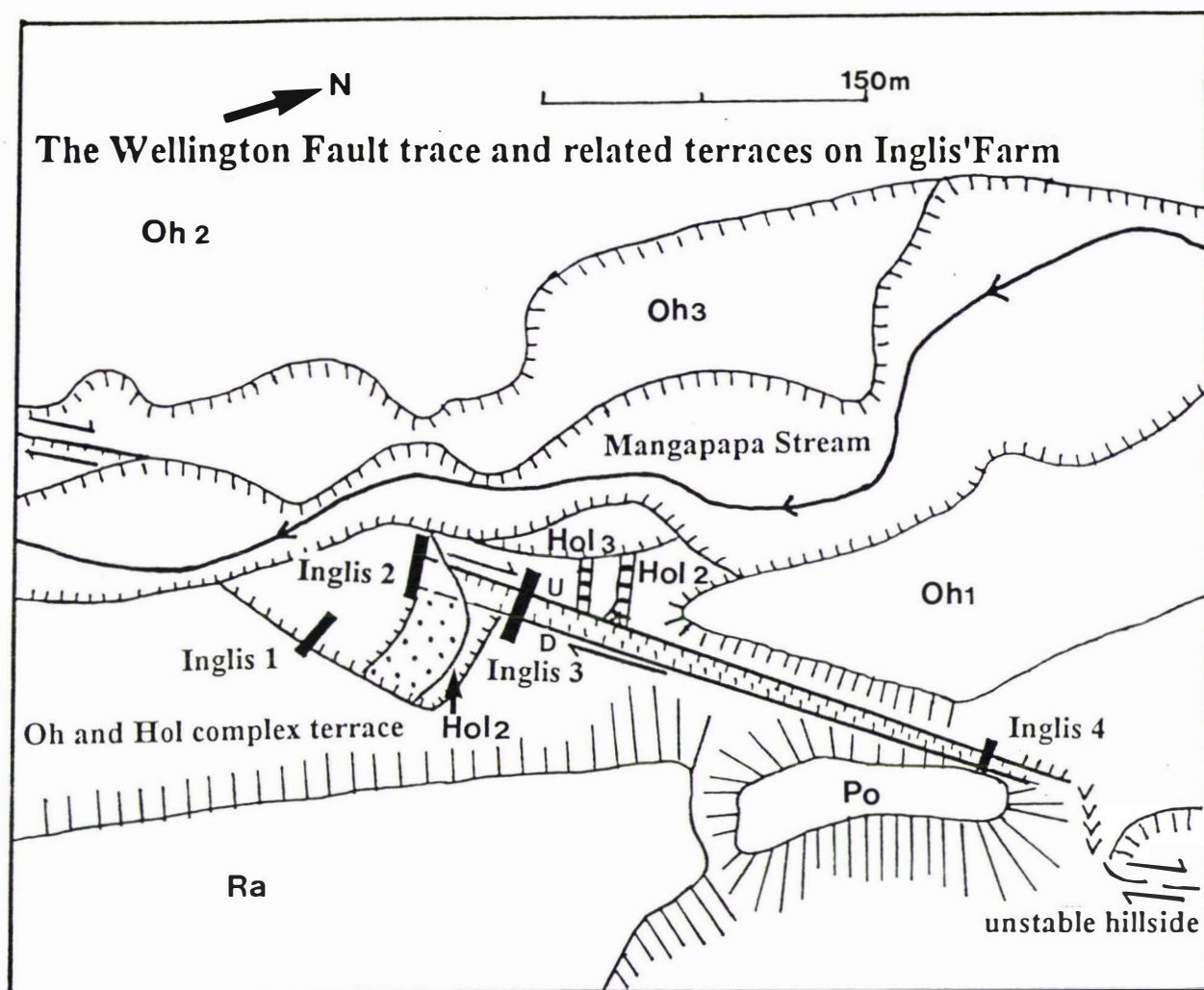
Figure 3. Locality map NZMS Sheet 24 1:50 000 showing the location of the Wellington Fault Trace (WF) and the Ruahine Fault Trace (R) in the Woodville area. L is the Nukumaruan limestone block at the east end of the Manawatu Gorge, BR is the locality of the Ballantrae Research Station and I and B are the localities of Inglis' Farm and Beagley Farm, the arrows are strike slip direction indicators and U and D show the latest vertical movement direction.

There are three lines of evidence for this proposal. Firstly the fault trace cannot be seen traversing the limestone, however there are significant fault scarps (up to 19m toward the west) to the north and south of this unit (Plates 4 and 5). Secondly there are synclinal features which may be of slump origin mapped within the limestone by Marden (1984). A well defined head scarp and some slump structures can be observed on the archival aerial photographs (Plates 4 and 5) and also within a conglomerate unit within the limestone (Plate 6) which has been folded into a weak anticline. Thirdly the eastward-dipping unit underlying the limestone consists of weakly consolidated siltstone containing rounded greywacke pebbles (Plate 7) an excellent medium on which to facilitate sliding. The contact between the limestone and siltstone units is variable, but at its steepest is 43° (Plate 8). The fault trace is found again immediately north and 200m west of the limestone block (Plate 5) and has a single eastward-facing scarp between 10 and 19m high. Holocene uplift has been dominantly to the west and minimum rates of vertical offset are estimated at between 0.76 and 1.23mm/yr (Marden and Neall 1990). The steep (30° to 40°) eastward-facing scarp continues northward until it is covered by Holocene sediments of Mangapapa Stream, 6km north of Woodville (Figure 4).

INGLIS' FARM TRENCHES

On the eastern side of Mangapapa Stream the fault trace divides and is seen as a small graben 28m wide (Figure 4). The fault scarps making up the graben walls are generally between 2 and 6m high, with the free face surfaces having angles of 30° to 40° (Plate 9). The free face is the steep scarp produced by initial faulting activity and is related to the mechanical properties of the faulted material and the fault plane at the surface (Mayer 1984). On the western side of this graben are two abandoned stream channels (Plate 9). In this general locality (T24/545980, Figure 3) four trenches were excavated across or adjoining the fault on Inglis' farm (Figure 4).

The Inglis' property was selected for several reasons. Firstly the locality is in close proximity to Palmerston North and any large magnitude



trench sites  abandoned river channels  poned drainage 
 young Holocene alluvial fan  scarps 

Figure 4. The Wellington Fault trace and related Quaternary gravel terraces on Inglis' Farm after Marden (1984). The Inglis trench sites are numbered as in the text. Oh are Ohakean gravel terraces aged between 10000-25000 yrs B.P. Ra is a Ratan gravel terrace aged between 30000-40000yrs B.P. and Po is thought to be a Porewan gravel terrace aged between 70000-80000 yrs B.P. (based on its stratigraphic locality). Hol are Holocene fluvial terraces less than 10000 yrs B.P.

earthquakes on the Wellington Fault here are likely to have a significant seismic hazard impact on the city. Secondly, the position and ages of Holocene and late Pleistocene river terraces in the area are well known (Marden, 1984). Thirdly because the fault trace and its associated offsets appear fresh it was assumed that faulting activity had occurred within recent times. The trenches were excavated perpendicular to the fault trace. The vertical trench walls were cleaned and marked with a 1m string grid and then logged at a scale of 1:20 (see Vol 2 map pocket).

Inglis 1 and 2 trenches were excavated through the recent sedimentary fan that overlies the southern portion of the faulted graben (Figure 4). No relevant covered stratigraphy or suitable carbonaceous material was obtained from these sites for dating purposes.

INGLIS SITE 3 TRENCH

The Inglis 3 trench (38m long and up to 4m deep) was excavated across the graben, through a ponded drainage site (Plate 9). Between the horizontal 15m mark to the 9m mark the trench was excavated 2m deeper to expose more of the main fault plane between uplifted Tertiary sediments and downthrown Quaternary sediments. The sediments exposed in the trench walls are divided into 6 genetic units (Figure 5).

Stratigraphy

The *western* wall of the excavated trench is composed of grey Tertiary mudstone (upthrown to the west) covered by Holocene gravels. The gravels are composed of rounded to sub-rounded greywacke boulders up to 0.36m across and clast supported. These bouldery gravels are overlain by weakly layered pebbly gravels which contain rounded 10mm to 50mm clast-supported pebbles with patches of yellow-brown weathering stains throughout the unit. The same unit in the northern trench wall also contained thin layers of very fine sandy gravel.

The *central* portion of the excavated trench consists of fine sandy river gravels with clasts up to 20mm across, overlain by up to 2m of unctuous

clay. The depth of this unit was ascertained by auguring. Sedigraph and XRD analysis show the clay is probably composed of weathered and redeposited Tertiary mudstone (Appendix 1). Tree roots, branches and stumps (some in growth position) up to 0.15m in diameter were distributed throughout the unctuous clay. Overlying the clay are bouldery gravels which are identical to those overlying the Tertiary mudstone on the upthrown western end of the graben. Within the bouldery gravels are lenses of finer material including, cobbly gravel, pebbly gravel, sandy-pebbly gravel, sand and pebbly loam.

The *eastern* wall of the excavated trench is composed of Ohakean (Appendix 3) river gravels. These contained clasts varying from 0.05m to 0.13m across that were highly oxidised. Overlying these gravels was a unit of yellow-brown silt loam.

Structures indicative of faulting events

The *western* wall of the excavated trench is composed of uplifted Tertiary mudstone which forms the western boundary lithology of the main fault plane (Plate 10). The fault plane shows reverse movement and it strikes 038/85W. Strike-slip movement on the main fault plane within the trench was not discernible but was inferred from drag structures (Plate 14, Figure 5) seen in the unctuous clay and the varying thicknesses of the bouldery gravels. Between the Tertiary mudstone to the west and the bouldery gravels to the east (parallel to the main fault plane) was a 0.03-0.05m thick seam of Tertiary mudstone mixed with carbonaceous material. Within this seam were embedded many cobbles, pebbles and some boulders. These gravels were rounded to sub-rounded and closely packed. Measurements of their boulder axes indicate that short axes were (82 times out of the 100 counted pebbles, cobbles and boulders) at right-angles to the fault plane. There were no slickensides visible but there was one clear groove made by a boulder trending 114° with a plunge of 14°. This boulder-made groove serves to confirm the oblique-slip nature of this fault.

Immediately east of the main fault plane and underlying the bouldery gravel was a smaller mini-graben containing fault breccia with an average clast size of 10mm 30mm in diameter (Figure 5). This mini-graben featured offsets and drag structures in the unctuous clay unit and within the bouldery

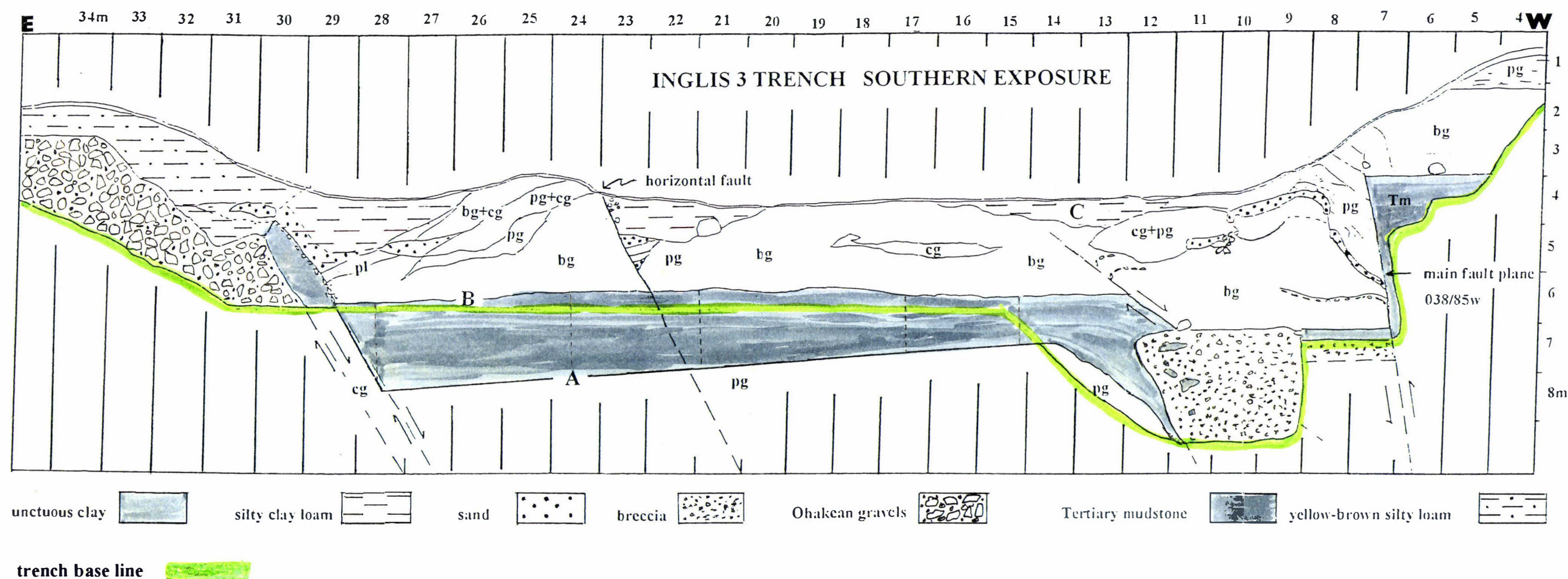


Figure 5. Stratigraphic cross section of the Inglis 3 trench, logged on a scale of 1:20. Tm is Tertiary mudstone, bg is a bouldery gravel, cg is a cobbly gravel, pg is a pebbly gravel and pl is a pebbly loam. A, B and C show the localities of radiocarbon dated samples. Sample A is charcoal from the base of the unctuous clay (NZA 3113) aged 9439 $\pm$ 77 yrs B.P. Sample B is wood found at the top of the unctuous clay aged (NZ 8001) 4335 $\pm$ 66 yrs B.P. Sample C is charcoal found in the upper silty clay loam unit aged (NZA 3698) 211 $\pm$ 63 yrs B.P. The vertical dashed lines in the unctuous clay represent auger holes which were used to find the depth of the clay unit.

gravels (Plates 12 and 13). Overlying the breccia and bouldery and cobbly gravels were layers of finer sandy pebbly gravels. These have been buckled and dragged down to the east of the 1.5m. During the second episode the finer gravels and unctuous clay were displaced another 0.90m vertically (Figure 5 and Plate 10).

In the *centre* of the excavated trench is another fault striking parallel to the main fault and dipping 75° to the west (Plate 11). This fault extends up to the present topsoil and has displaced lenses of finer material within the bouldery gravel. It shows horizontal strike-slip movement only, because the underlying unctuous clay shows no vertical displacement. There is however a slight compressional surface bulge directly to the east of this fault.

The *eastern* wall of the excavated trench has another fault which strikes 030/46W and displays normal fault movement. Here Ohakean gravels and a segment of unctuous clay have been dragged up 1.5m to the east (Figure 5).

INGLIS SITE 4 TRENCH

This trench site preserves the geological oldest record determined in this study having an earthquake history extending back prior to 29,200 yrs B.P. The site is located on the flank of what is thought to be a Porewan-aged, gravel terrace (Marden, 1984, Figure 4, Appendix 3). Unfortunately no distinct volcanic ash marker beds were found in the trench to provide stratigraphic dates (Figure 6). The Inglis 4 trench is situated at the upper (uphill) narrow end of the graben approximately 175m north of site 3. The trench was excavated at right angles across the northern end of the graben; it was 18m long and up to 6m deep.

Stratigraphy

The oldest rock type in this trench is again the Tertiary mudstone unit which is uplifted to the west. At the east end of the trench are Porewan-aged gravels. These are tightly packed pebbles, cobbles and boulders. The clasts are angular to subangular and stained yellow-brown. At the bottom of the trench are two layers of gravels. The lower consists of

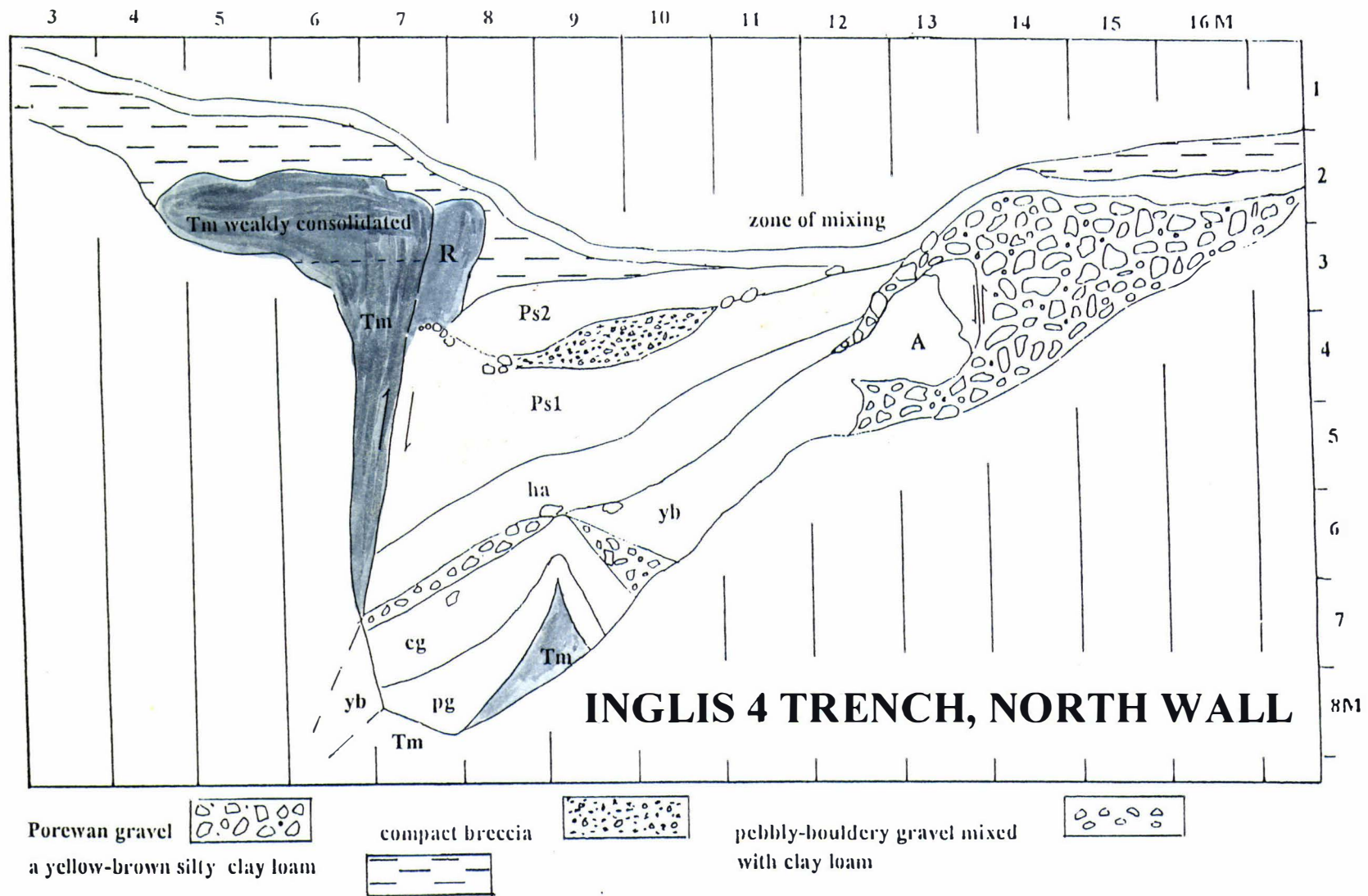


Figure 6. Inglis 4 trench showing soil ages and stratigraphic sequences. The description of units is as follows: Tm is Tertiary mudstone, pg is pebbly gravel, cg is cobbly gravel, yb is a yellow-brown sandy loam, ha is a highly allophanic soil, and R is a rubble unit with a Tertiary mudstone matrix. A is the locality of a radiocarbon dated charcoal sample aged (NZA 3071) 29,200 $\pm$ 320 yrs B.P. Ps1 is the oldest paleosol which formed in a silty clay loam aged (NZA 3114) 10,286 $\pm$ 79 yrs B.P. Ps2 is a younger paleosol which formed in a grey silty loam, charcoal from this unit is dated at (NZA 3070) 1105 $\pm$ 65 yrs B.P.

a pebbly gravel, the upper is a cobbly gravel. Above this are more gravels mixed with yellow-brown silty clay loam. Overlying the gravels is a yellow-brown coloured loam, above which is another yellow-brown coloured unit which is highly allophanic and contains some pebbles. This is overlain in turn by a silty-clay loam unit in which a paleosol has formed in the upper part. This is overlain by a tightly packed breccia unit. On top of this is a grey silt loam containing a second paleosol with carbonaceous material. The uppermost unit is yellow-brown silty clay loam covered by a dark topsoil with scattered pebbles and cobbles between 0.06m and 0.15m in diameter.

Structures indicative of faulting events

This trench exposes the main Wellington Fault trace (striking at 039/75W) which forms the western graben wall (Plates 15 and 16). Here there is a reverse component with a total upthrow of Tertiary mudstone against late Quaternary materials within the trench of 6m. At the bottom of the trench, 2.2m east of the main fault plane, is a listric fault underlain by upthrust Tertiary mudstone (Figure 6, Plate 15). This fault has deformed the three lower units of gravel and sediment but not the overlying units. The eastern end of the trench is composed of Porewan gravels which have been displaced 1.2m upwards to the east. Within the trench are three structural features called horses (Ramsay and Huber 1987) or slices (Hatcher 1990) where different sedimentary units have been thrust into either younger or older material. Horses or slices are units which have been completely enclosed on all sides by faults (Figure 6). The lowermost horse is a wedge of yellow-brown silty clay loam (without pebbles) which appears to have been pushed obliquely into the Tertiary mudstone (Plate 16). The second horse is also a wedge of yellow-brown silty clay loam within the Porewan gravels (Plate 17). The boundaries of this structure were diffuse. The third horse consisted of a wedge of Tertiary mudstone pushed horizontally into the fault trench sediments (Plate 18). This structure had a bearing and plunge of 235/40° and was 15° oblique to the main fault plane. The first two horses or slices are composed of competent materials (Figures 17 and 18) derived from the fault footwall, which is commonly the case (Hatcher 1990). The third horse is much less common and derives from the hanging wall of the fault.

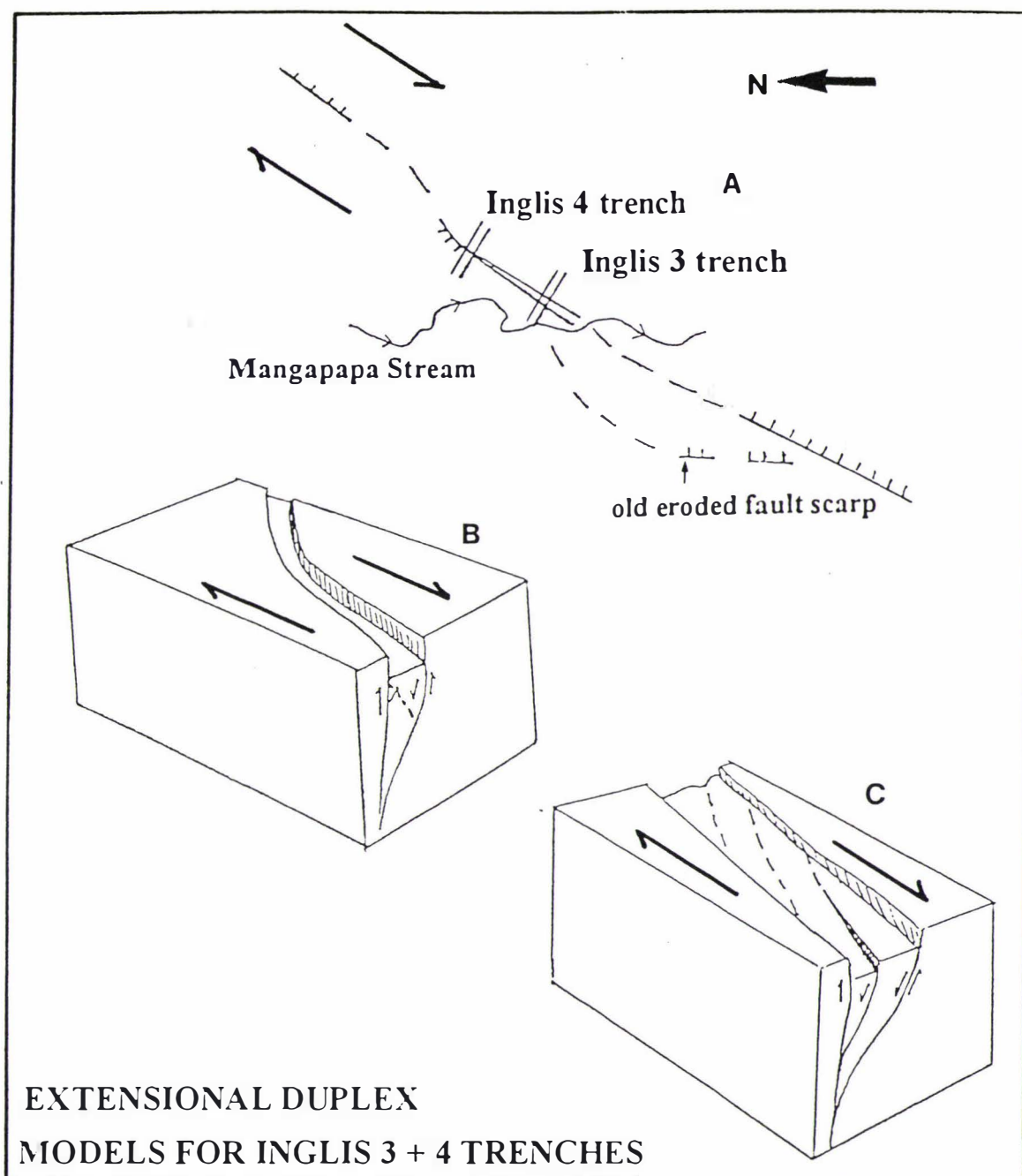


Figure 7. Extensional duplex on the Wellington Fault at Inglis' Farm. Large arrows indicate the dominant shear sense of the fault zone; small arrows indicate the sense of strike-slip and normal components of motion on the fault splays. A is a sketch of the fault from aerial photographs showing the two right-stepping extensional bends plus the localities of the Inglis 3 and 4 trenches. B is a cross section model through the Inglis 4 trench. C is a cross section model through the Inglis 3 trench showing the normal or negative flower structures, typical of extensional fault zones.

DISCUSSION AND PROPOSED SEQUENCE OF EVENTS FOR THE INGLIS' FARM TRENCHES

The Inglis 3 and Inglis 4 trenches were excavated through a small structure which exhibits all the features of an extensional strike-slip duplex (Woodcock and Fischer 1986, Twiss and Moores 1992). This duplex was formed by a double right-stepping extensional bend in the fault trace. The southernmost bend has a change in direction of only 5° while the northern bend differs by 10° (Figure 7A). The 5° bend may account for the narrowness of the graben.

Reconstructed cross-sectional paper cut-out models of the main units in the trenches show gaps between the main fault plane and the graben structures confirming the extensional mode of the basin. Cross-sectional models of the Inglis 3 and 4 trenches show negative flower-like structures with the main fault plane having a reverse component and normal faults to the east (Figures 7B and C). These structures are also fairly typical of dextral fault bends (Woodcock and Fischer, 1986, Twiss and Moores, 1992). The horse structures (Plates 16, 17 and 18) seen in the Inglis 4 trench serve to reinforce the above models. The negative flower structures also act as individual horses or slices within the pull-apart basin. These horses appear to move independently of each other during intervals of faulting activity which is possibly due to the oblique nature of the strike-slip regime. The westerly younging trend of the normal faults within the Inglis 3 trench is thought to be typical of the evolutionary stages in a pull-apart basin. This process is seen in the continuing deformation of the unctuous clay unit (Inglis 3 trench, Figure 8). In many such cases it has been observed that continual displacement leads to the basin being finally split by a later fault which often, typically separates opposite sides of the basin from each other (Twiss and Moores, 1992). The youngest fault in this case is the only structure to reach upwards to the topsoil. This is the strike-slip horizontal fault (Inglis 3 trench, with no vertical displacement, Plate 11) which separates the opposite sides of the basin as described above, confirming the Twiss and Moores (1992) model (Figure 5).

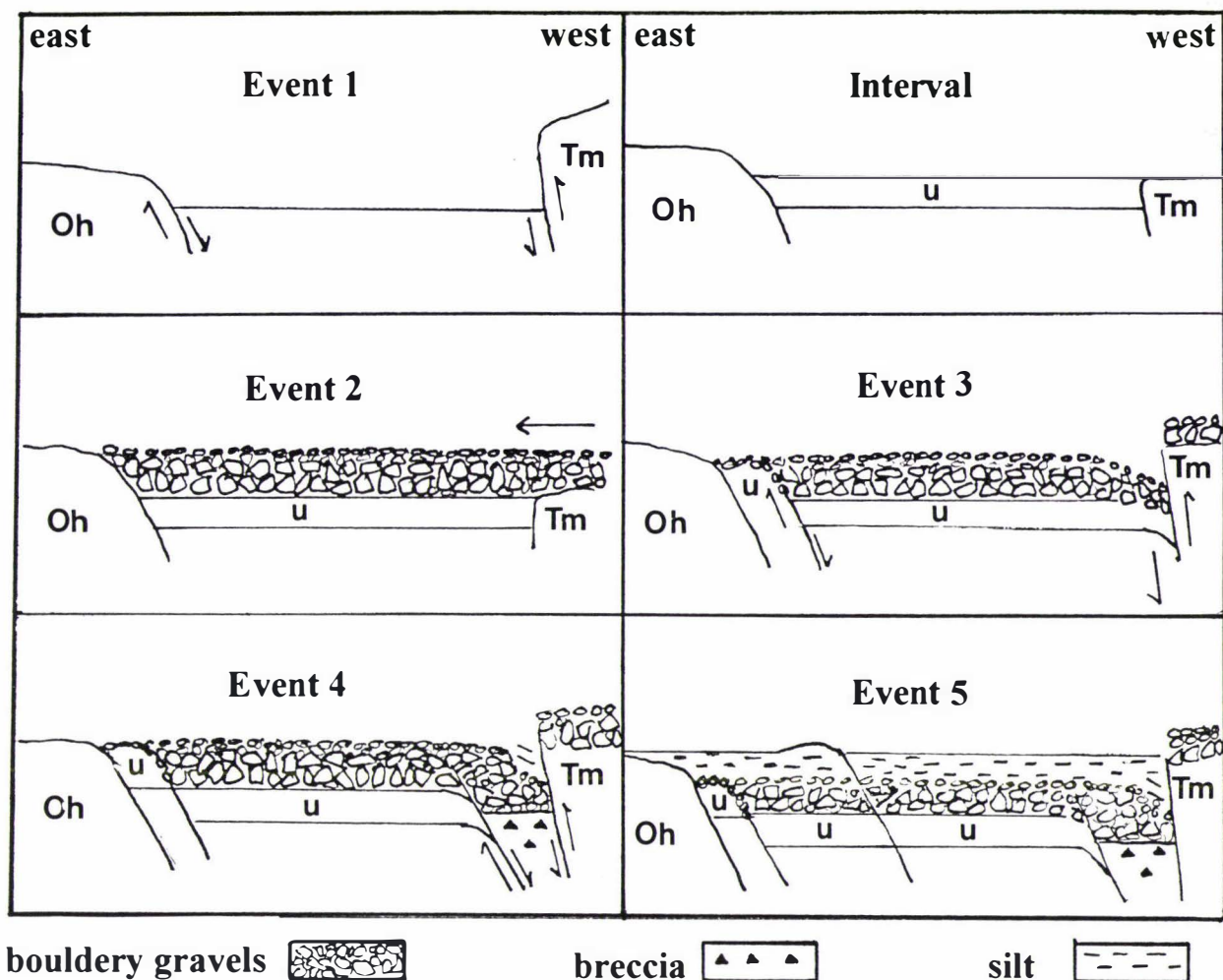


Figure 8. Cartoon of the inferred sequence of events seen in the Inglis 3 trench excavated across the Wellington Fault. Oh are Ohakean gravels, Tm is Tertiary mudstone and U is the unctuous clay unit. The first movement (graben formation) recorded in the trench occurred between 10286 and 9434 yrs B P. Followed by an interval where upthrown Tertiary mudstone (event 1) eroded into the trench forming the unctuous clay unit. A second earthquake event (post 4335 yrs B P.,) moved the trench area into a position where bouldery gravels are washed into the graben by the Mangapapa Stream. A third earthquake disrupts the unctuous clay unit. A fourth earthquake event forms the small graben at the west end of the trench. The fifth earthquake event (pre or post 211 yrs B P.,) is pure strike-slip which disrupts units in the centre of the trench area but does not change the height of the unctuous clay unit.

INGLIS 3 TRENCH

Since there are the same number of faulting events observed within the trench as there are offset features on the surface. Events within Inglis 3 trench have been correlated with nearby surface structures. This may be a coincidence. However the possibility that there is a relationship cannot be discounted.

- (1) The first event formed the small graben with gravels in the base (Figure 8). The Tertiary mudstone was then upthrown to the west and the Ohakean gravels were preserved to the east. The Tertiary mudstone was then eroded into a sheltered basin to form the unctuous clay unit. A carbonaceous sample from the base of the clay gives an age (NZA 3113) of 9434 ± 77 yrs B.P. In contrast, a tree root at the top of the clay was dated (NZA 8001) at 4335 ± 66 yrs B.P. This implies that it took approximately 5000 years for the 2m of unctuous clay to accumulate reflecting a quiescent backwater environment protected from the Mangapapa Stream. There is no evidence seen within the trench for earthquake events over this time. However if the compact breccia layer seen in the Inglis 4 trench represents an earthquake event then a faulting event may have occurred during this time period. Further uplift to the west would have allowed more Tertiary mudstone to erode into the basin during this time.
- (2) The second recognised event occurred post- 4335 ± 66 yrs B.P. This involved the unctuous clay unit which was moved by strike-slip action from its sheltered locality (behind the Ohakean gravel hill to the northwest, Figure 10) to a position which allowed the river to sweep onto the basin depositing the bouldery river gravels. On top of these coarser gravels, thin (up to 0.40m) layers of pebbly, cobbly and pea gravel were deposited. These gravels formed the Holocene 2 surface mapped by Marden (Figure 10) through which the stream cut a channel 12.3m south of the upthrown Ohakean gravel hill. As there were no gravels in direct contact with the main fault plane within Inglis' 4 trench to be carried along by strike-slip action it is assumed that the clast-oriented gravel unit on the main fault plane began to accumulate

here due to the pull-apart action in the basin (as described in the structural section) at this time.

- (3) During the third faulting event the Holocene 2 surface was uplifted further and the Mangapapa Stream cut a second channel through these deposits. This channel is 12.4m south of the first channel and the vertical offset between these channels is 1.80m. The centre of the pull-apart basin dropped vertically at this time. This movement displaced the unctuous clay (1.50m, downwards) on the eastern side of the basin and the gravels on the main fault plane (1.80m, downwards) to the west (Plate 10).
- (4) A fourth faulting event caused the second channel to be abandoned and the Holocene 2 surface displaced downwards a further 0.90m (Plate 10). Pull-apart movement is also seen in this displacement of the unctuous clay (0.90m) and formation of the mini graben (Plates 12 and 13).

The above faulting event or a build-up of river sediments then shifted the course of the Mangapapa Stream to the west causing it to abandon the second river channel. A Holocene 3 surface was then formed (Marden, 1984). The latest movements seen within the trench are dominantly strike-slip with no vertical component.

(5) The latest faulting events, cuts through the central portion of the pull-apart basin and is visible from the top of the unctuous clay to the base of the topsoil (Plate 11). The distance from the second abandoned river channel to the excavated trenches present position was 30.3m. It is not known how many faulting events are involved in this horizontal offset, if there were only two (event 4 and 5) then the offset for each must average approximately 15m. Wood samples 0.4m below the present topsoil and above the displaced Holocene 2 surface were dated at (NZA 3696) 211 ± 63 yrs B.P. Unfortunately the relationship between the silty clay loam containing the above sample and the horizontal fault is unclear. However as this sediment interdigitates with other upper trench deposits, suggesting coeval deposition (Figure 5) then it is likely that there was fault movement during deposition of this unit.

Finally a sedimentary fan was deposited over the southern part of the graben (trenches 1 and 2, Figure 4). It is possible that the youngest silty sediment found in the trench is a part of the above fan, which would give a minimum age for the last fault movement of 211 ± 63 yrs B. P.

INGLIS SITE 4

The displaced Tertiary mudstone within this trench shows 6m of vertical offset upthrown to the west along the western boundary fault. Deposits within the trench show a strong similarity to the higher Porewan gravel deposits to the east. It is significant that no appreciable amount of uplifted Tertiary mudstone has been eroded (from the hanging wall) into the trench at this site. Because the fault trench occurs on a west-facing slope and the fault is upthrown to the west, successive faulting events probably led to westward downhill erosion of exposed lithologies. This dictated rapid redeposition of Porewan gravels into the fault trench, while the Tertiary mudstone was always eroded downhill to the west of the trench.

The proposed sequence of events observed within this trench are as follows (Figure 9):

- (1) Formation of the graben and subsequent deposition of fine, followed by coarse gravels into the fault trench.
- (2) Deformation of the gravels within the trench by faulting, along a listric fault, followed by the deposition of a gravelly clay. There also may have been uplift along the main fault plane at this time.
- (3) Tilting of the gravelly clay caused by further movement of the listric fault.

A yellow-brown loamy unit was then deposited in the trench. A charcoal sample, in the upper eastern part of this unit gave a radiocarbon age (NZA 3071) of $29,200 \pm 320$ yrs B.P., providing a minimum age for the former three events.

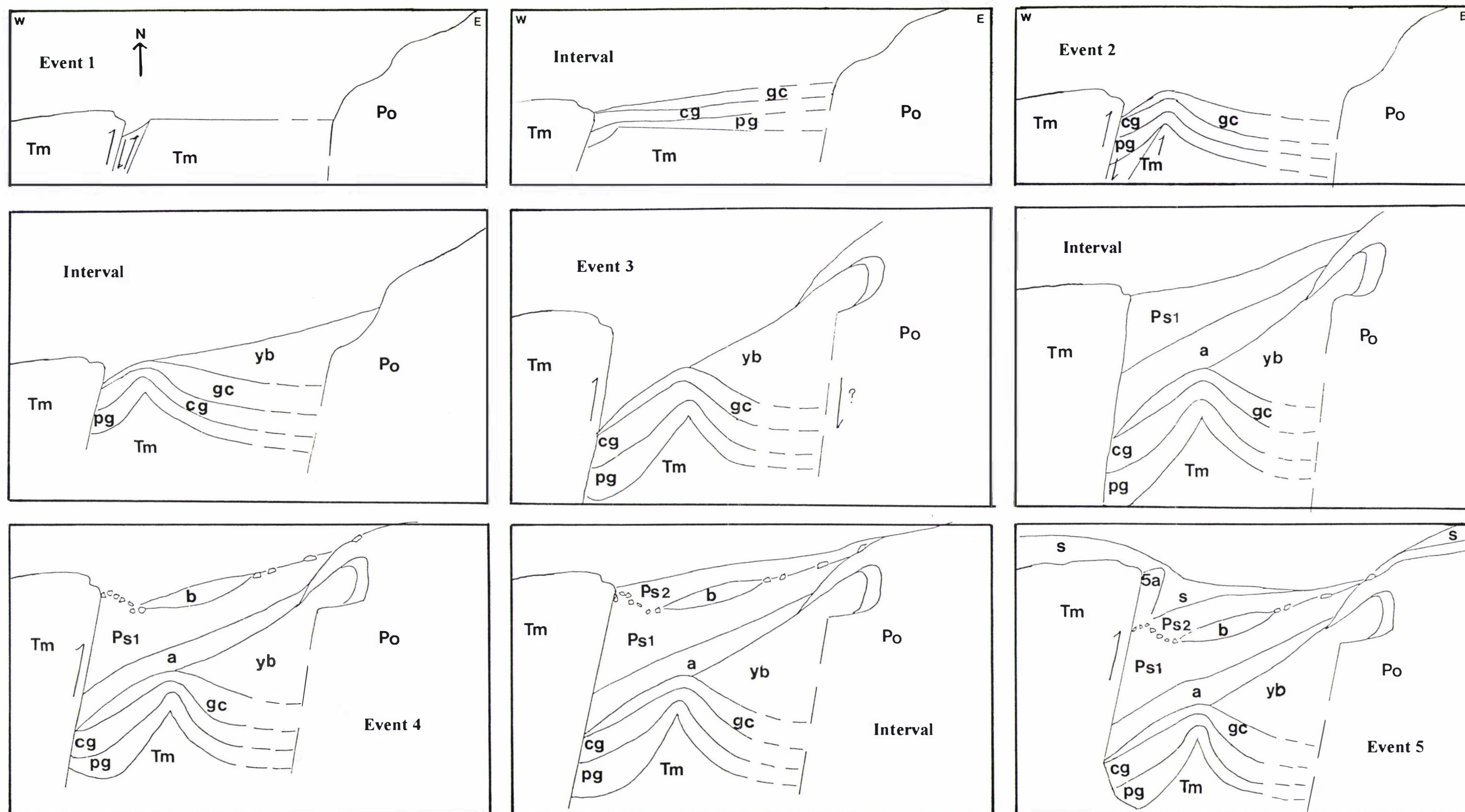


Figure 9. Cartoon of the proposed sequence of earthquake events for the Inglis 4 trench (Wellington Fault). Tm is Tertiary mudstone, Po are Porewan gravels, pg is pebbly gravel, cg is cobbly gravel, gc is a gravely clay, yb is a yellow-brown loamy unit aged 29 200 yrs B P., a is a highly allophanic unit, Ps1 is the older paleosol aged 10 286 yrs B P., b is a compact breccia unit, Ps2 is a younger paleosol aged 1105 yrs B P., S is a silty loam unit and 5a is a Tertiary mudstone-rubble unit. Earthquake event 1 is graben formation and deformation of the Tertiary mudstone, followed by an interval where pebbly gravels, cobbly gravels and gravely clay are deposited. Earthquake event 2, faulting causes further deformation of the Tertiary mudstone, and overlying gravel units. Interval where the Yellow-brown loamy unit is deposited around 29200 yrs B P. Earthquake event 3 where Porewan boulders fall into the trench. Interval, a highly allophanic unit is deposited into the trench and Ps1 is formed age 10 286 yrs B P. Earthquake event 4 where the compact breccia unit and some boulders fall into the trench. Interval, a second paleosol forms Ps2 aged 1105 yrs B P. Earthquake event 5 occurs and Tertiary mudstone (5a) and the overlying silt unit is also deformed (5b) this may be two separate events.

(4) Subsequently eastward uplift and deformation of the Porewan gravels occurred along the eastern boundary fault of the graben. This led to the erosion and deposition of more boulders into the trench on top of the yellow-brown loamy unit post-29,200 $\pm$ 320 yrs B.P.

Another silty clay loam then accumulated and a soil was formed in the upper portion. Charcoal from this soil gave a radiocarbon date (NZA 3114) of 10,286 $\pm$ 79 yrs B.P. The 10,286 year date provides the maximum age for the earthquake which uplifted the Tertiary mudstone at Inglis site 3. After this event the deposition of the unctuous clay commenced. The 9434 year date (Inglis 3 trench) from within the base of the unctuous clay provides a minimum date for this event.

- (5) A faulting or storm event, then caused the deposition of a lens of compact breccia into the fault trench. As this breccia is not seen within other deposits in this area it is possible the unit has been carried along the fault plane by strike-slip activity. This gravel is much finer and more angular than other locally derived gravels, it is similar to the gravel seen at the base of the mini-graben in the Inglis 3 trench.

A new soil then formed in finer silty materials above the compact breccia. It contained charcoal in its upper part dated (NZA 3070) at 1105 $\pm$ 65 yrs B.P.

- (6) A new layer of yellow-brown silty clay is deposited in and over the western wall of the trench. The drape structure formed at this locality could be due to a faulting event or it may be a natural gravitational depositional feature. If this does indicate a faulting event then there is an offset of 2.5m up to the west.
- (7) Subsequent to event 5, faulting has also deformed the Tertiary mudstone to the east of the main fault. This deformation caused a slice or horse of Tertiary mudstone to be torn off the hanging wall and thrust into footwall sediments. As in the Inglis 3 trench this last movement may represent strike-slip movement only because no vertical offset is seen here.

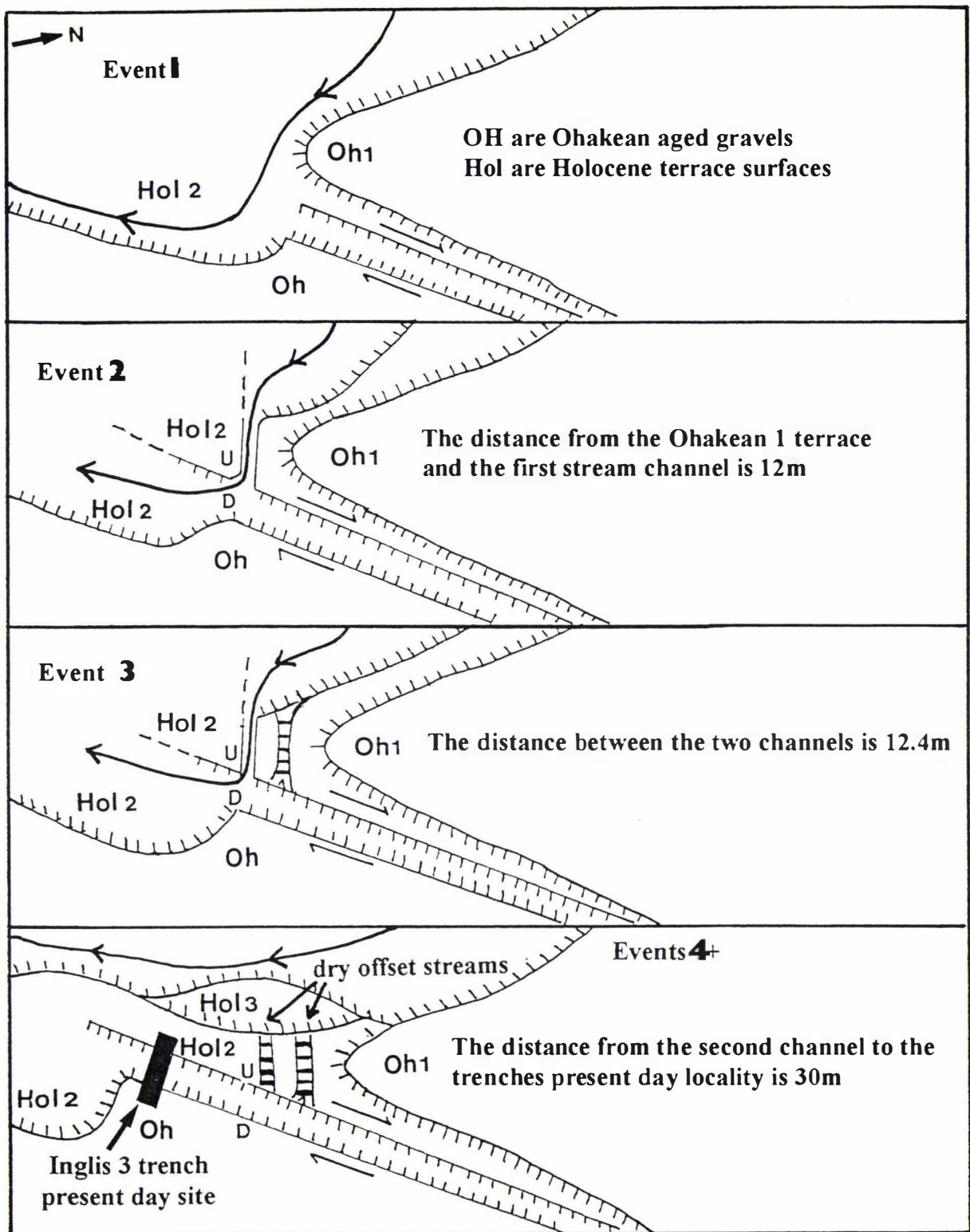


Figure 10, Cartoon of proposed surface faulting events for the Inglis 3 site on the Wellington fault. Event 1=graben formation. Event 2 bouldery gravels dumped into the graben and first channel is cut post 4335 yrs B.P. Event 3=first stream abandoned, horizontal offset is 12.4m vertical offset is 1.8m and the second stream is cut. Event 4=second stream abandoned vertical offset is approx 0.9m.

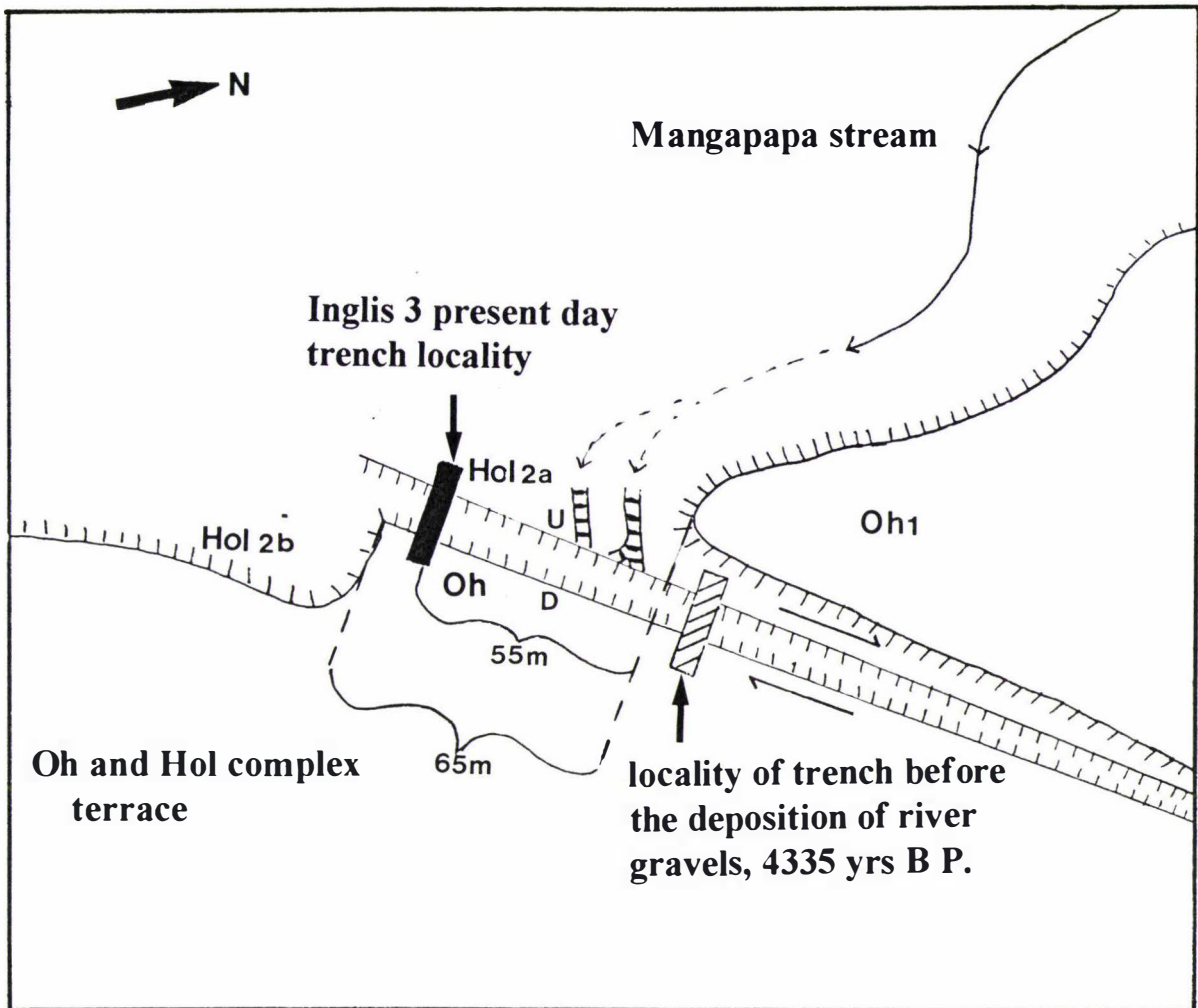


Figure 11. Horizontal and vertical displacements of the Inglis 3 trench on the Wellington Fault. The total vertical displacement between Oh and Oh1 is 12m giving an offset rate of .6 to 1.2 mm/yr. The vertical distance between Hol 2a and Hol 2b is 4.68m. The total minimum horizontal offset comes from the distance the trench locality moved from its sheltered locality behind the Ohakean gravel hill to the trenches present position. This is based on the assumption that the unctuous clay must have formed in a sheltered locality away from the river as the clay contains no gravels. When the trench area was moved from behind the hill due to strike-slip action the stream then deposited gravel into the down dropped trench area. The offset rate is based on the age of wood from the top of the unctuous clay unit (4335 yrs B P). This gives a minimum offset rate of 13 mm/yr, the maximum horizontal offset rate comes from the distance the Hol 2 terrace scarp moved. From the Base of Oh 1 to its present day locality (65 m) giving an offset rate of 15 mm/yr.

SUMMARY OF FAULTING EVENTS ON INGLIS' FARM

The total Holocene movement in this area (Figures 10 and 11) is deduced from the offset of displaced river terrace surfaces. Total vertical movement is seen in the 12m displacement of Ohakean gravels which is the height difference between the Ohakean gravels forming the east wall of the graben at Inglis site 3 and the Ohakean gravel terrace 55m to the north-west of Inglis site 3. From these measurements a vertical offset rate of 0.66 to 1.2 mm/yr is calculated depending on the inferred age range for the Ohakean surface. This offset rate is similar to that calculated by Marden and Neall (1990) farther to the south. A maximum single vertical offset of 1.8m comes from the height difference between the two offset paleo-stream channels. The minimum single vertical movement is seen where the finer sandy gravels and the unctuous clay are displaced 0.90m downward (Plates 10 and 12).

The total minimum horizontal offset of 55m was measured from the previous sheltered locality of the unctuous clay to its present day position (Figure 11). Since there are no gravels or boulders within the unctuous clay it was assumed it was deposited in a sheltered locality away from the area of river deposition. This gives a minimum horizontal offset rate of 12.6 mm/yr dated from the tree root at the top of the unctuous clay 4335 ± 66 yrs B.P. A maximum offset can be measured from the base of the Ohakean gravel hill (the sheltered locality to the northwest, Figure 10) to the Holocene 2 scarp which cuts the downthrown Ohakean gravels on the eastern side of the fault. This distance is 65m which gives a maximum rate of 15mm/yr. The maximum horizontal estimated offset for a single earthquake event is the distance between the two abandoned river channels of 12.4m.

Some 50m north of Inglis 4 the Wellington Fault trace traverses along an unstable eastward-facing slope of a hill composed mainly of Tertiary mudstone. Here only suggestions of the fault trace can be seen. Uplift remains to the west but shows only as a vague break in slope. Farther north the fault trace is clearly visible again, 100m west of the end of Beagley Road.

TRENCHING ON BEAGLEY FARM

Beagley Farm is situated at the north-west end of Beagley Road, at T24/554996 (Figure 3). The Wellington Fault can be seen crossing the hillside directly opposite the end of this road. At this locality a small stream is offset dextrally 53m (Plate 19) but the sense of uplift is unclear. The fault scarp is composed of Tertiary mudstone fault gouge with angular to subrounded greywacke pebbles, its free face is steep ($>40^{\circ}$) and heavily eroded (Plate 20). Tertiary strata on the eastern side of the fault dip between 10° and 15° towards the fault plane and on the western side, dip inward at 40° towards the fault.

Approximately 500m north of Beagley Road is a dextrally offset stream pair which angle across the Wellington Fault. The channels are part of the upper Mangapapa catchment system. This offset stream pair and a third older highly eroded channel are clearly seen on aerial photographs (Plate 22). The distance between the dry fossil stream bed and the active stream bed is 30m. The active stream also has a 26.5m dog-leg where it flows along the fault. As a part of this study a trench was excavated at right-angles through the fossil stream bed to determine when faulting beheaded the channel (Figure 12). The object of this exercise was to retrieve datable material from the fossil stream bed. The trench was 17m long and up to 3.5m deep; it was logged at a scale of 1:20 (Vol 2 map pocket).

Stratigraphy of the Beagley Farm trench

The lowermost unit within the trench (Figure 13) is grey Tertiary mudstone similar to that found in the Inglis trenches. Above the mudstone, in the centre of the stream bed, are matrix-supported subrounded bouldery gravels (representing the paleo-stream bed). A wood sample was retrieved from the top of the grey Tertiary mudstone unit. It was found in growth position and was thought to have been overwhelmed by gravels brought down by the then newly active stream (Plate 21). It gave a radiocarbon age (NZA 8229) of 5324 ± 61 yrs B.P. The unit which formed the north bank of the stream is composed of orange mottled silty sandstone. The south stream bank consisted of unconsolidated blue-grey sandy mudstone on top of which are redeposited cobbly gravels with a yellow-brown loamy matrix.

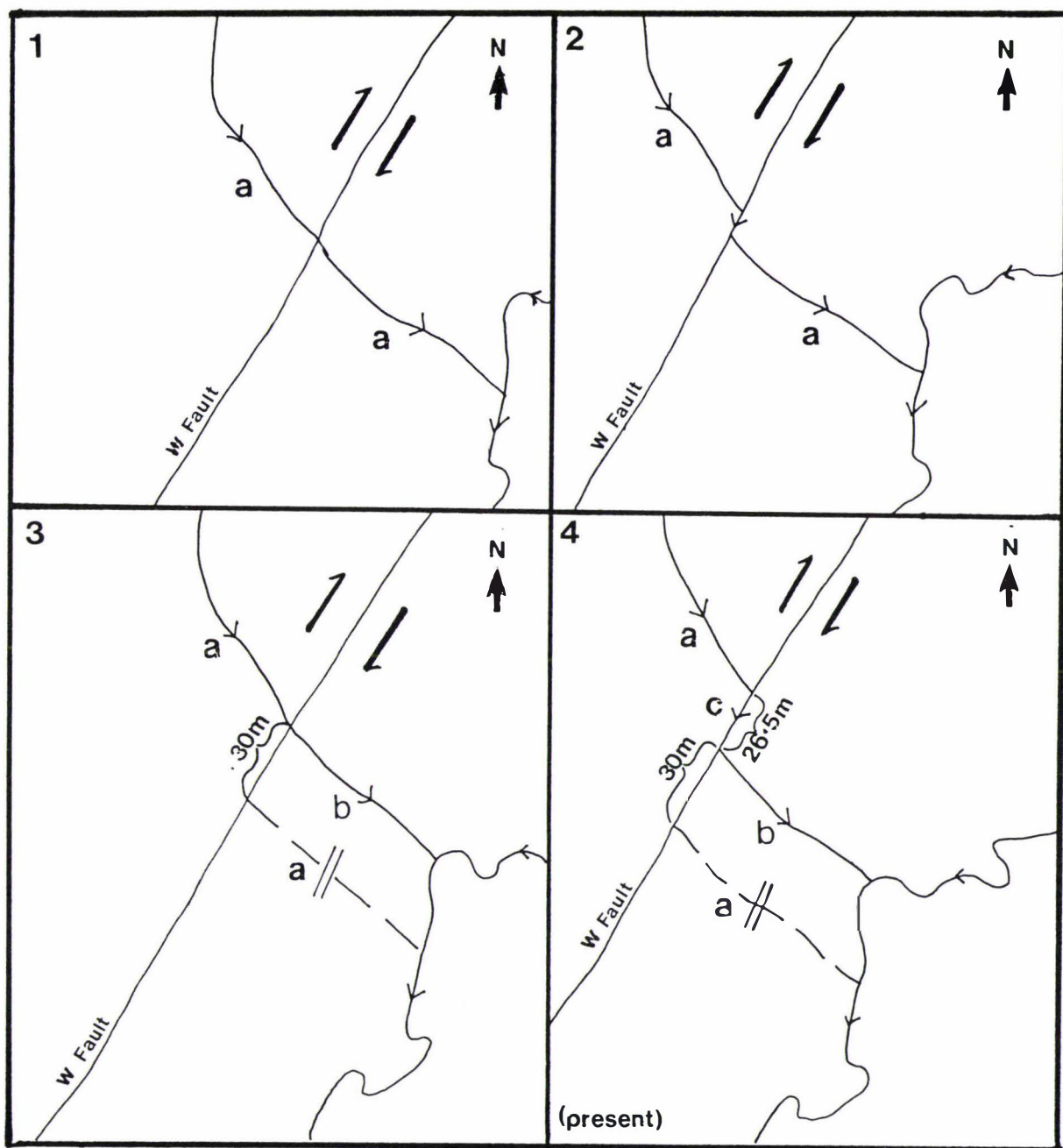


Figure 12, Cartoon of the sequence of events for the Beagley Farm stream pair which was offset by the Wellington Fault: 1. the original stream (a) crosses the fault. 2. faulting occurs and stream (a) is offset. 3. after a number of earthquakes the stream is offset by 30m and a new stream (b) is cut. 4. after further earthquake events stream (b) has a 25.5m dogleg (c). The total horizontal offset is 56.5m and is dated from a wood sample found in growth position beneath sediments of stream (a) giving an offset rate of 10.6mm/yr. Parallel lines on the paleo-stream bed (a) indicates the locality of the Beagley Trench.

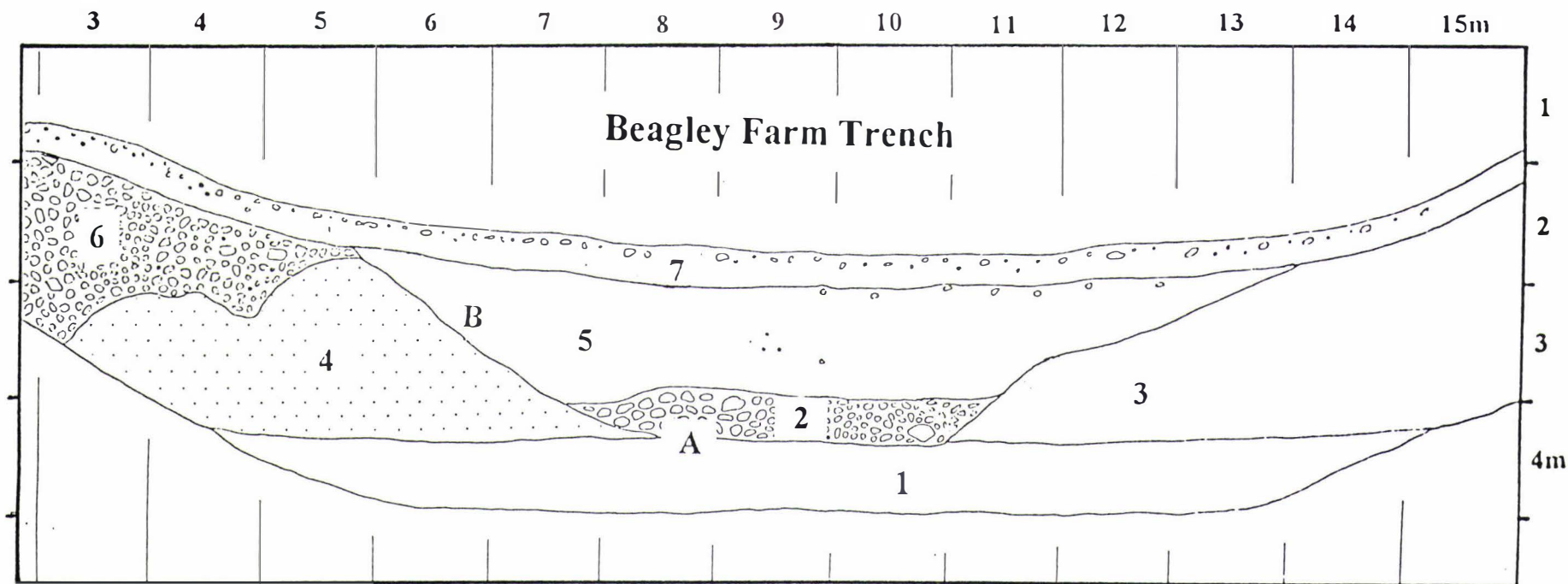


Figure 13. Cross-section of the western trench exposure at Beagley Farm, logged on a scale of 1:20. Units are as follows; 1 is a Tertiary mudstone, 2 Bouldery gravels, 3 an orange mottled sandstone, 4 is an unconsolidated sandy mud, 5 is a B horizon subsoil coloured yellow-brown with some scattered pebbles and cobbles, 6 is a cobbly gravel matrix supported and 7 is the topsoil with some scattered pebbles and cobbles. A is the locality of a radiocarbon wood sample age (NZA8229) 5324 $\pm$ 61 yrs B P. B is the locality of a radiocarbon dated sample age (Wk3151) 290 $\pm$ 50 yrs B P.

In between the north and south banks is a B horizon of yellow-brown loamy material containing some dispersed pebbles and cobbles, regarded as a subsequent channel infill of preweathered colluvium from the nearby hill slopes, following stream abandonment. A wood sample (Figure 13) 0.6m below the top of this unit was radiocarbon dated (Wk 3151) at 290 ± 50 yrs B.P. Overlying all the above units is the present topsoil which is 0.2m thick and has scattered cobbles and pebbles throughout.

PROPOSED SEQUENCE OF EVENTS

The proposed sequence of events that led to the offset streams is as follows. The offset stream originally flowed across the Wellington Fault, cutting through Tertiary mudstone before draining into the Mangapapa Stream.

- This stream (a) is offset by an earthquake post- 5324 ± 61 yrs B.P. and flows some distance along the fault before continuing its original path.
- The fault moved again and the original channel (a) is abandoned. A second stream channel on the eastern side of the fault (b) is cut parallel to the first but 30m farther north. The number of earthquakes that make up the 30m offset are unknown (Figure 12).

Following the abandonment of channel (a) the dry stream channel was infilled with colluvium including sample Wk3151, radiocarbon dated at 290 ± 50 yrs B.P.

- A subsequent faulting event or events created a 26.5m dogleg in the active stream (c).

The overall horizontal offset rate for the Beagley Road area is 10.6mm\yr, measured from the total 56.5m offset of both streams and the date of the wood in growth position. There was no vertical offset recorded at this locality. The Trotter trenches some 8km to the north of this site have 5 faulting events recorded in the last 5000 yrs. If this provides a full record of all the major earthquakes in this region of the fault then each earthquake event at Beagley Road must have involved an average horizontal

displacement of about 10m since the formation and subsequent abandonment of the paleo-stream.

Most Holocene movement at the stream site took place on the single strand of the Wellington Fault as shown (Plate 22). There is no evidence either in the field or on aerial photographs of multiple fault scarps in this area. Approximately 1km to the north the Wellington Fault does have a braided trace where there are horse blocks up to 100m wide.

From Beagley Road, the Wellington Fault trace continues northward trending 040° . Just before the fault crosses Coppermine Road there is a 93m offset (Plate 24) along a small stream which has been dammed by the farmer and is now a small lake. Here the fault scarp is seen as a minor break in slope. To the south and north of the dammed stream the latest series of vertical displacements appear to be mainly up to the east. This has been complicated by slumping and erosion on displaced hillsides. Between Oxford Road, just north of Woodville and Coppermine Road, four parallel splinter faults strike northeast (between 67° to 80°) from close to the trace of the Wellington Fault. These splinter faults were mapped by Marden (1984) and named (from south to north) the Mangarawa Fault, Beagley Road Fault, James Hill Road Fault and Coppermine Road Fault. The faults all show vertical uplift predominantly to the northwest and displace Pleistocene marine strata and or late Quaternary alluvial terraces (Marden 1984). Horizontal movement on these faults has not been detected and none of the fault traces can be seen directly joining the Wellington Fault trace.

THE PAPER ROAD SITE

From Mang-a-tua Stream to Loveday Road the Wellington Fault trace curves more northward in a series of sinistral en-echelon steps. In this area strike-slip faulting activity has dislocated surfaces to form shutter ridges. In some localities these ridges have blocked narrow gullies to form ponded drainage sites (Plate 23). A hand augured core was obtained from approximately halfway across, one of these sites at T23/580028. In this area the effects of a reverse faulting component are clearly seen. Footwall scarp dips vary between 40° and 50° to the west. The hanging walls on the

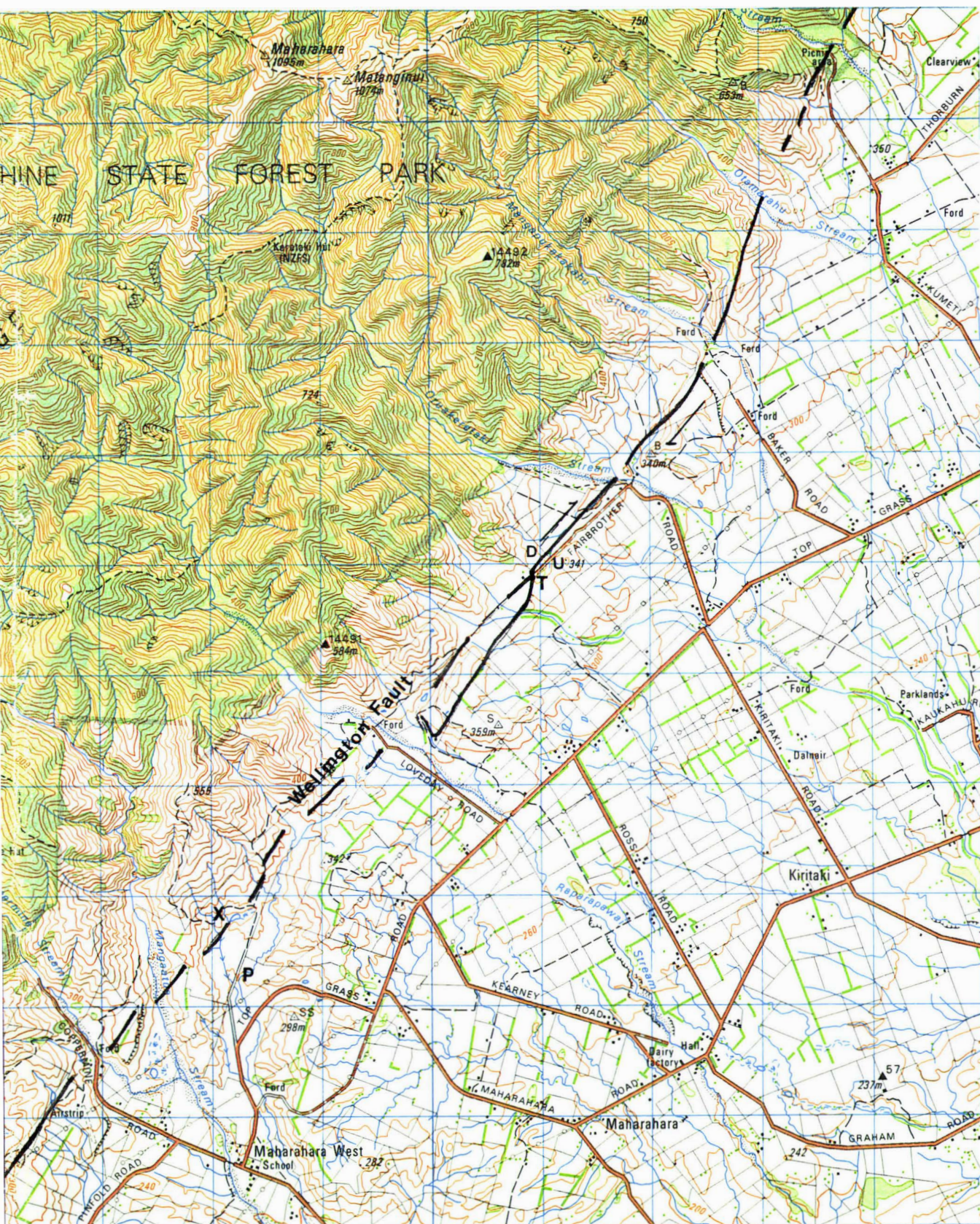


Figure 14. Locality map (NZMS 260 T23 1:50 000) showing the location of the Wellington Fault between Coppermine and Kumeti Roads. P is the paper Road and X is the site of the auger hole, T is the locality of the Trotter trenches. From the end of Graham Road it is 20 km south to Woodville and 7 km north-east to Dannevirke.

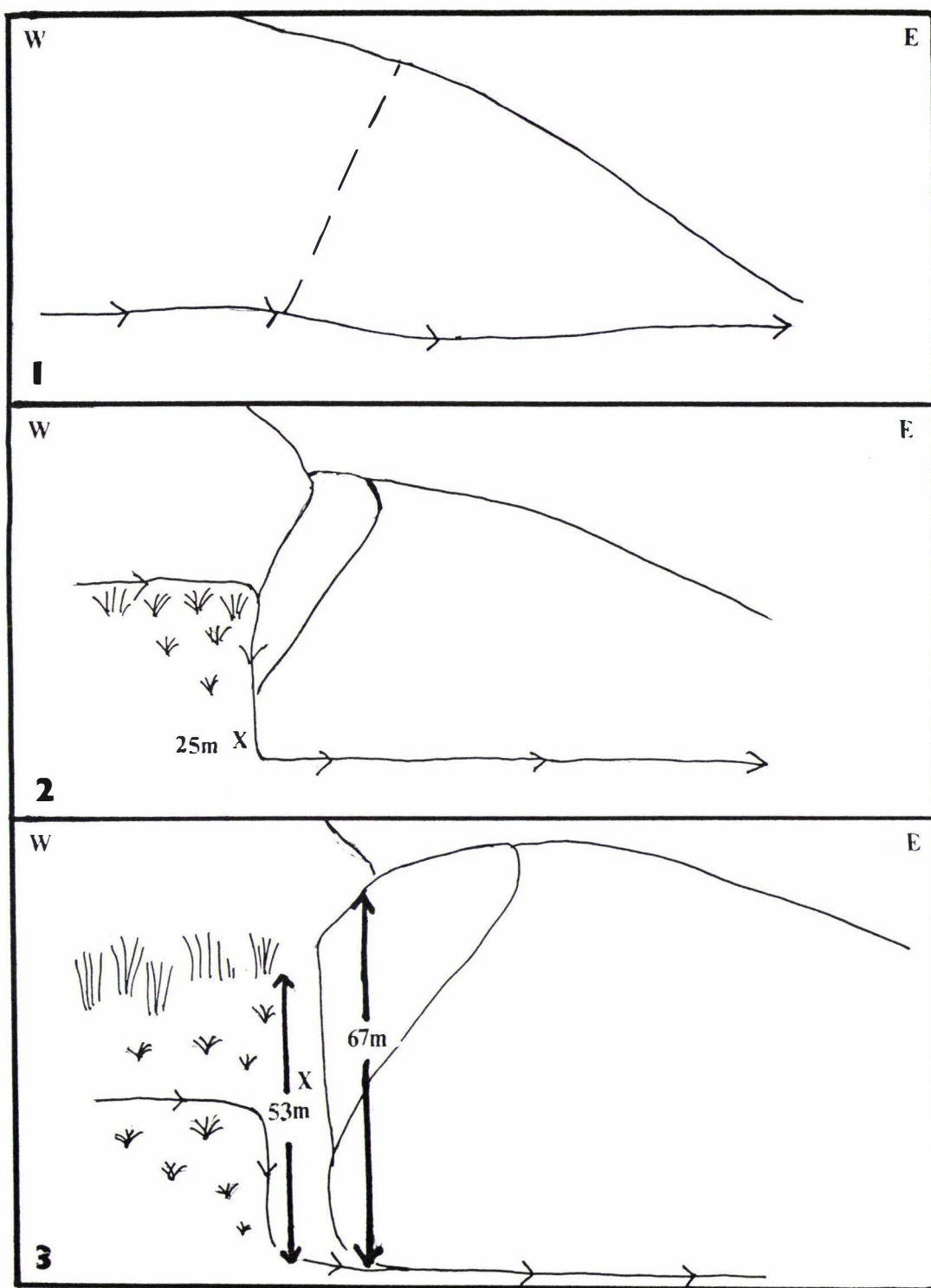


Figure 14A, Cartoon diagram showing progressive displacement by earthquakes of the Paper Road site. 1 represents the shutter ridge and stream before displacement, 2 the swamp forming at 25m of displacement and 3 the site today, X is the locality of the auger hole, the swamp is 53m across but the total ridge offset is 67m.

west side of the fault plane have all collapsed across the fault trace. Access to this area is reached via Top Grass Road and a paper road used by farmers whose properties adjoin the road (Figure 14).

Stratigraphy within the auger hole at T23/580028

The base of the core showed Tertiary mudstone, above which is a thin sandy silt unit at 3.75m depth from which a radiocarbon sample (NZA 5365) was dated at 1746 ± 78 yrs B.P. On top of this unit was a log (perhaps dislodged by faulting). Above the log was 1.5m of peat covered by 0.3m of sandy silt, this was overlain by 0.3m of fibrous peat. Overlying the peat was a unit of fine sand on top of which was the uppermost unit of mud about 1m thick.

PROPOSED SEQUENCE OF EVENTS AND OFFSETS FOR THE PAPER ROAD SITE

The general rule of peat accumulation of 1m to 1000 yrs (A.S. Palmer pers. comm.) applies at this locality. A peat units up to 1.8m thick formed behind the scarp plus an additional 1.95m of silty sandy materials which took 1746 ± 78 years to accumulate. The silty sandy units are thought to derive from debris due to the collapse of the nearby hanging fault wall following earthquake events. There are three such sandy silty units which represent a minimum of three earthquake events. The Inglis trenches record at least one faulting event during the last 1746 years B.P. and the Trotter trenches record 3 events over the same time period. If the sandy units were deposited over short periods of time after earthquake events then the peat accumulation rate has been approximately 1m per 1,000 years.

The swamp began to form after one or more earthquake events had moved the shutter ridge across the gully. Onset of peat accumulation would have occurred when the old stream channel became partially blocked. The shutter ridge would have had to move more than 25m across the gully before the swamp could form i.e. where the sample (NZA 5365) was located, but not the whole 53m seen today (Figure 14a). Based on faulting rates at other trench sites and the sediments found in the auger hole, this

seems to have involved at least 3 faulting events averaging 8.3m each, of horizontal offset. A horizontal offset rate can be obtained by using the age of the sample and at least the 25m distance the ridge had to move from 3m past the sample locality to its present day position of 14.3mm/yr. This is a conservative estimate, the distance from the sample locality to the scarps present day locality is 28m the above rate was calculated from the trapping of the sample behind 3m of shutter ridge. The main faulting action at this locality is strike-slip, there may have been a small amount of uplift to the east but this vertical offset could not be calculated due to the collapse of the hanging wall.

The Wellington Fault trace can be seen just south of Loveday Road as series of steep scarps and shutter ridges with uplift shifting most recently to the east. Adjacent to Raparapawai Stream all traces of the fault have been destroyed or buried under recent stream sediments.

North of Raparapawai Stream is a 2km long duplex where the fault trace splits into two segments. These traces continue northward until they meet again in a single strand at the end of Fairbrother Road, where Trotter farm is located.

TROTTER FARM TRENCHES

The geology either side of the Wellington Fault at this locality (Figure 14) consists mainly of Pleistocene marine sediments overlain by younger Pleistocene gravel terraces (Marden 1984, Appendix 3). Three trenches were excavated on Trotter's Farm at T24/609059 (Plate 26) through steeply dipping fault scarps (30° to 45° , Plate 25). The first two were located on the downthrown eastward and westward limbs of a complex duplex structure on the Wellington Fault (Figure 18). The third trench was excavated through an offset paleo-stream channel which yielded no datable material. Vertical profiles of Trotter 1 and 2 trenches were logged at a scale of 1:20 (Vol 2 map pocket).

TROTTER 1 TRENCH

This trench was 12m long and up to 3.4m deep. It was excavated at right angles through part of the Wellington Fault plane between an Ohakean gravel hill and adjoining peat swamp on the western side of the downthrown section of the duplex (Plate 26). The Ohakean gravels have been down faulted to the east and covered by swamp sediments.

Stratigraphy

The eastern trench wall (Figure 15) showed only three lithologic units. The lowermost unit was a dark grey-brown peat which contained a large amount of wood. An auger hole sunk a further 2.5m below the eastern trench footwall showed similar peat to that seen at the trench base. This peat extended upward from the trench base to within 1.4m of the surface, making a minimum thickness of 4.5m. Above the peat was a 1m thick horizontal layer of silt covered by 0.40m of peat swamp surface.

In the north and south walls of this trench (Figure 15), were layers of rubble within the peat which dipped east. The lower unit consisted of peat, on top of which was a gravel wedge which thinned toward the east. Above the wedge was a grey silt unit with some pebbles. Directly above the silt was a wedge of colluvium which also thinned eastward. On top of the colluvium was more peat, above which was the horizontal silt unit the same as that seen in the eastern trench wall. Above this unit, is the peat which forms the swamp surface.

Structures indicative of faulting events

The fault plane in this trench dips eastward at 26° and strikes northeast 74° . Pebbly sediments and the older peats within the south wall of this trench have a dip of 23° (Figure 15). Other sediments are all horizontal except where the peat unit appears to have been dragged upward by fault movement (Figure 15, Plate 27).

TROTTER 2 TRENCH

This trench was excavated perpendicular to the fault plane between a westward-facing Ohakean gravel terrace and downthrown valley sediments (Plate 26). The trench was 10m long and up to 5m deep. All four trench walls were logged at a scale of 1:20 (Vol 2 map pocket).

Stratigraphy

The *eastern* trench wall was composed entirely of Ohakean gravels. At the trench base were layers of silt up to 0.50m thick between the gravel units. These layers were composed of grey silty carbonaceous clay and carbonaceous sandy silt containing wood (sample Wk3146) radiocarbon dated at $22,020 \pm 150$ yrs B.P. The gravels showed a weak horizontal layering and were mostly angular to subangular clast-supported pebbles and cobbles. The upper gravels were heavily oxidised, the lower reduced; the line between the two was 3.6m up from the trench base representing the level of the water table.

The *western* trench wall was composed of units that were continuous with the north and south walls. At the trench base was a pebbly silty unit with some wood fragments. Overlying this was an 0.80m-thick peat unit, above which was a thin layer of carbonaceous silt. On top of this was a grey silt unit some 0.25m thick. Overlying the silt was a unit of river gravels containing sub-angular to rounded pebbles on top of which a thin topsoil had developed.

The *southern* trench wall (Figure 17) was composed of a number of units some of which were continuous, others occurred only in lenses. The lowermost unit was a woody peat, on top of which was a gravel lens of clast-supported, well sorted, rounded pebbles. Above the gravel lens was the previously identified pebbly silty unit with some wood (continuous with the west and north trench walls). Overlying the pebbly silt was a 1m thick continuous unit of peat, a sample of which was radiocarbon dated (Wk 3174) at 3110 ± 60 yrs B.P. On top of the peat was the continuous layer of carbonaceous silt, above which was a lens of solid wood and woody debris radiocarbon dated (Wk 3149) at 2030 ± 60 yrs B.P. Overlying the wood was another lens of fine sandy gravel. Above this was another continuous

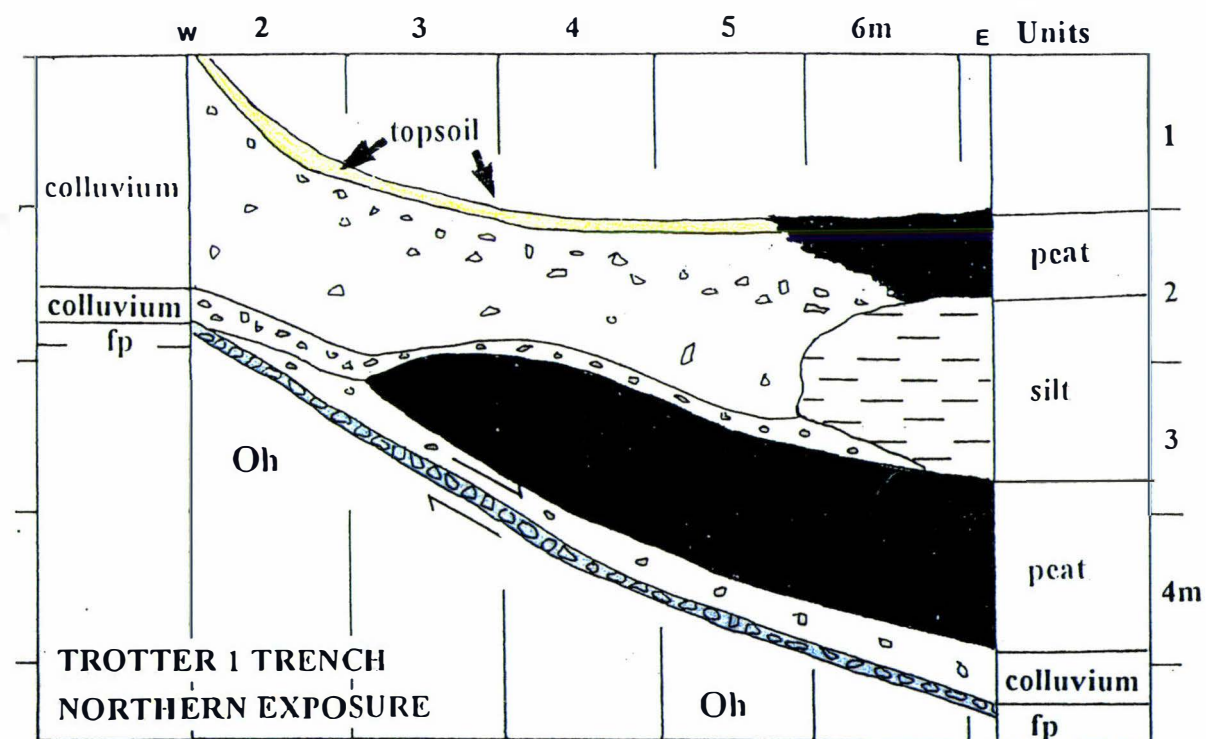
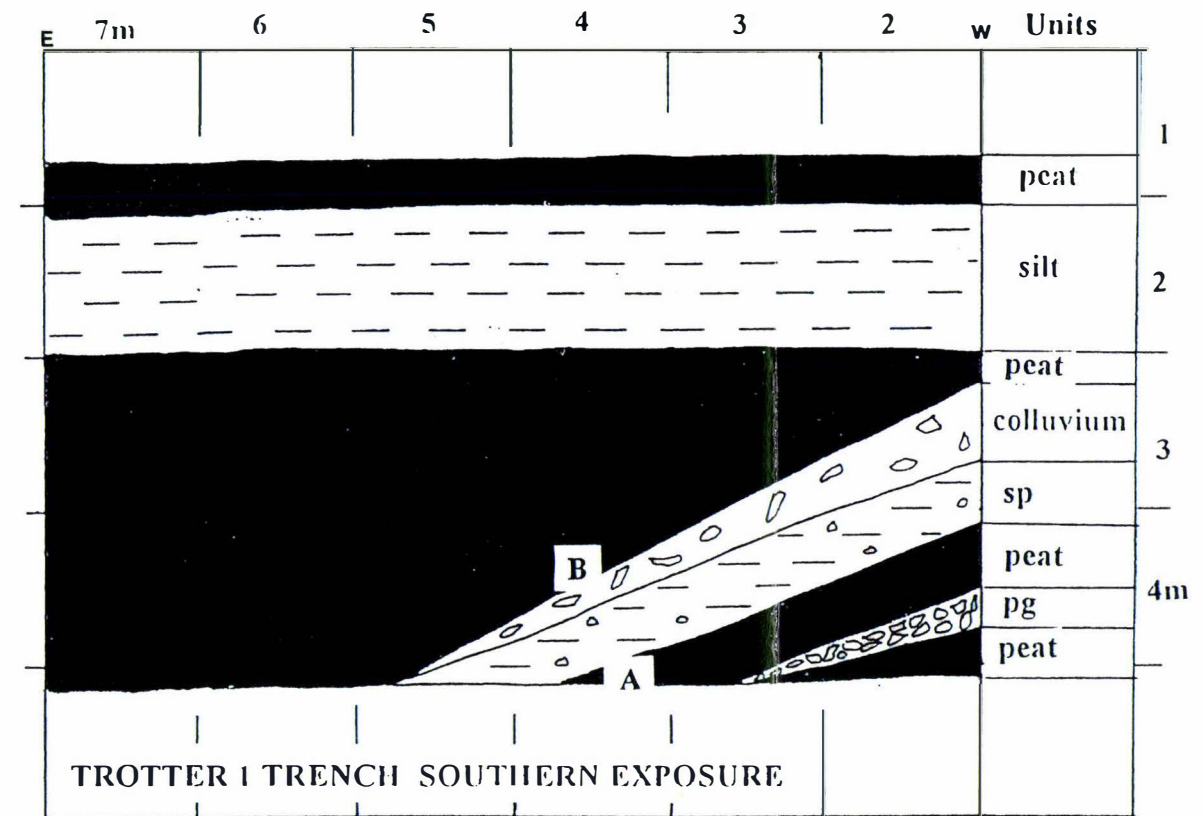
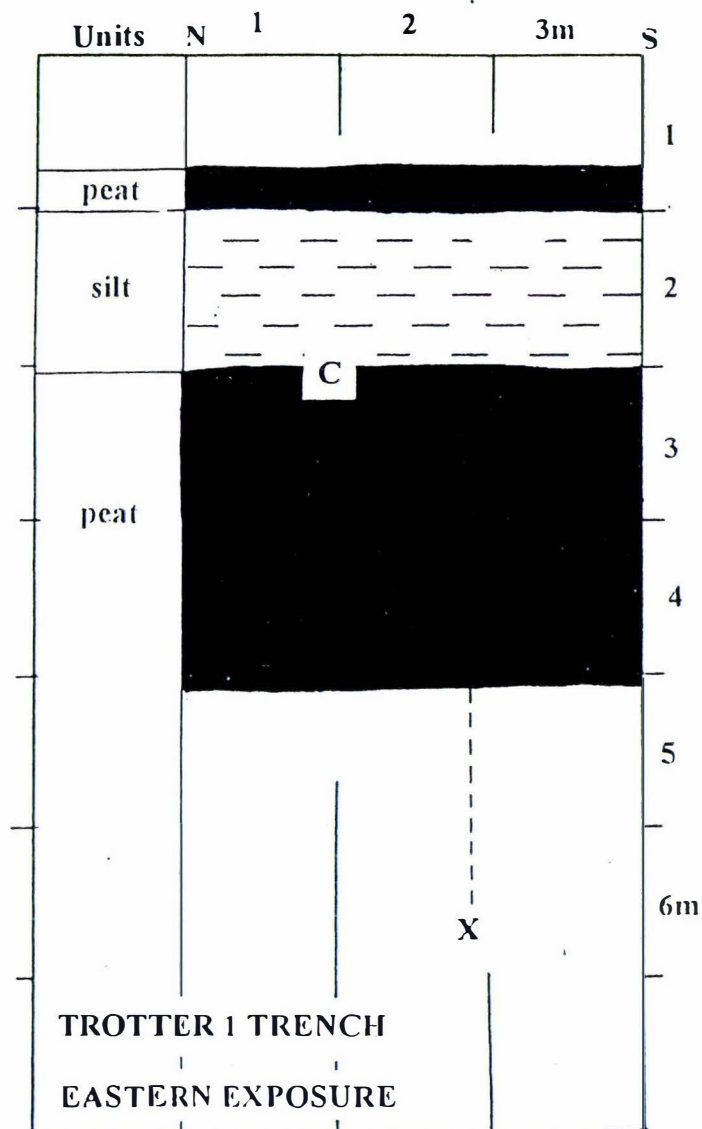


Figure 15. Trotter 1 trench excavated across the Wellington Fault at Fairbrother Road and logged on a scale of 1:20. Oh are Ohakean gravels, fp is the fault plane, sp is a silty gravel unit and pg is a pebbly gravel unit. A B and C are radiocarbon dated sample localities and X is a peat sample locality which was obtained by augering but not dated. All dated samples are wood found within the peat units (coloured black) A (Wk 3145) age 6080 $\pm$ 60 yrs B.P. B (Wk 3144) age 5000 $\pm$ 60 yrs B.P., and C (Wk 3143) age 2090 $\pm$ 50 yrs B.P.

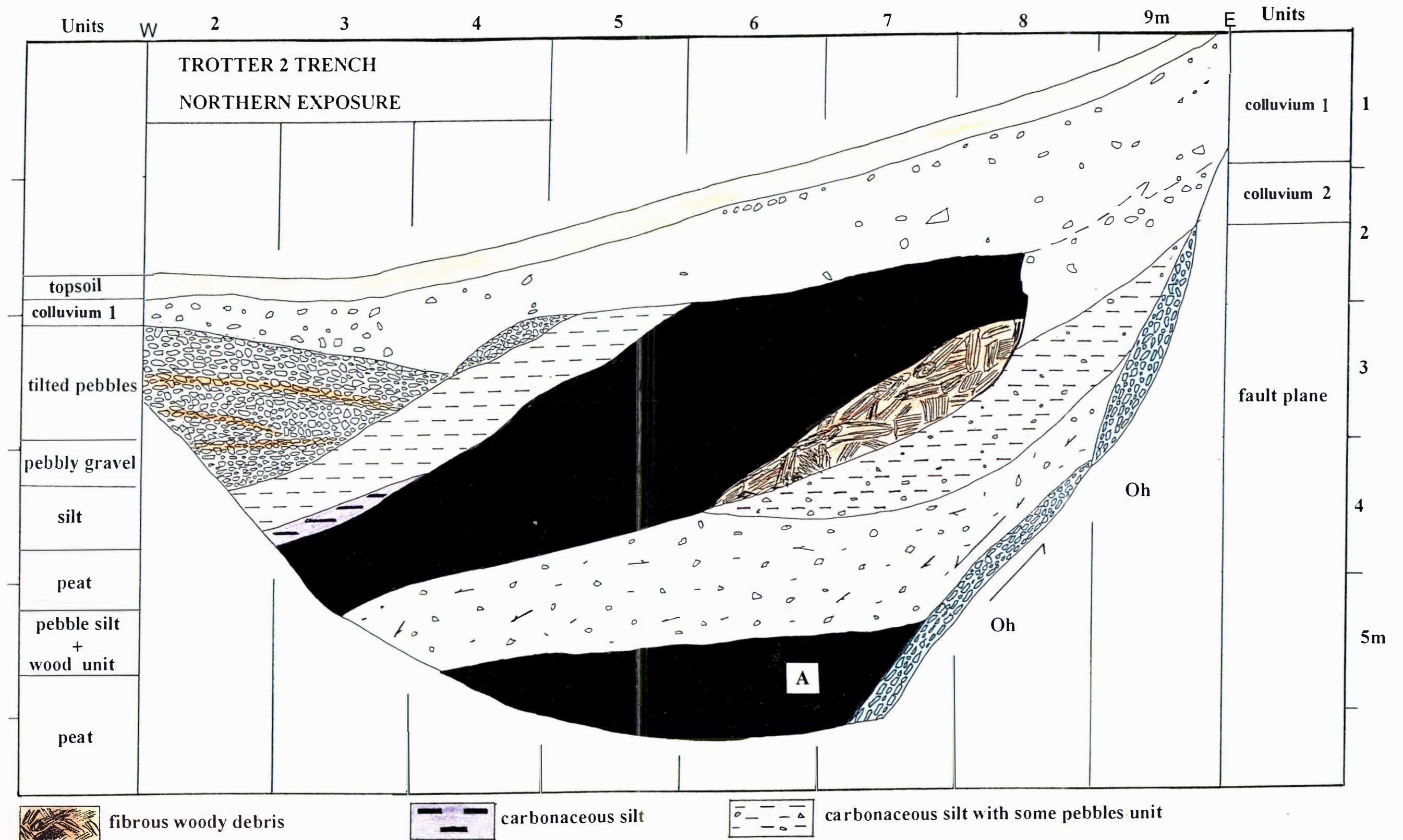


Figure 16. Cross section of the Trotter 2 trench northern exposure excavated across the Wellington Fault at Fairbrother Road, showing younger strata faulted against upthrown Ohakean gravels, logged on a scale of 1:20. Oh are Ohakean gravels, A is the location of a radiocarbon dated sample (Wk 3147) age 6750 +/- 60 yrs B.P.

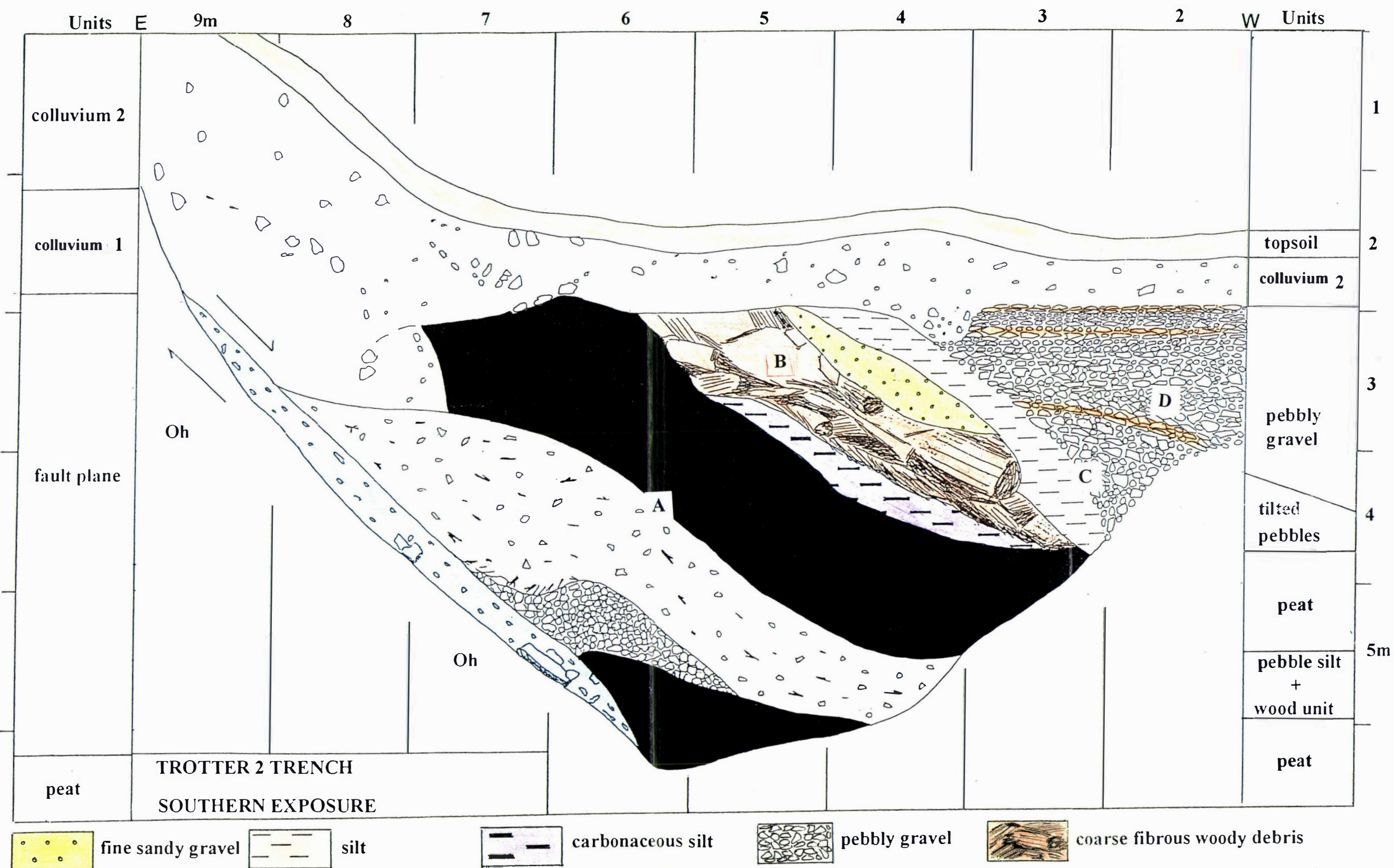


Figure 17. Cross section of the Trotter 2 trench southern exposure excavated across the Wellington Fault at Fairbrother Road, showing younger strata faulted against older Ohakean gravels, logged on a scale of 1:20. Oh are Ohakean gravels. A, B, C and D are radiocarbon dated wood samples, A (Wk 3148) age 3110 $\pm$ 60 yrs B.P., B (Wk 3149) age 2030 $\pm$ 50 yrs B.P., C (Wk 3150) age 960 yrs B.P., and D (NZA 8228) age 257 $\pm$ 44 yrs B.P.

unit of grey silt on top of which a wood sample (Wk3150) was radiocarbon dated at 960 ± 50 yrs B.P. Overlying the grey silt were weakly aligned river gravels consisting of rounded to sub-rounded greywacke pebbles which were clast supported and fairly well sorted. A large tree root from this unit was dated (NZ 8228) at 257 ± 44 yrs B.P. Covering all these units was a layer of colluvium and a thin covering of topsoil.

The lowermost unit of the *northern* trench wall (Figure 16) was composed of woody peat, the same as that seen in the south trench wall and radiocarbon dated (Wk3147) at 6750 ± 60 yrs B.P. Above, was the continuous unit of pebbly, silty gravel with some wood. Overlying this unit were two lenses, the first was composed of carbonaceous silt with some pebbles and the second consisted mostly of wood fragments. On top of these lenses was the continuous peat layer up to 1m thick. Overlying the peat was a unit of carbonaceous silt which lenses out to the east. Above this is the grey silt unit which at the west end of the trench wall is overlain by weakly aligned, rounded river pebbles. The upper unit on the eastern end of the trench consisted of a mixture of pebbly, cobbly and silty colluvium with an overall covering of colluvium and a thin topsoil. The fault plane unit consisted of a narrow zone (0.25m in width) of brecciated gravel and angular to sub-rounded pebbles and cobbles (Plate 29).

Structures indicative of faulting events

The Ohakean gravel terrace surface dips gently away from the fault at 3° toward the east. Holocene sediments forming the west trench wall dip 10° to the west but close to the fault plane are more deformed and the dip changes to 40° at its steepest. This change in dip suggests drag structures where sediments have been dragged upward with the faults dextral movement toward the narrow end of the duplex (Figures 16 and 17, Plates 29 and 30). The upper gravel unit seen in the west end of both north and south trench walls consists of two discrete layers the lowermost of which is tilted. The main fault plane seen in the south trench wall has pebbles and cobbles with their long axes parallel to the fault plane (Plate 29). The main fault plane seen within the north wall of the trench strikes northeast at 041° but the fault plane has a bend, the lower part of the fault plane dips at 44° west while the upper portion of the fault dips at 62° west (Figure 16, Plate 30).

PROPOSED CORRELATED SEQUENCES OF EVENTS FOR TROTTER 1 AND 2 TRENCHES

In correlating these events the assumption has been made that the colluvium units (related to nearby lithologies) were deposited down slope into the trench sites were earthquake-derived erosional events. At the time of these earthquakes the region would have been heavily forested making colluvial deposits less likely to be storm derived from the fault scarp. Other materials such as wood debris and the rounded pebbly river gravels are more likely brought in to the trenched locality via storm events. These latter units are not locally derived but have been transported some distance. However both types of units could have been initially triggered by earthquakes causing landslides upstream which created the sediment that was then transported into the area. The stream that probably transported these materials into the trench area is at present located some 300m south of the Trotter 2 trench site (and 450m south of the Trotter 1 site). This distance from the stream would account for the Trotter 1 trench having fewer clastic sedimentary units and more peat than the Trotter 2 trench. There is another minor stream close to both trench sites but it is fed from a spring on the fault plane.

A summary of integrated events on the Wellington Fault interpreted from the Trotter 1 and 2 trenches is as follows (see Vol 2 map pocket):

- (1) The first recorded earthquake event occurred post the formation of the Ohakean gravels. At this site the gravels contain the sample dated (Wk 3146) at $22,020 \pm 150$ yrs B.P. but the terrace was probably not offset (or the offset was not recorded) until post 10-12,000 yrs B.P. when terrace aggradation in the region ceased (Marden and Neall 1990). As the terrace surface is offset then the earthquake event must be post-aggradation. This event caused the fault-bounded graben to form (Figure 19a).

During an interval between faulting events, woody peat accumulated in both trench areas. This peat accumulated where drainage was blocked by the scarps from the previous earthquake.

- (2) A second earthquake event deposited gravel into Trotter 1 trench on top of a tilted deformed peat unit prior to 6080 ± 60 yrs B.P. based on sample Wk3145 from Trotter 1 trench. As there is no deformation recorded in the Trotter 2 trench which contained the oldest dated peat, radiocarbon dated (Wk 3147) at 6750 ± 60 yrs B.P. it can be assumed that this event occurred c. 6800 and post 10,000 yrs B.P. when terrace aggradation ceased.

An interval occurred where more peat accumulated in both Trotter 1 and 2 trenches followed by deposition of a silty pebbly unit (Trotter 1). It is possible that the deposition of the above units was related to a storm event because deformation could not be directly associated with these units.

- (3) A third earthquake event occurred, and silty colluvium is deposited into the Trotter 1 trench on top of the silty pebbly unit prior to 5000 ± 60 yrs B.P. based on a wood sample (Wk 3144) above the colluvium unit, the pebble unit seen in the south wall of Trotter 2 trench may have been deposited at this time.

This is followed by an interval where a silty unit containing small pebbles and wood fragments was deposited (continuous unit Trotter 2 trench). Above this a lens of carbonaceous silt and some pebbles was deposited and preserved only in the north wall of Trotter 2 trench.

- (4) A fourth earthquake event deposited the lower colluvial unit (colluvium 1, see Figures 16 and 17) into the Trotter 2 trench. Colluvial woody debris is also recorded in the north wall of Trotter 2. The woody debris may have accumulated as a result of an earthquake and accompanying landslides to be later transported downstream by a storm event. There is an earthquake event recorded in the Inglis 3 trench which occurred post-5000 yrs B.P. and pre-3000 yrs B.P. which may correlate to this event.

There then followed an interval where peat accumulates at the sites of both trenches, beginning in Trotter 2 at 3110 ± 60 yrs B.P. This date (sample Wk3148) was obtained from wood located at the base of the peat in the south wall of the Trotter 2 trench. This peat has an average thickness of at

least 1m which under normal conditions would take c. 1000 yrs to accumulate, as seen at the Paper Road site.

- (5) During a fifth earthquake event the peat in the Trotter 1 trench was deformed and dragged 0.80m up to the west (Figure 15). Coarse colluvial woody debris was deposited as seen in the south wall of Trotter 2 an earthquake and/or storm event; the wood from which was dated (Wk3149) at 2030 ± 50 yrs B.P.

There follows an interval, where up to 1m of grey silt was deposited in both trenches post- 2090 ± 50 yrs B.P. based on sample WK3143 which was located at the base of the silt in Trotter 1.

- (6) A sixth earthquake occurs and all the upper units in Trotter 2 were dragged upward and buckled (Figures 16 and 17). This is probably due to a compressional strike-slip event. The event was dated from a wood sample (WK3150) which was located at the top of the tilted grey silt unit and dated at c. 960 ± 50 yrs B.P.

This was followed by an interval where rounded and well sorted river pebbles are washed into the trench in 3 layers during a possible storm event, the upper layer of this gravel was oxidised.

- (7) These gravels were then tilted up to 10° during the seventh earthquake event pre 257 ± 44 yrs B.P.

More weakly aligned, horizontally bedded gravels were then deposited into the trench (Trotter 2) during a storm event, the upper layer of this unit was oxidised. A wood sample from within these gravels was radiocarbon dated (Wk 8228) at 257 ± 44 yrs B.P. The older sediments in the Trotter 2 trench (Figures 16 and 17) and especially the 1m-thick upper peat unit show some evidence of periodic erosion where the tops of the beds have been truncated. This erosional event would have destroyed any ruptures created during the 7th earthquake event.

- (8) An eighth earthquake event causes colluvium to fall into the sites of both Trotter 1 and 2 trenches, post 257 ± 44 yrs B.P. burying the peat units.

Following this last faulting event a thin (0.20m) top soil developed over the Trotter 2 trench site, while more peat accumulated over the Trotter 1 trench site.

WELLINGTON FAULT STRUCTURE IN THE TROTTER FARM AREA

Between Loveday Road and Fairbrother Road the Wellington Fault forms a duplex which appears to be a complex horst and graben system (Figure 18). From Loveday Road north across Raparapawai Stream, the central area between the east and west limbs of the fault appears to be upthrown. However no right step in the fault was observed at this locality to create a compressional bulge. It is possible for duplexes to form on straight sections of faults. Sometimes duplexes formed at bends are subsequently shunted by faulting activity onto straight sections. These duplexes commonly have both contractional and extensional features (Woodcock and Fischer 1986) somewhat similar to the Kahuki horst and graben system described by Marden (1984). Farther north at Fairbrother Road the central area between the fault limbs is downthrown. Where the fault crosses Fairbrother Road it steps to the right forming a compressional bulge to the east of the road.

The overall horizontal offset rate for the Fairbrother Road area is estimated to be approximately 10mm /yr. This rate is measured from a 100m dogleg in a stream which had cut down through an Ohakean gravel terrace (Plate 28) and been subsequently diverted from its original course by faulting (Figures 18 and 19). This offset rate is based on the date of $22,020 \pm 150$ yrs B.P. from the Trotter 2 trench which demonstrates the terrace is of Ohakean age. The upper terrace surface is therefore no older than 12,000 yrs B.P. and here is assumed to be 10,000 yrs B.P. of age (Marden 1984).

The total vertical offset comes from the Trotter 1 trench where the Ohakean terrace surface is upthrown to the west 5.15m above the swamp surface. Added to this is the thickness of the sediments (5.9m) within the trench on the downthrown side of the fault. As the Ohakean gravel surface was not

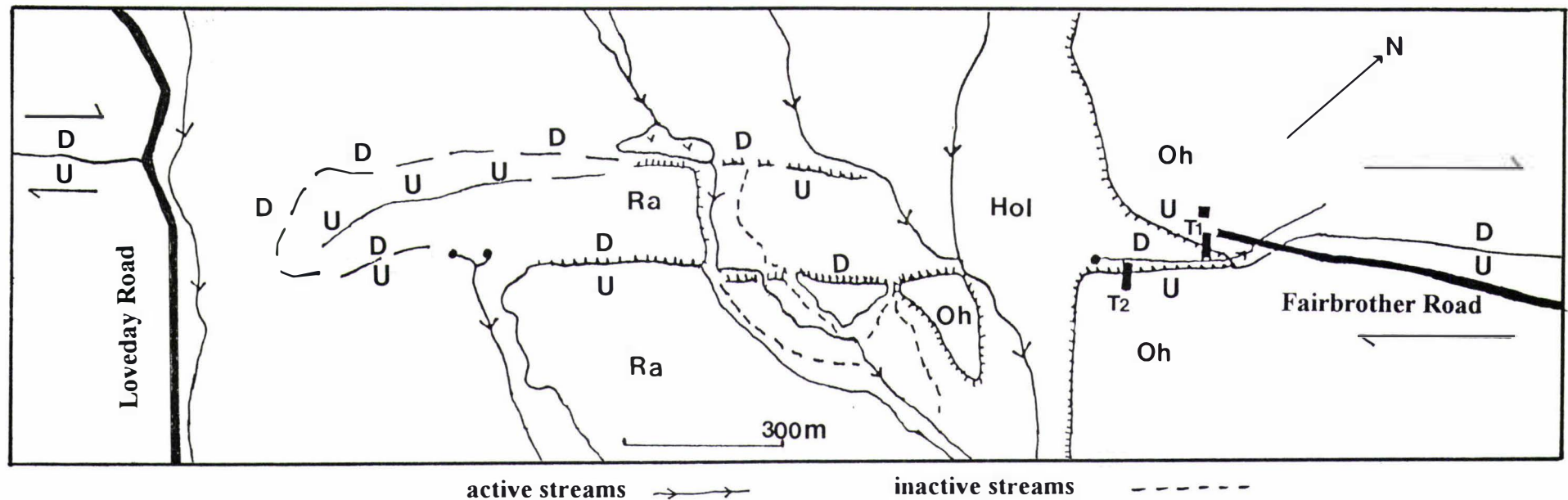
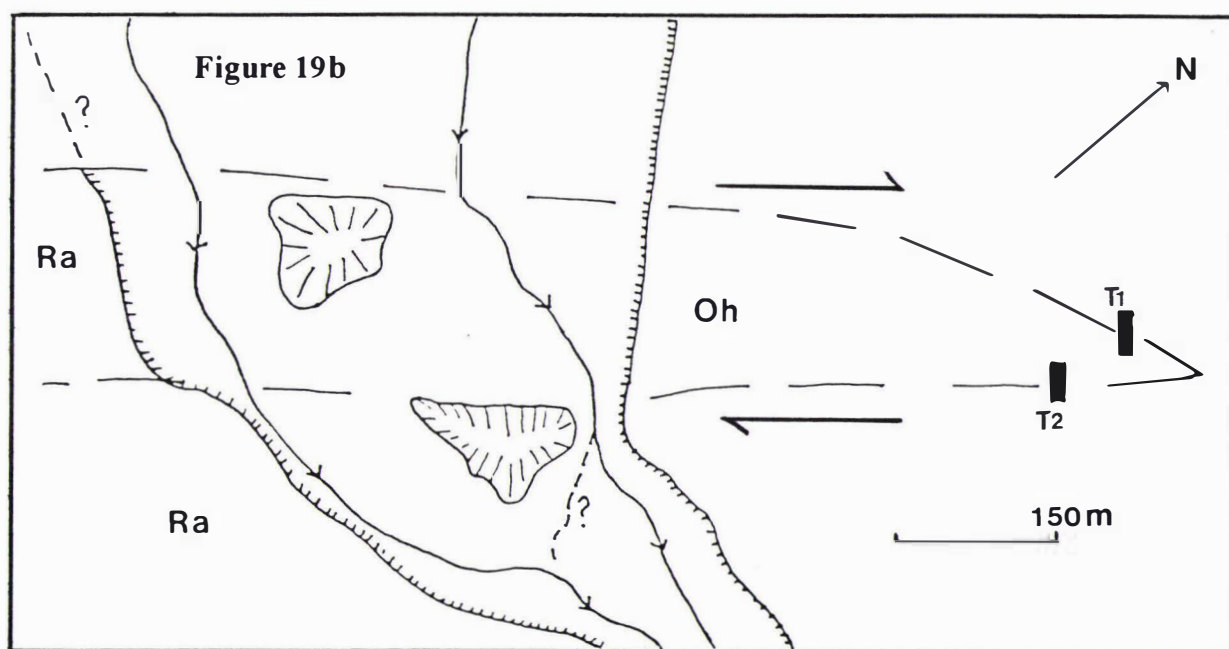
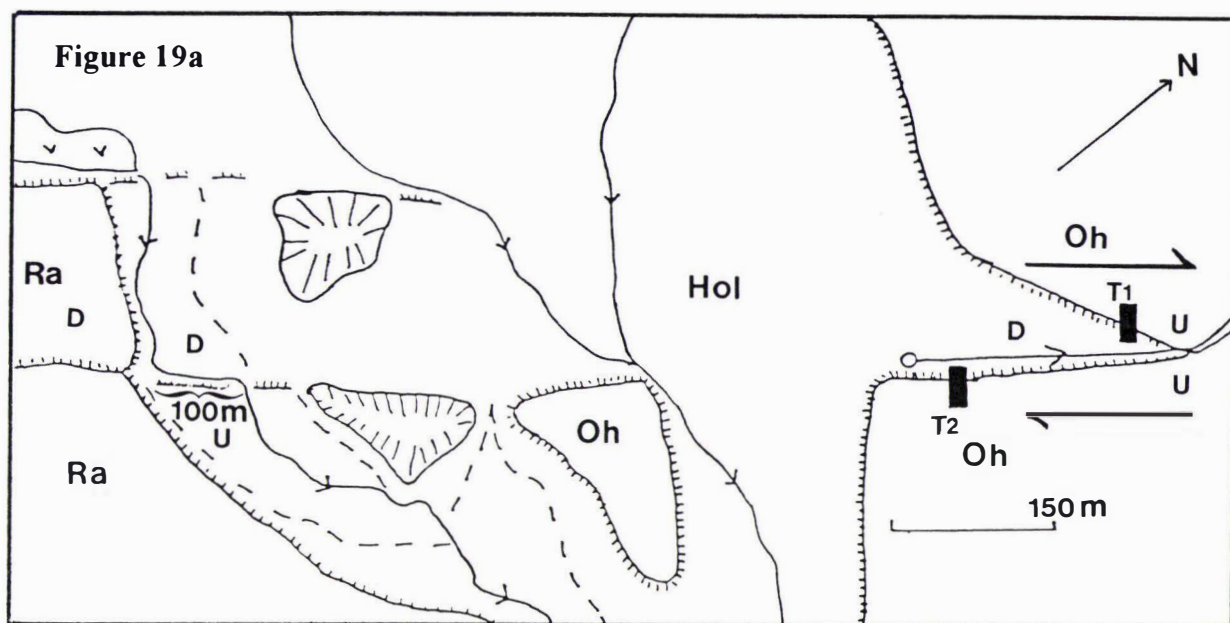


Figure 18. Map of the Duplex on the Wellington Fault between Loveday and Fairbrother Roads showing the upthrown southern section and the downthrown northern section where the trenches were excavated. T1 and T2 are the trench localities U are upthrown areas and D are downthrown areas. Ra are Ratan terraces aged 30,000 to 40,000 yrs B.P., Oh are Ohakean terraces aged 10,000 to 25,000 yrs B.P., and Hol are Holocene terraces less than 10,000 yrs B.P., (Marden 1984).



scarp  active streams  inactive streams 

Figure 19a. Northern segment of the duplex on the Wellington Fault between Loveday and Fairbrother Roads. Ra is a Ratan Terrace, Oh is an Ohakean Terrace, Hol is a Holocene terrace and T1 and T2 are the Trotter trench sites. The offset stream is in a Holocene Terrace less than 10,000 yrs in age making a horizontal offset rate for this section of the fault of 10 mm/yr.

Figure 19b. Cartoon representation of how the northern segment of the duplex might have appeared less than 10,000 yrs B P., before the offset occurred and after the streams had cut down through the Ohakean terrace.

found on the downthrown side, a minimum vertical offset rate for this area was estimated at 1.14mm/yr.

The Wellington Fault is upthrown to the east along the western end of Fairbrother Road, which runs parallel to the fault scarp. At this locality the fault scarp is steep (30° to 40°) and almost blocks the valley to the west of the scarp. North of the Oruakeretaki Stream, upthrow is continuous to the east. This trend alters again at Bakers Road only 1km to the north where a Porewan-aged hill (Marden 1984) is upthrown to the west and offset horizontally 150m. Some 500m north of the Porewan hill, Pleistocene sediments with a 0.20m-thick layer of ash to the west of the fault dip 10° to 15° toward the fault. Dips of other Tertiary and Quaternary marine sediments in the area are difficult to determine due to a lack of outcrops. On the south side of Kumeti Road the fault crosses an unstable greywacke slope bearing 030° . From Kumeti Road north, uplift is mainly to the west and Tertiary and Quaternary sediments are faulted against greywacke. From Otamaraho Stream, less than 2km north of Kumeti Road, the Wellington Fault then strikes through forested greywacke terrane.

SUMMARY OF PALEOSEISMIC DATA FOR THE WELLINGTON FAULT BETWEEN THE MANAWATU GORGE AND KUMETI ROAD

Trenching studies of the Manawatu Gorge to Kumeti Road segment of the Wellington Fault show a history of over 29,000 years of faulting activity. Most of the evidence for these faulting events is based on deformation seen within the trenches. Some of these events are inferred from colluvium presumed to have fallen into the trench during faulting activity. Most of this colluvium derives locally from nearby fault scarps. Colluvial deposition is considered a moderately rare event in dense podocarp forest which covered this area prior to European settlement (Blakely 1981). The major periods of storm-induced erosion seen within New Zealand in the last 1800 yrs are 1764 yrs B.P., 1,500 to 1600 yrs B.P., 1300 to 1900 yrs B.P., 600 to 680 yrs B.P., 330 to 450 yrs B.P., and 150 to 180 yrs B.P., (Grant 1985). There are no earthquake events in this study based on colluvial deposits that fall within the above time periods. However these erosional

events do not extend back very far in time (< 2000 yrs). Farther back there are major erosional events that took place in the West Tamaki catchment of the Ruahine Range (Hubbard and Neall 1980) have been dated at 20,500 yrs B.P., 12,150 yrs B.P. and >770 or c. 770 yrs B.P. It is possible that these erosional events were initiated by earthquake activity on the Wellington Fault which traverses this catchment.

Table 1, Summary of paleoseismic events for the Wellington Fault between the Manawatu Gorge and Kumeti Road. EQ is a deformation event seen in a trench that was not datable, other events are dated either post or pre the event in yrs B.P. There are 12, interpreted earthquake events over the period since 29,000 years B.P.

No. EQ Events	Inglis 3 trench	Inglis 4 trench	Beagley trench	Trotter 1 trench	Trotter 2 trench
12	c. 211	EQ	c. 290	post 257	post 257
11	EQ	EQ			pre 257
10	EQ	post 1105			c. 960
9				pre 2090	post 3110
8	post 4335				EQ
7			post 5324	pre 5000	EQ
6				pre 6750	pre 6080
5	pre 9434	post 10,286			
4					post 22,020
3		pre 29,200			
2		EQ			
1		EQ			

Vertical offset rates given by other workers for the Wellington Fault and the Southern Ruahine Range are similar of those for this study. Vertical offsets from Ballantrae (Marden and Neall 1990) are in the range of 1.23 to 0.76mm/yr, vertical offsets recorded for Ingles and Trotter Farms are similar (Table 2). The estimate by Beu et al. (1981) of 1.3mm/yr for the overall uplift rate of the Ruahine Range makes for a general consensus of opinion.

Table 2, Vertical offset rates seen along the trace of the Wellington Fault between the Manawatu Gorge and Kumeti Road.

Inglis' Farm	Trotter Farm
0.76 to 1.23mm/yr	0.66 to 1.2mm/yr

Table 3, Maximum horizontal offset rates measured on surface features with dates from nearby trenches along the Wellington Fault trace between the Manawatu Gorge and Kumeti Road.

Inglis' Farm	Beagley Farm	Paper Road	Trotter Farm
13 to 15mm/yr	10.61mm/yr	14.31mm/yr	10mm/yr

Horizontal offset rates measured by other workers for the more southern segments of the Wellington Fault are much lower. These rates range from 4 to 7.6mm/yr (Berryman 1990 Van Dissen et al. 1992,, and Grapes 1993). In contrast Beu (1995) proposes a total horizontal offset for the Wellington Fault of 40km over 2.5ma which amounts to an average of 16mm/yr.

CHAPTER 4

THE WELLINGTON FAULT FROM KUMETI ROAD TO THE NGARURORO RIVER

From just north of Kumeti Road through to the Waipawa River the Wellington Fault passes mainly through unfossiliferous basement greywacke thought to be of Jurassic age (Kingma, 1958). Basement greywacke in the southern Ruahine Range has been subdivided into 3 north-east trending belts of different lithologies (Sporli, Bell, 1976 and Marden 1984). The Wellington Fault lies within the Kashmir Belt (Sporli and Bell, 1976) which consists of alternating sandstone and argillite beds from 0.10 to 0.50m thick. Thicker ridge-forming sandstone beds are found east of the fault in the West Tamaki, Mangatewainui, Makaretu and Tukituki River catchments. Bedding units within the Kashmir belt in the above areas, strike parallel or sub-parallel to the fault.

The Wellington Fault trace is seen as a break in slope along the heavily bushed eastward-facing slopes of the west Tamaki catchment area. In this area the only deformation which can be directly related to the fault is a 50 to 100m-wide zone of crushed greywacke along the fault trace. Within this crush zone remnant bedding parallel to the fault can still be found in places. The fault trace appears prominently on aerial photographs especially where it crosses the Apiti Saddle. There are dextral offsets of 80 to 100m on small streams just south of the Saddle. In the field, offset ridges are well defined with uplift being toward the northwest (Plate 30a). From the Saddle northward the trace is less clear where it follows and crosses the upper reaches of the Makaretu River. Parallel to the northern branch of the Makaretu River and to the west of the Wellington Fault trace is another linear feature seen on aerial photographs. This feature (on the aerial photographs) appears to be a fault with the opposite sense of shear to that of the Wellington Fault. It was not possible to establish the nature or shear sense of this feature in the field due to heavily regenerating bush

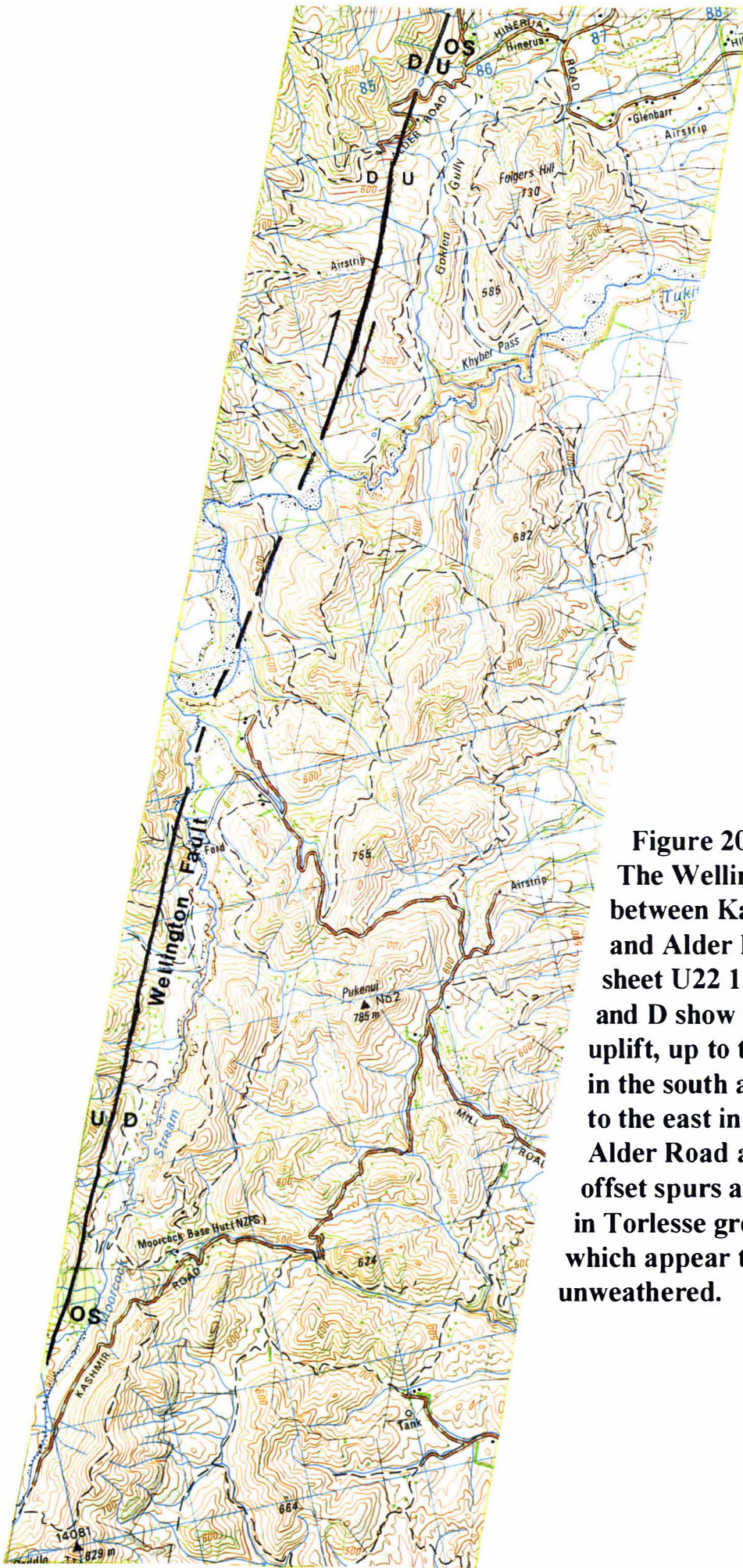


Figure 20.
The Wellington Fault
between Kashmir Road
and Alder Road, (NZMS
sheet U22 1:50 000. U
and D show the latest
uplift, up to the west
in the south and up
to the east in the
Alder Road area. OS are
offset spurs and ridges
in Torlesse greywacke
which appear to be largely
unweathered.

the region. It is likely however, that this lineation is the boundary between in the Kashmir Belt and the Pohangina Melange Belt and not related to today's tectonic regime (Sporli and Bell 1976, Marden 1984). Where the Wellington Fault crosses the Moorcock Saddle there are a series of springs along and parallel to the fault trace with no appreciable vertical offset. The fault trace can be then followed along the westward side of Moorcock Stream (Figure 20) where there is a series of classical dextrally offset shutter ridges and spurs. The ridges and fault are prominent on aerial photographs and have well defined edges that have been resistant to heavy erosion suggestive of their youthful nature. These offsets have changed some local drainage patterns resulting in swampy patches behind the ridges. Horizontal offset on one of these shutter ridges was measured at 100m (Plate 31) with uplift toward the northwest. The free face of the fault footwall dips at 60° to the west. At the end of Mill Road there are spectacular exposures in the greywacke close to the fault. These exposures as described in Sporli and Bell (1976) are the result of ductile deformation and were not thought by Sporli and Bell to be related to deformation on the present day Wellington Fault which is brittle. The fault trace lies less than 100m to the east of these outcrops but its exact locality is unclear due to erosional features in the greywacke caused by faulting and flooding from the nearby Moorcock Stream (there may be a dual trace at this locality).

North of the Tukituki River at Alder Road the most recent uplift is to the east, the height of the fault scarps is variable and may represent only a few faulting episodes. On the Oakley property at the head of Alder Road (Figure 20) a small scarp parallel to the fault trench has been upthrown to the east between 2 and 4m. The fault trace (bearing 034°) appears clear, straight and distinct in this area. Offset shutter ridges are very noticeable especially when seen from a distance and like those parallel to Moorcock Stream are well defined. Dextrally offset ridges were measured at 60 and 100m, the smaller offset probably representing a younger geomorphic landform.

From Alder Road northward the Wellington Fault passes through the Ohara Depression which is a region of low relief between the Ruahine and

Wakarara Ranges. The Ruahine Fault forms the western boundary of the Depression adjacent to the Ruahine Range. The Wakarara Range is an upthrown block of Mesozoic greywacke bounded to the east by the Wakarara Thrust Fault and to the west by the Wellington Fault (Figure 2). Between the Wellington and Ruahine Faults the Ohara Depression is formed of a thick sequence of Miocene to Pleistocene sediments. These consist of marine mudstone, sandstone and limestone, which are overlain by terrestrial greywacke conglomerates and pumiceous units (Raub, et al., 1987). Sediments in the southern part of the Depression dip to the east and southeast at 15° to 35° . However close to the Wellington Fault (east of the fault) the Kereru Limestone has been folded into a syncline sub-parallel to the fault trace. At Wakarara the Wellington Fault trace is more eroded with scarps having a more rounded appearance, here there is a 500m-wide compressional left step in the fault trace (Figures 2 and 21). The sediments between the sidestep have also been folded on a small scale into a syncline, anticline and another syncline (Raub, 1985) all of which lie subparallel to the fault trace. Raub's map of the area also shows a 4km horizontal offset in the basement greywacke on the fault trace at the southern end of the Waipawa Reentrant. The Reentrant is a structural feature, described by Raub (1985) as a broad, asymmetric, south-plunging synclinal warp affecting the Pliocene unconformity and overlying strata. A northwest-trending fault (Mangaraura Fault) has been postulated to account for the synclinal warp forming the Waipawa Reentrant. But this postulated fault is visible only as a surface lineament having no discernible offset, however offset has been identified on seismic reflection data (Leslie and Hollingsworth 1972).

Farther north, the Wellington Fault trace bears 036° crossing an old gravel terrace surface on Gull Road. Harvey Boyden, a farmer in the area, reports that since 1960 he has twice repaired a galvanised pipe which crosses the fault scarp. This pipe supplies his son's house with water. It crosses the fault scarp at a 90° angle and had been pulled apart "due to stretching across the fault plane" (Plates 32 and 33). The house is located on the eastward upthrown side of the fault trace (Figure 22). There is no evidence of slumping or settling across the fault scarp which is well defined and planted with mature pines. The scarp has a free face that dips

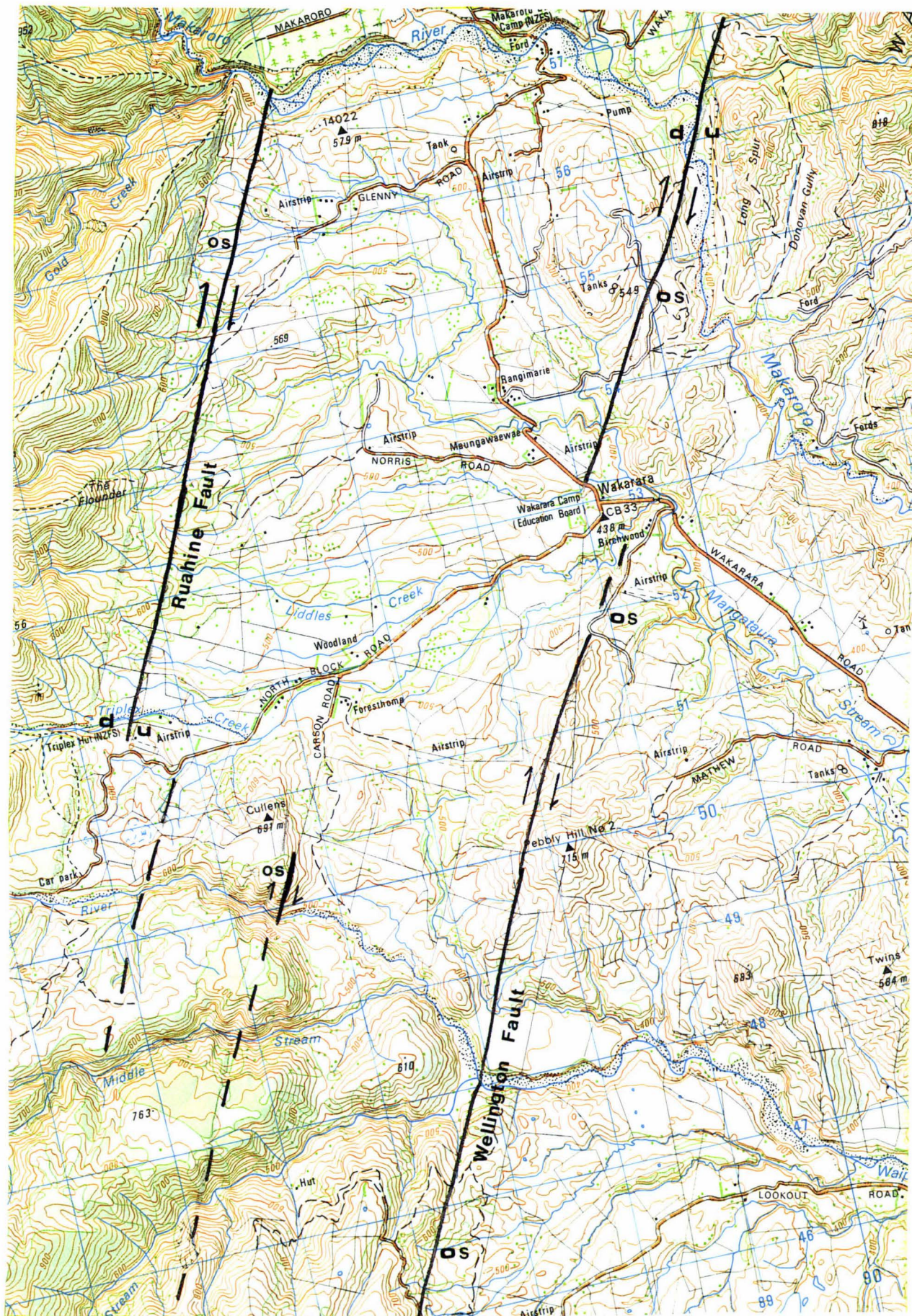


Figure 21. The southern section of the Ohara Depression showing the localities of the Ruahine and Wellington Faults (NZMA, U22 1:50 000) OS are sites with horizontal offset and u d are sites with vertical offset.

between 35° and 40° to the west. Fences in the area have not been affected but these are more flexible fixtures which stretch with age. Such reports may indicate that a small amount creep is occurring both vertically and horizontally on this section of the Wellington Fault.

At the north end of the Ohara Depression the Big Hill Fault diverges in a north-westerly direction from the Wellington Fault (Figure 2). These two faults bound another upthrown block of basement greywacke. Deformation in this area lies parallel to the Big Hill Fault and occurs in the Tertiary sediments of the Depression on the northern side of the fault. This deformation is contained within the Herricks syncline and anticline plus the Thorn Flat thrust fault (Erdman and Kelsey 1992, Figure 2). Other sediments in the area dip to the east and southeast between 12° and 22° . The Wakarara Monocline can be located less than 1km east of the Wellington Fault and 3km north of the Big Hill-Wellington Fault junction (Figure 2). The Wakarara Monocline (Figure 2) is an east-west compressional structure trending north to northeast on the east side of the Wakarara Range. The monocline is divided into two structural levels the lower level is comprised of a reverse fault (uplifting the east side of the Wakarara Range) but to the north and south of the range the upper level forms a syncline characterised by a tight, steep monoclinal flexure (Raub 1985).

TRENCHING ON MC COOL FARM

From Big Hill Road to the Ngaruroro River the Wellington Fault trace can be seen clearly on aerial photographs. The fault is the boundary between the upthrown Big Hill greywacke basement to the west and downthrown Tertiary sediments to the east. Aerial photographs show tectonic and geomorphic landforms represented by ponded drainage, offset spurs and streams with the latest episodes of vertical faulting being up to the east. Tertiary sediments except where they lie vertical to sub-vertical close to the fault trace dip generally eastward between 15° and 35° . On McCool

farm at the end of Nelson Road three trenches were excavated across or close to the Wellington Fault trace.

MC COOL 1 TRENCH

This trench was 16m long and up to 6.6m deep. It was excavated perpendicular across the fault trace through a blocked drainage site U21/010746 (Figure 22, Plate 36). The trench walls were cleaned and marked with a 1m string grid and logged and at a scale of 1:20 (Vol 2 map pocket).

Stratigraphy

The base of the trench on the downthrown side of the fault consisted of a cobbly and pebbly gravel which was mainly clast supported; the matrix was composed of a silty coarse sand. These are interpreted as Ohakean gravels and are dated from the overlying unit. Overlying the gravel unit was a dark-brown carbonaceous silt which contained wood fragments one of which was radiocarbon dated (NZ8287) at $14,082 \pm 156$ yrs B.P. This carbonaceous silt unit thinned and wedged out to the west. Above the carbonaceous silt was a silty sandy colluvial unit which was either blue-grey at the trench base or brown-grey toward the trench surface depending on oxidation level. Contained within this unit (from the base to the top) is a layer of cobbly gravel (dated NZ8288 at 5206 ± 81 yrs B.P.). Above this is a thin layer of peat dated (NZ8289) at 4295 ± 56 yrs B.P. Higher up in the colluvial unit is one dispersed tephra, two distinct tephras, patches of peat (thought to be dislocated) and two more tephras (Figures 23 and 24). The upper-most tephra layer is thought to be from the 1850 yrs B.P. Taupo eruption the one below almost certainly Waimihia Lapilli (Froggatt and Lowe 1990, Appendix 2) due to the ages of the sediments above and below these units. The above tephras are overlain by peat dated (NZ8291) at 605 ± 35 yrs B.P. This unit contained a thin layer of fine sandy gravel and a layer of angular pebbles. The angular pebble layer was only found within the north trench wall. The upthrown side of

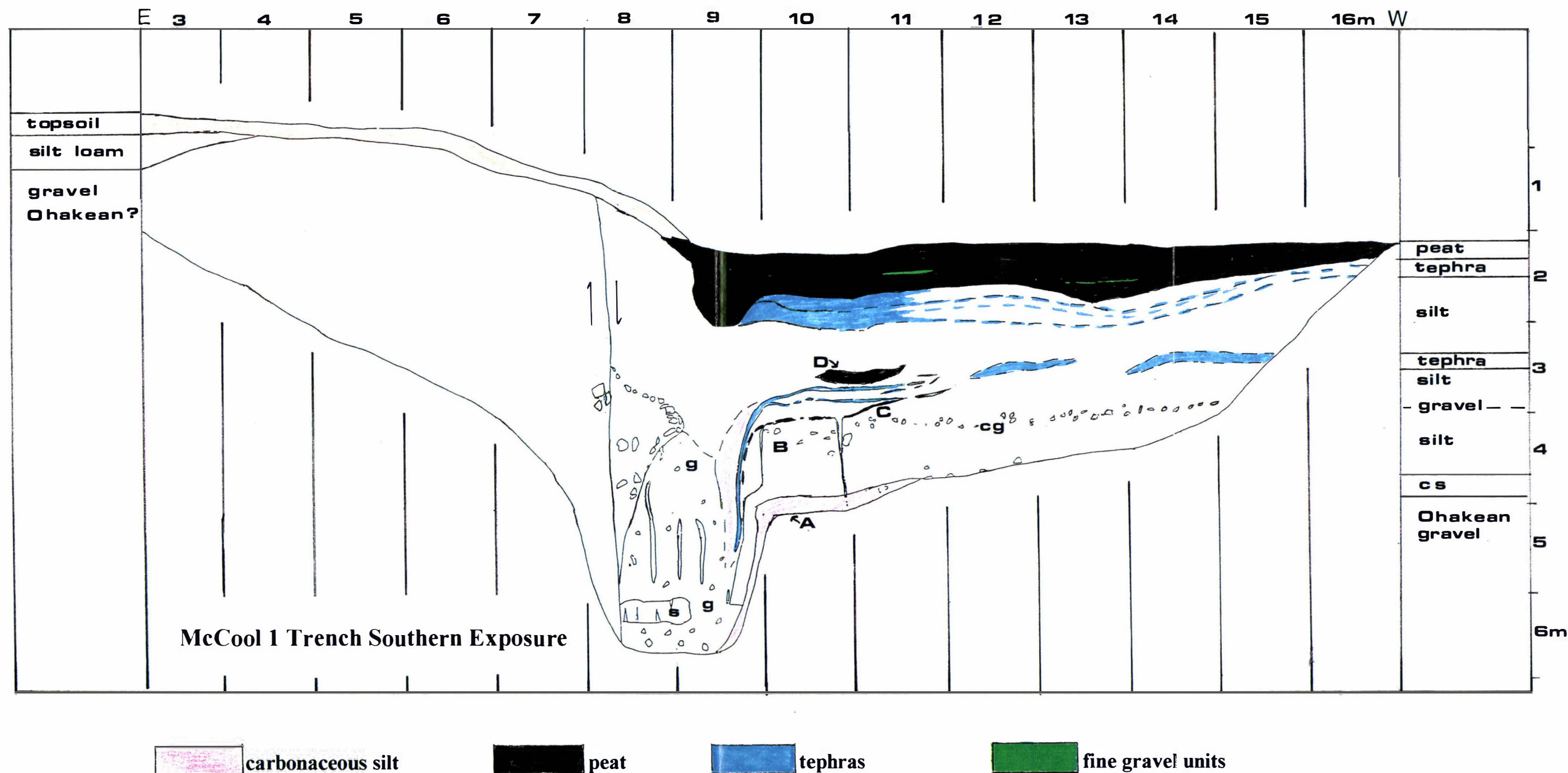


Figure 24. Cross section of McCool 1 trench (southern exposure) excavated across the Wellington Fault at Big Hill, showing stratigraphic units and their ages. A is the locality of a radiocarbon dated wood sample age (NZ8287) 14 082 +/- 156 yrs B P. B is the locality of a radiocarbon dated peat sample age (NZ8288) 5206 +/- 81 yrs B.P. C is the locality of a radiocarbon dated wood sample age (NZ8289) 4295 +/- 56 yrs B.P. D is the locality of a radiocarbon dated peat sample age (NZ8290) 6561 +/- 79 yrs B.P. This peat unit is thought to have been displaced during faulting activity, cg is a dispersed cobbly gravel, g is fault gauge consisting of silty clay with pebbles, s is a displaced silt block and cs is a carbonaceous silt unit.

the fault consisted of a cobbly pebbly gravel, mainly clast supported with a coarse sandy matrix. This may be the same Ohakean gravel unit as that at the base of the trench on the downthrown side.

Structures indicative of faulting events

The fault plane within the excavated trench strikes 020° and was vertical. Tephras between the 9 and 10m interval (south trench wall, Figure 24) are dragged downward 1.6m (Plate 35) while the same tephras at 9 and 10m (north trench wall, Figure 23) are only disrupted (Plate 34). Above these tephras and close to the fault plane ($020^{\circ}/v$) are lenses of peat (north trench wall) dated (NZ8290) at 6561 ± 156 yrs B.P. These units are older than the fragments of wood found in the peat layers below and are thought to have been dislocated upwards and sideways during faulting activity. The peat lenses are more likely to have been displaced because they are isolated units, whereas the younger peat below is a distinct layer stretched and thinned by faulting activity. Other displaced blocks within this trench are found at the base of the south trench wall between the 7 and 9m vertical intervals and in the north trench wall between the 10 and 11m vertical marks. They are probably derived from the carbonaceous silt unit above the Ohakean gravel at 4.5m depth within the trench. There are no tephras found on the upthrown side of the fault.

MC COOL 2 TRENCH

This trench was situated east of the Wellington Fault. It was 16m long and less than 2m deep and was logged at a scale of 1:40 (Vol 2 map pocket). The trench was excavated through the youngest of three paleo-overflow channels. These channels previously drained from a lake which formed along the fault trace in response to successive earthquake events where uplift to the east blocked drainage (Plate 38). The oldest paleo-channel is dextrally displaced a total of 66m from today's overflow channel.

Stratigraphy

This trench was excavated through recent sediments overlying the east-to-southeast-dipping Tertiary Limestone. The lowermost unit consisted of a pebbly and cobbly (greywacke) gravel which was mainly clast supported with a matrix of coarse sand. The south wall of the trench was composed of a thick pan developed within loess or loess soil colluvium which had been cut through by the, then active overflow channel. This unit contained some poorly preserved carbonaceous material which was not submitted for dating. Above the pebbly cobbly gravel unit and abutting the pan were colluvial sediments deposited by the overflow stream. These consisted of silty oxidised greywacke gravels (of pebble and cobble size). On top of these above units was a silty loamy paleosol containing some wood fragments. It was thought that this was a post-European soil because there were orange burn marks within the soil. Covering these units was the present topsoil which was 0.2m thick.

This trench was excavated in the hope that material conclusive for dating the horizontal offset of the paleo-channels might be provided unfortunately no such material was found.

MC COOL 3 TRENCH

This trench was 13m long and up to 4m deep. The sides were cleaned and logged at a scale of 1:20 (Vol 2 map pocket). The trench was excavated through a swampy area across the fault trace (Plate 37). However the main fault plane appears to be farther to the east within the upthrown hill which could not be practically excavated. As the eastern end of the south trench wall was destroyed by slumping only 8m of the southeast wall was logged. Although there was swamp and peat on the surface of this trench site the sediments below were remarkably dry and oxidised, it contained no datable material.

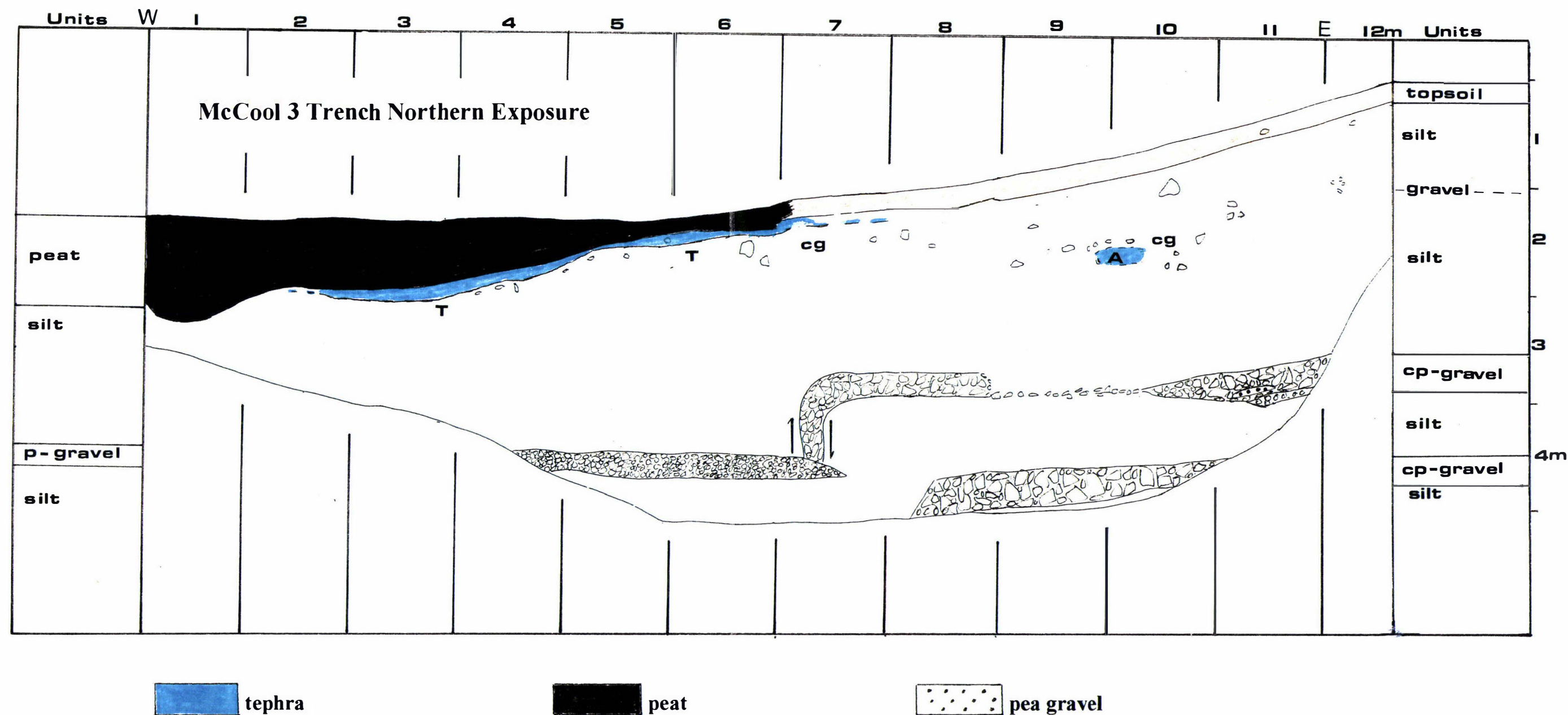


Figure 25. Cross section of McCool 3 trench (northern exposure) excavated across the Wellington Fault at Big Hill, showing stratigraphic and deformed units. A is an andesite tephra and T is thought to be Taupo tephra dated at 1850 $\pm$ 10 yrs B.P. (Froggatt and Lowe 1990), cg are dispersed cobbly gravels, p-g is a pebbly gravel unit and c-p gravel is a cobbly pebbly gravel.

Stratigraphy

The base of the trench on the downthrown (westward) side of the secondary fault consisted of a grey-brown sandy silt. On the upthrown side of the trench was an angular greywacke gravel consisting of cobbles and pebbles with a coarse sand matrix. Above both of these units was a pan developed with silty sandy colluvium with layers and lenses of gravel. What was thought to be Taupo Tephra from the 1850 yrs B.P. eruption (Appendix 2) was found at the base of the peat unit on the downthrown side of the fault only.

Structures indicative of faulting events

The fault plane is not apparent in the upper part of this trench (Figure 25) possibly due to the main fault plane at this locality not being excavated. However a fault was found at the base of the trench approximately 0.5m wide. Which may be a subsidiary to the main fault plane because no major unit dislocation either vertical or horizontal could not be determined. The north trench wall (Figure 25) has a horizontal gravel unit that is bent vertically (0.5m, Plate 39) downward parallel to the fault. The south trench wall shows thrusting of one gravel unit above another (see map pocket Vol 2).

PROPOSED SEQUENCE OF EVENTS FOR MC COOL FARM

The following series of events is established from the stratigraphy in the McCool 1 trench and confirmed in part by the features seen in McCool 3 trench.

- (1) Initiation of uplift to the east. A minimum age (14,082 yrs B.P.) for this first earthquake was given by the carbonaceous silt unit overlying the offset gravels found at the base of the trench (Figure 24).

A time interval in which a brown carbonaceous silt unit with wood dated (NZ8287) at $14,082 \pm 156$ yrs B.P. accumulated after which the lower grey/brown sandy silty loam units were deposited.

(2) A second earthquake event is recorded by the carbonaceous silt unit being deformed, blocks of this material fall into the fault graben. Angular greywacke cobbles also fall into the trench during this event. The event is dated between (NZ8288) 5206 ± 81 yrs B.P. (maximum) and (NZ8289) 4295 ± 56 yrs B.P. (minimum) by samples found above and below the cobbly gravel unit.

A time interval follows where more carbonaceous silt, peat and blue/grey sandy silty loam accumulates in the trench. Two tephra layers identified only, as being of Taupo origin (Cronin pers comm.) are also deposited in the trench at this time.

- (3) A third earthquake event is recorded by all the above units being deformed this event occurred post-deposition of the above tephtras. This event occurred post 4295 ± 56 yrs B.P. dated from the wood sample obtained below these units. In the south trench wall (Figure 24) tephtras have been dragged downward, and the north trench wall (Figure 23) abruptly terminated against the fault.

Another time interval ensues with additional brown/grey sandy silty loam being deposited into the trench. This unit appears to have the same composition as the blue/grey sandy silt loam below, only it is more oxidised. The Waimihia Tephra, brown grey sandy silty loam and Taupo Tephra are then deposited.

- (4) A fourth earthquake event is recorded by the Waimihia and Taupo tephtras being displaced and wood sample (NZ8293) dated at 805 ± 58 yrs B.P. is folded (Figure 23, locality E) between the sandy silty loam and the gravel unit, due to offset both vertical and horizontal, drainage from this area was partially blocked at this time.

An interval occurs where peat accumulates over all downthrown units.

- (5) A fifth earthquake or storm event deposits a fine sandy gravel into the trench. There may be a small amount of deformation associated with this unit seen on the north trench wall where the fine sandy gravel is dragged down to the east; this could also be a depositional feature. This event post dates a sample of the underlying peat dated (NZ8291) at 605 ± 35 yrs B.P.

Another interval follows with more peat accumulation.

- (6) A sixth earthquake or more likely a storm event is recorded where angular greywacke pebbles are deposited into the fault trench. This unit is seen within the north trench wall only and there is no deformation associated with this event.

A further interval of time is recorded to the present with more peat accumulation.

Other features in the adjoining area along the fault includes offset streams, spurs and upright bedding. A short distance south of McCool 1 trench a streamlet has been offset by 53m. To the north of the trench site there are offset spurs but the fault trace has been destroyed in places by a road on the Big Hill Station. Between two ponded drainage sites an auger hole was bored into the fault trace. The surface peat was only 0.2m thick. Below this to the base of the hole at 1.6m was a sandy clayey fault gouge.

Close to McCool 1 trench Tertiary bedding appears to be vertical close to the fault trace. Tertiary bedding close to the fault on the south bank of the Ngaruroro River is tilted at 70° to the east. These bedding planes are not obvious close to the fault where they are highly fractured and jointed. It is possible that the northern end Wakarara Monocline merges with the Wellington Fault at these localities; 50m south of McCool 1 trench and on the south bank of the Ngaruroro River (Figure 2).

DISCUSSION AND PROPOSED OFFSET RATES FOR THE OHARA DEPRESSION

North of the trench sites and south of the Ngaruroro River a natural lake has been formed on the fault trace due to eastward uplift (Plate 35). This lake can be seen on aerial photographs and has three paleo-overflow channels (the McCool 2 trench was excavated through the youngest paleo-channel). These channels and the present active channel are cut through the Tertiary and Quaternary upthrown sediments on the east side of the fault trace. The distance between the two older paleo-channels is 32m and the distance from the younger of these two channels to the active channel is 34m. This makes a total of 66m of dextral offset. The rate of horizontal offset at McCool farm can be found by using distance/time relationships established from this work. The earliest evidence here for the initiation of uplift toward the east appears to have been around 14,082 yrs B.P. (McCool 1 Trench). If this age is assumed to date commencement of the total offset of the overflow channels then a maximum rate of 4.70mm/yr is determined. A minimum horizontal offset rate comes from the small offset stream just south of McCool 1 trench and the initiation of eastward uplift (McCool 1 trench) giving 3.76mm/yr. Raub et al., (1987) determined a horizontal offset rate of 3.36mm/yr using the horizontal offset of a stream in the Wakarara area and the age of the uplifted terrace which caused the stream to change course. This rate for the southern Ohara Depression is of a similar order of magnitude to that found on McCool Farm.

The minimum vertical offset from the McCool 1 trench is 4m of uplifted Ohakean gravels occurring over 14,082 yrs B.P. (from the onset of eastward offset) is 0.28mm/yr. Evidence compiled by (Raub et al., 1987) suggests that eastward uplift further south in the Wakarara area began somewhere between 60,000 and 80,000 yrs B.P. and 11,000 yrs B.P. This evidence comes from terraces with estimated ages of 60,000 to 80,000 yrs B.P. which were upthrown to the northwest and those upthrown to the southeast dated at c 11,000 yrs B.P.

The Wellington Fault has fresh steep scarps (30° to 45° , Plates 36, 37 and 38) and a straight trace where it crosses McCool farm. Where the trace enters the southbank of the Ngaruroro River the scarps are very steep and scarp walls have eroded and collapsed. Where the west fault trace wall has been pushed dextrally into the river, debris has created small rapids as seen by the white water in Plate 40.

CHAPTER 5

THE WELLINGTON FAULT FROM THE NGARURORO RIVER THROUGH THE PUKETITIRI AREA TO THE NAPIER-TAUPO HIGHWAY

On the north bank of the Ngaruroro River the Wellington Fault trace crosses a series of river terraces (Figure 26, the terrace locality is marked T). These terraces are considered to be of Ohakean age (Appendix 3) due to their lack of loess cover and the much higher loess-mantled Ratan terrace situated above and to the northwest (Figure 27, Plate 41). The fault trace strikes 034° across the Ohakean 1 surface and is seen as a broad shallow u-shaped depression containing sags, bridges and rent features (Plate 42). The latest vertical uplift is to the east (approximately 2m) and the latest horizontal offset on what appears to be an Ohakean 2 terrace surface is approximately 43m. This makes a horizontal offset rate of 3.3mm/yr for this portion of the Wellington Fault, based on the tread age for the Ohakean 2 terrace (Marden 1984, Appendix 3). These terraces are somewhat complicated by later Holocene events which eroded away most Ohakean 3 surfaces on the downthrown side of the fault.

North of the terraces the fault trace is found in a valley which has fault gouge on both sides bearing 020° . The trace can be followed along to the southeast flank of the Fort (Figure 26, Plate 41) so called because of its outcrop of Whanawhana limestone (Beu 1995). North of the Fort on Awapai Station, the fault trace is indistinct. There is no evidence of offsets either vertical or horizontal, only a swampy area fed by a spring on the fault trace. As the regional dip of the Tertiary Limestone remains unchanged either side of the fault it appears that fault deformation is merely a change in height or dextral offset. There appears to be no internal deformation of these surfaces due to fault activity. Farther north the fault has offset a number of streamlets south of Glenross Road. The largest of these horizontal offsets is approximately 200m.

At Willowford Tertiary sediments with a regional east to southeast dip have been deformed and dragged down to the west close to the Wellington Fault.

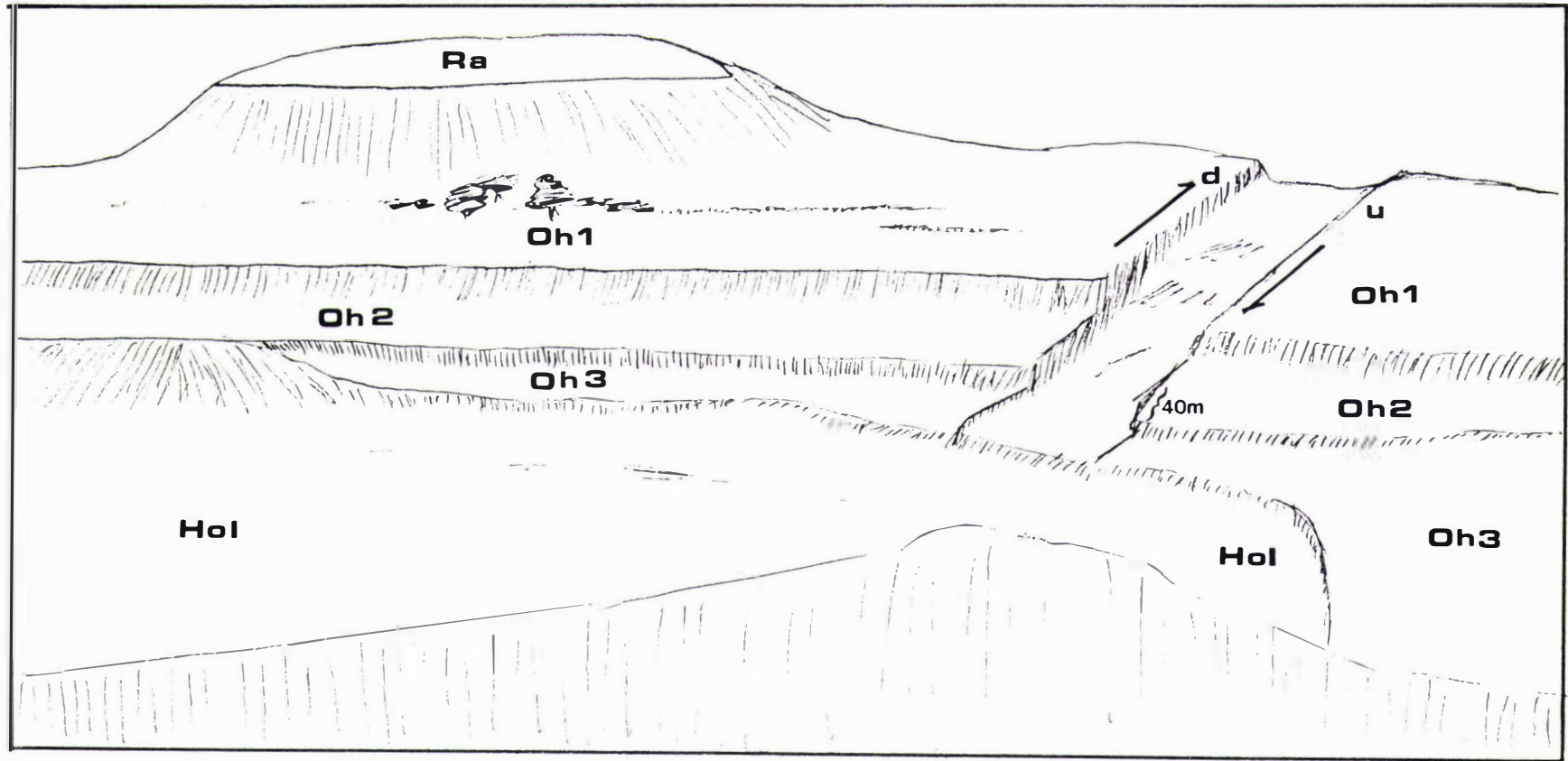


Figure 27. Field Sketch of offset terraces on the Wellington Fault located on the north bank of the Ngaruroro River. The fault scarp is not continuous through what is thought to be a Holocene terrace. This terrace lies some 60m above the river. The offset is measured from the leading edge of the Ohakean 2 terrace on the west side of the fault to the leading edge of what is thought to be a continuation of the same terrace on the east side of the fault. Using the tread age of the Ohakean 2 terrace (Pillans 1994) and the horizontal offset of approximately 40 m a tentative rate of 3.3 mm/yr is obtained for this portion of the Wellington Fault. The throw of the fault is up the east.

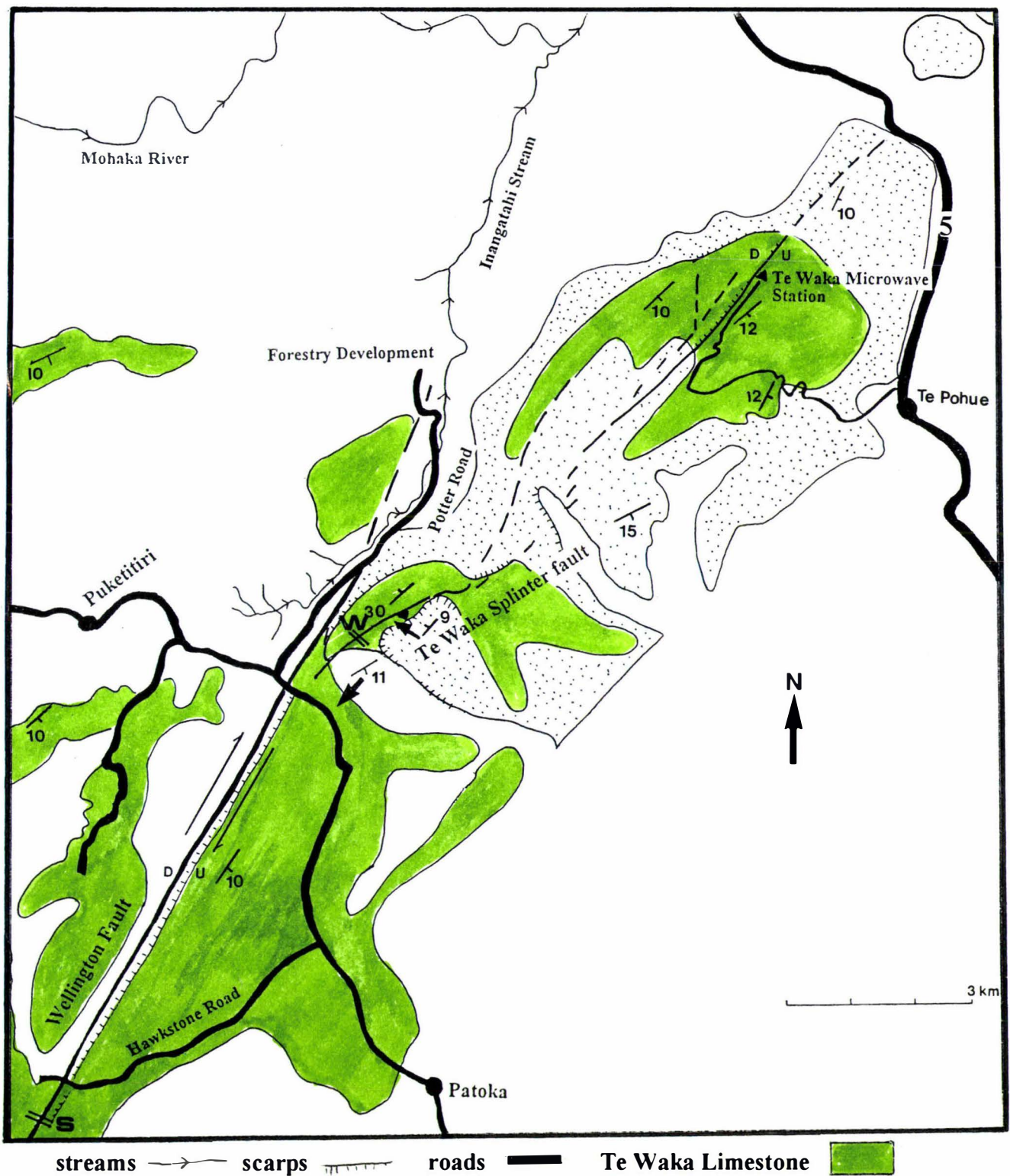


Figure 28. Map of the Wellington and Te Waka Splinter Faults showing trench sites and limestone outcrops (after Beu et al., 1980). S is the Syme trench site and W is the Wedd trench site. The regional dips of the Te Waka limestone and underlying Titiokura limestone (stippled pattern) remain unchanged by faulting activity. The major changes to the limestone through faulting are caused by vertical and horizontal offsets.

However the overlying late Pleistocene (Ohakean) river terrace remains undeformed and the tread dips at 3° to the east. Aerial photographs show that between the Tutaekuri River (to the north) and Willowford (to the south) is an area covered with slump and landslide features. Here the trace of the Wellington Fault has been erased by landsliding except for about 4m at the northwest end of a semi-circular sag pond on Willowford Road. It is not known if the fault trace has been obliterated by one massive landslide or in a number of isolated smaller events. What is apparent is that there has been no surface rupture on this section of the Wellington Fault since the landslides occurrence. The probability of the landslides having been triggered due to activity on the fault is high. On Willowford Station there is a linear feature (possibly a right stepping extensional splinter of the Wellington Fault) which can be traced on aerial photographs to the north side of the Tutaekuri River to the head scarp of another large landslide in the Waldon Road area.

North of the Tutaekuri River the Wellington Fault is upthrown mainly to the east. The geology either side of the fault consists of Tertiary siltstone, fossiliferous sandstone and the overlying Te Waka limestone. The trace is clear and distinct in the field largely due to the hardness of the displaced limestone blocks. On aerial photographs and in the field, there are numerous offset streams and ridges (Plate 43). The height of these ridges and scarp surfaces is variable, from 4m to 10s of metres north of Hawkstone Station where the fault scarp becomes the western face of the Maniaroa Range (Plate 44).

TRENCHING ON HAWKSTONE STATION

Hawkstone Station is located at the end of Hawkstone Road on the west side of the Wellington Fault, at V20/137986 (Figure 28). At this locality the fault scarp has been upthrown to the east. This movement has blocked drainage and most of the smaller streams oblique or perpendicular to the fault trace show dextral offset (Plate 43). The Syme trench was excavated through the upper end of a blocked drainage site against the Te Waka limestone fault scarp. The trench was 16m long and up to 6m deep; and was logged at a scale of 1:20 (Vol 2 map pocket). Only the north wall of

this trench was logged, the south wall was destroyed to allow drainage from the trench excavation.

Stratigraphy

The eastern wall of the trench is composed of limestone (Figure 29). To the west of this the fault trace is filled with younger sediments. The lowermost layer of these sediments (north trench wall) is composed of gleyed unconsolidated sandy loam. At the trench base is a tephra unit, thought (by its stratigraphic position) to be Karapiti Tephra dated at c. 10,100 yrs B.P. (Wilson 1994). To the east of the tephra is a more consolidated, iron stained sand unit. Above the tephra unit is a paleosol with Mangamate Tephra located in its base (c. 10,000 yrs B.P. Donoghue et al. 1991, Appendix 2). Laterally to the east of the paleosol is a mottled iron-stained sandy clay unit with some carbonaceous material. Overlying the paleosol and the sandy clay unit is a layer of colluvium containing some limestone rubble. A charcoal fragment from within this colluvium (0.2m from the top of this unit) yielded a date (NZA 4557) of 8770 ± 120 yrs B.P. Above the paleosol to the west end of the north trench wall is a peaty loam. Within it at 0.6m from its base is the Waimihia Tephra dated at 3280 ± 20 , (Froggatt and Lowe 1990). In the top of the peaty loam is the Taupo Tephra dated at 1850 ± 10 yrs B.P. (Froggatt and Lowe 1990). Opposite the peat on the eastern side of the north trench wall, is a unit of yellow-brown highly allophanic loamy material. This unit extends upward from the base of the peat (which it is in contact with) to the base of the topsoil and bears no distinct compositional relationship to any other sediment seen in the area.

Structures indicative of faulting events

The main fault plane strikes 030° and dips between 80° east and vertical. It extends 2.5m upward from the trench base. There is also a parallel fault 0.2m west of the main fault plane. It has more of an eastward dip and extends only 0.8m upward from the trench base (Figure 29). The westward-facing surface of the upthrown limestone block dips at 60° . If this surface had any slickenslides they were destroyed by excavation processes. Between the limestone and the fault plane is a colluvial unit of unconsolidated sands containing a few limestone blocks and pebbles.

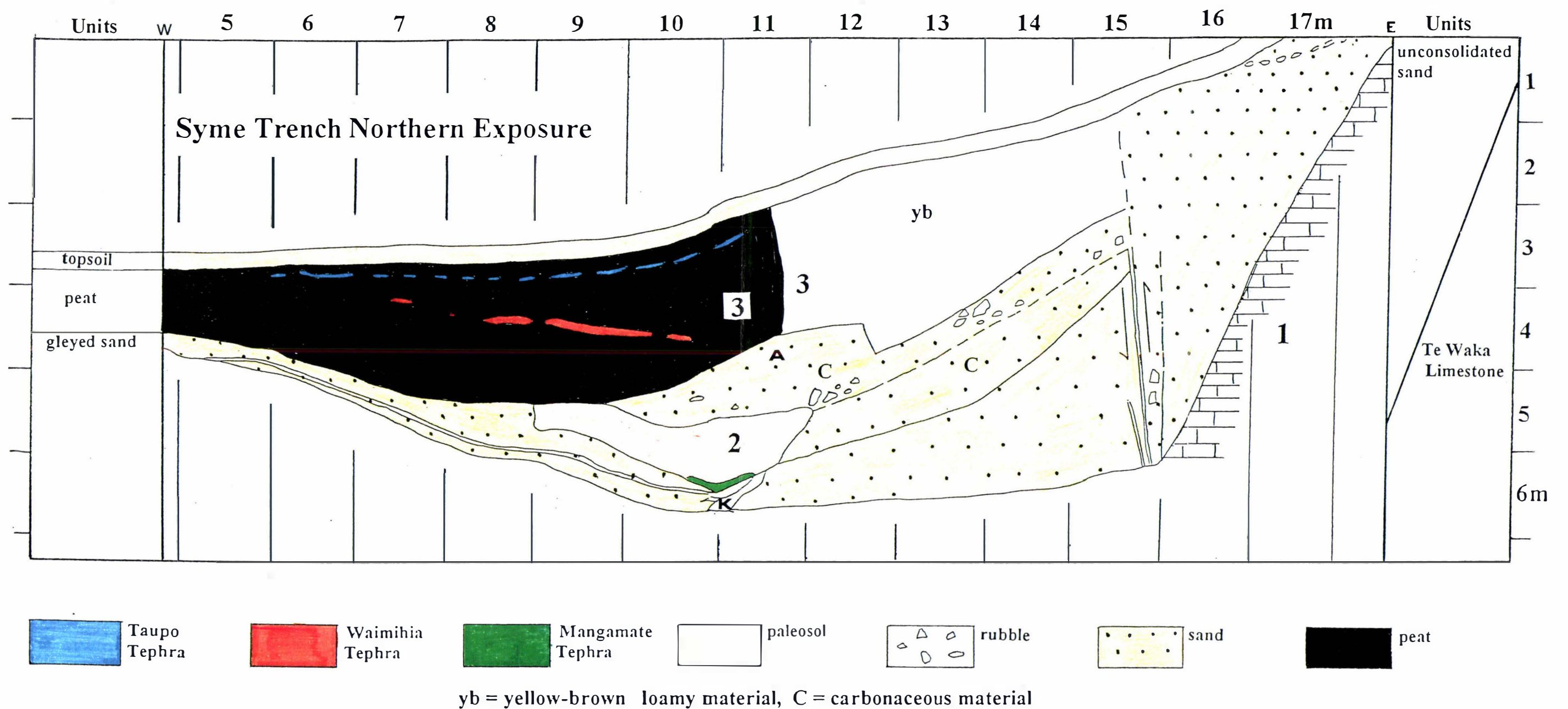


Figure 29. Cross section of the Syme trench excavated across the Wellington Fault at Hawkstone Station, showing stratigraphy, proposed sequence of earthquake events and age of the units. Event 1 initiation of vertical movement up to the east pre (K) Karapiti Tephra, age 10,100 yrs B.P. Event 2 disruption of the paleosol and deposition of colluvium at locality (A) dated at (NZA4557) 8770 $\pm$ 120 yrs B.P. Event 3 post Taupo Tephra deposition 1850 $\pm$ 10 yrs B.P. C are units containing carbonaceous material, yb is a yellow-brown allophanic loamy unit.

Toward the western end of the trench the paleosol and the unit containing the Waimihia and Taupo Tephra appear to have been truncated but there is no visible fault plane surface present (Plate 45). These tephras stop abruptly close to boundary of the yellow-brown loam unit (Figure 29) between the 10 and 11m vertical markers). There are no tephras present on the upthrown (eastward) side of the fault.

PROPOSED SEQUENCE OF EVENTS FOR THE SYME TRENCH AT HAWKSTONE STATION

- The first movements preserved at this locality would be the initiation of the change in throw of the fault. Upthrow to the east began to cause ponding of drainage to the west and continuing offset in the nearby streams. This event or events occurred pre 10,100 yrs B.P. based on the age of Karapiti Tephra (Wilson 1993) preserved in the base of the trench.

Then an interval followed when sediments accumulated in the newly formed fault trench. These are the gleyed sandy unit containing Karapiti Tephra, on top of which is the Mangamate Tephra followed by the paleosol. Charcoal found 0.4m above the paleosol unit was dated (NZA 4557) at 8770 ± 120 yrs B.P.

- During a second earthquake event recorded within the excavated trench, the paleosol was then faulted against the mottled sandy clay, close to 8770 yrs B.P. During or shortly after this event colluvial material from the newly uplifted scarp (consisting of sandy clay with limestone rubble) fell into the trench along with the dated charcoal fragment.

This was followed by another interval where (due to blocked drainage) a peaty loam accumulated. The Waimihia Tephra was then deposited and more peaty loam accumulated. Taupo Tephra was then deposited into the trench followed by more peaty loam.

- A third faulting event or events occurred post-Taupo Tephra, ie., since 1850 yrs B.P. where the above units are disrupted and a yellow-brown

allophanic unit is either deposited or faulted into the trench site. This unit does not resemble any of the surrounding present day sediments nor could this colour be obtained by weathering in 2000 yrs. If there was no earthquake at this point the tephra would have continued across into the yellow-brown loamy unit.

Finally the trench site was covered by a thin topsoil between 0.20m and 0.30m thick.

DISCUSSION OF OFFSETS FOR THE HAWKSTONE AREA OF THE WELLINGTON FAULT

Along this segment of the Wellington Fault are horizontally offset spurs, ridges and streams. Approximately 500m north of the Syme trench is a blocked drainage site which was offset horizontally a minimum of 60m. Based on the minimum date for eastward uplift from the trench base, where the Karapiti Tephra was dated at c. 10,100 yrs B.P. and the nearby 60m offset a minimum horizontal offset rate of 6mm/yr is obtained.

A minimum uplift rate of 0.6mm/yr can be estimated using the age of the Karapiti Tephra and the height of the upthrown limestone block. A further date for the onset of eastward uplift comes from the Willowford area where eastward dipping Tertiary sediments were dragged downwards to the west by faulting activity prior to 10,000 but not post 10,000. This date comes from the overlying Ohakea terrace which is not deformed but retains its original tread dip of 3° to the east. The deposition of this terrace ceased c.10,000.

Farther north where the Puketitiri Road crosses the Wellington Fault there is a 140m height difference between the highest (upthrown) point of the Te Waka limestone dipslope (Maniaroa Range) and the lowest point of the dipslope on the opposite (west) side of the fault. This measurement is not a direct vertical offset as it does not allow for dextral offset (Plate 44).

North of Hawkstone Station, the Wellington Fault forms the western scarp of the Maniaroa Range which has been upthrown to the east. The Te Waka limestone forms the cap of the Range and dips gently to the southeast.

The fault then crosses Puketitiri Road and runs parallel to Potter Road for some distance where it is seen as a break in the west-facing slope of the Maniaroa Range (Plate 48). A local farmer (Mr Durno) reports that his predecessors felt an earthquake sometime after the Tarawera eruption in 1886 and that a shallow lake in the Potter Road area drained out at this time. This report could not be verified. However a landslide across the Wellington Fault trace did block drainage of the Inangatahi Stream in this area causing a temporary lake to form (Plate 46). Other local farmers and historians have verified the existence of a shallow lake in the same locality and report that it existed during early European settlement (1850s). There are small scarplets in the area exposing Taupo and Waimihia Tephra which may record a post Taupo Tephra earthquake event (Plates 49, 50 and 52).

The fault trace then crosses Potter Road and can be followed across farmland, before becoming untraceable in the Awahohonu State Forest where it is obscured by forestry activity. The fault trace can be seen again on the north side of the Napier-Taupo Highway at Waitara Road. Here the westward-facing scarp can be clearly seen. The paddock through which the trace passes has since been planted in pines (Plate 47). On the west side of Te Waka summit there is a steep road cutting on the Napier-Taupo Highway 2-3km east of the Wellington Fault trace. Here Tertiary sediments dip steeply to the east at 70° , forming a monocline. However closer to the Mohaka River and just to the east of the fault trace Tertiary sediments again show the regionally characteristic southeasterly dip of 10° to 20° .

THE TE WAKA SPLINTER FAULT

Just north (200m) of where Puketitiri Road crosses the western scarp of the Maniaroa Range is the trace of a major eastward splinter of the Wellington Fault, referred to here as the Te Waka splinter fault (Figure 28). Looking north across Puketitiri Road (upslope, above an old landslide) this fault

scarp can be seen diverging to the northeast (Plate 48). On aerial photographs the fault trace is clearly marked as it crosses the Maniaroa Range in a northeasterly direction toward the Te Waka microwave station. This fault steps to the right from the Wellington Fault and is seen as an extensional feature which has created broad u-shaped (pull-apart) valleys within the Te Waka limestone (Plates 49 and 52). The eastern wall of these valleys is always higher than the western wall. South of Puketitiri Road, Te Waka limestone dips to the southwest while north of Puketitiri Road between the upper reaches of the Mangaone Stream the Te Waka limestone dips in the opposite direction to the northwest (Figure 28).

TRENCHING ON WEDD'S FARM

This trench was excavated across the Te Waka Splinter Fault on the Wedd property (V20/074184, Figure 28) which can be reached from Puketitiri Road. The Wedd trench was situated across the eastern flank of a broad u-shaped faulted valley, in the north westward-dipping Te Waka limestone. This dip is opposite to the regional southwesterly dip seen at Te Waka Trig to the north and along the Maniaroa Range to the south (Figure 28). The valley centre was composed of down-thrown weathered limestone and sandstone these were overlain by tephra deposits from the Central North Island. Most of the materials within the trench were highly allophanic in composition. The trench was excavated at right angles across the fault and was 18m long and up to 5m deep. The trench walls were logged at a scale of 1:20 (Vol 2 map pocket).

Stratigraphy

On the upthrown (eastward) side of the fault is composed of Te Waka limestone (Figure 30). The base of the trench consisted of downthrown Te Waka limestone covered by terrestrial sediments that were either eroded locally into the valley or consisted of volcanoclastics from the Taupo Volcanic Zone. The lowermost unit consisted of in-situ limestone bedrock overlain by limestone rubble. Above the limestone rubble a red-brown allophanic unit with rounded pebbles (0.1-2m across) occurred, which was in turn overlain by a 0.3m-thick layer of sand. Above the sand in the

yellow-brown allophanic unit are two discoloured patches formed by a high concentration of carbonaceous material. In the base of the trench between the 9 and 12m vertical mark was a brown allophanic unit with small 5mm angular pebbles. Overlying the preceding units was a yellow-brown allophanic unit. This yellow-brown unit contained a pocket of Waiohau Tephra and a number of tephra. These comprised a diffuse layer of what is probably (from its stratigraphic position) Karapiti Tephra, followed by Mangamate Tephra; on top of which was another diffuse layer of Poronui Tephra. Above the Poronui Tephra is more of the yellow-brown unit which contained the distinctive Waimihia Tephra. This was overlain by another layer of the yellow-brown unit and then the 1850 yrs B.P. Taupo eruptives consisting of the Hatepe Tephra (1-2mm thick) followed by Rotongaio tephra 1-2mm and then the Taupo Ignimbrite. On top of the Ignimbrite is a 0.2m thick layer of topsoil.

Structures indicative of faulting events

The main fault plane seen within the trench occurs between the plane of the upthrown limestone surface (striking 034° and dipping 85° west) and the sediments deposited within the trench. There are possibly other vertical faults within the trench, these are located either side of the red-brown allophanic unit with rounded pebbles and the brown allophanic unit with angular pebbles. Unfortunately there are no faulted surfaces preserved within these allophanic trench sediments. It is possible that the surface scarp between the 15 and 16m vertical marks in the trench is also fault derived (Figure 30). This scarp is seen on both east and west sides of the valley along the full length of the valley. The scarp is always the same height and exposes the same two units, the Waimihia Tephra in the base and the Taupo Tephra above, there is no evidence of slumping along these scarps (Plate 50). The lower sandy unit within the trench has been deformed and buckled upward, then abruptly terminates against possible unfaulted red brown allophanic materials (Plate 51). The Mangamate Tephra unit has been truncated, presumably having been disrupted by faulting events.

PROPOSED SEQUENCE OF EVENTS FOR THE TE WAKA SPLINTER FAULT

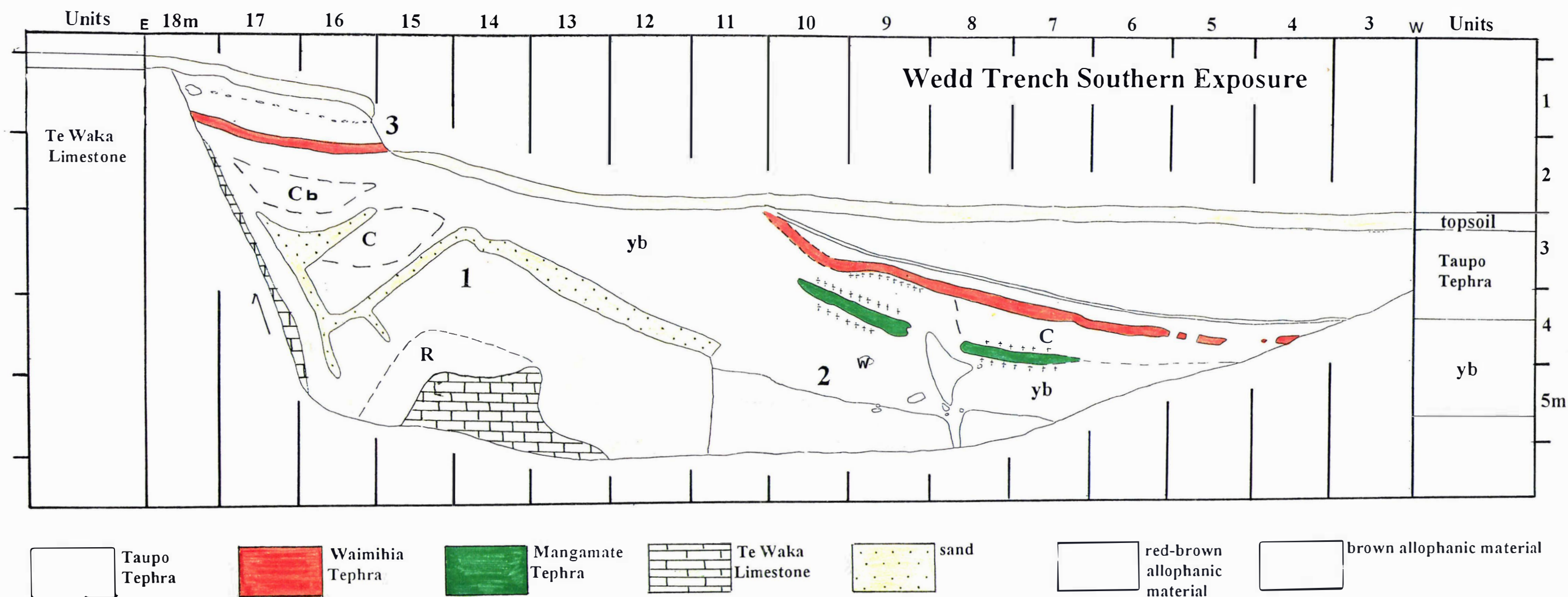
- The first faulting event or event preserved in this area occurred pre-Waiohou Tephra dated at 11,850 yrs B.P. (Froggatt and Lowe 1990). This resulted in the formation of the broad u-shaped pull-apart valley in which the subsequent late Quaternary terrestrial sediments accumulated.

A interval followed where the above sediments accumulated in the fault trench. These sediments were firstly the red-brown allophanic unit and the lower sandy layer followed by the deposition of the yellow-brown allophanic unit and accumulation of particles of carbonaceous material within it.

- The second faulting event is recorded by the deformation of the lower sandy and yellow-brown allophanic units (Plate 51). The thickness of the yellow-brown allophanic unit between the sandy units at the east end of the trench is similar to the thickness of the yellow-brown unit containing the Waiohou Tephra. The assumption could be made that this earthquake event occurred post-deposition of the Waiohou Tephra dated at $11,850 \pm 60$ yrs B.P. (Froggatt and Lowe 1990).

More sand and yellow-brown allophanic material is deposited into the east end of the trench. Within the yellow-brown allophanic unit a second paleosol starts to form. Subsequently the Karapiti, c. 10,100 yrs B.P., Mangamate c. 10,000 yrs B.P. and Poronui 9810 ± 50 yrs B.P. tephtras were deposited into the trench (Froggatt and Lowe 1990, Donoghue et al., 1991 and Wilson 1990, Appendix 2).

The third faulting event is recorded (post-Mangamate Tephra c. 10,000 yrs B.P.) by deformation in the centre of the trench between the 8-12m vertical marks. Where a unit is found which is unrelated to the same stratigraphic position on the other side. This allophanic brown unit may have been infaulted by strike-slip movement at this time or simply deposited into a faulted pull-apart rupture within the trench sediments.



R=limestone rubble, + =dispersed rhyolitic tephra, yb = yellow-brown loamy material, C = carbonaceous material

Figure 30. Cross section of the Wedd trench excavated across the Te Waka Splinter Fault in the Puketitiri area showing stratigraphy and proposed sequence of earthquake events and their ages. Event 1 pre Waiohau Tephra (11,850 yrs B.P.) buckling of the sandy unit and uplift of the limestone block. Event 2 burial of the upper dispersed carbonaceous unit (C b), disruption of the sandy unit and the Mangamate Tephra post 10,000 yrs B.P. Event 3 post Taupo Tephra (1850 +/- 10 yrs B.P.) and creation of the small scarp. W=Waiohau Tephra locality.

- During this event the lower sandy unit is abruptly terminated and the Mangamate Tephra is truncated.

After the above event the Waimihia Tephra was deposited into the trench, the age of this tephra being 3280 ± 20 yrs B.P. (Froggatt and Lowe 1990). Yellow-brown allophanic material is again deposited into the trench followed by the Taupo events. Firstly are the Taupo pre-cursors of Hatepe and Rotongaio followed by the main event with the ignimbrite unit.

- A possible fourth faulting event may have occurred sometime after the Taupo eruption because both Waimihia and Taupo Tephras were disrupted. Paper reconstructive models of this event cannot accommodate vertical faulting or slumping, so strike-slip movement is the most likely possibility. This event created the small scarp and may have dislocated the material sideways so to leaves a break in the upper units. There are a number of these small scarps on the Wedd Farm and the neighbouring Durno Farm. All the same height and all displace the Waimihia and Taupo Tephras. These scarps are mainly found within and parallel (up to 200m distant) to the Te Waka splinter fault trace (Plate 50 and 52).

The fault trace can be followed northward both in the field and on aerial photographs. North of the excavation site the fault narrows, then there is a right stepping extensional jog and the fault widens into another broad u-shaped valley west of the Maniaroa Trig. Upthrow is to the east and there are possible horizontal offsets of 60 to 100m. These horizontal offsets are seen along broken units of limestone forming a u-shaped valley south of the Maniraroa Trig. Due to the age and weathering of these scarps it was difficult to determine the morphological differences from faulted differences. The fault trace can then be followed as far as the upper reaches of the Mangaone River. The trace then becomes hard to follow. There may be a left step in the trace which has been eroded away in the softer sediments underlying the harder Te Waka limestone. Further north the trace is clear where it runs parallel to Camp Stream. From Camp Stream north it runs along the crest of the Te Waka Range (which appears to have been created by eastward uplift) to its northernmost point at the microwave station. At the microwave station the fault terminates in a three-fingered splay. This splay is typical of a fault termination where fault

rupture ceases (Aki, 1988, Plate 55). It was difficult to determine vertical offsets for these splays as the alternating thickness sequences of the sandy mudstone and limestone units of the Te Waka limestone facies is highly variable. The surface of one upthrown splay was capped with sandy mudstone and the other with a layer of limestone (Plate 55). These units could not be directly related to each other in the field. The outcrops of the Te Waka limestone terminate 250m north of the Microwave Station on the west side of the fault and just below the station on the east side of the fault. The underlying older Titikura limestone (Beu 1995) dips to the southwest between 10° and 15° (Plate 53).

OFFSET RATES FOR THE WELLINGTON AND TE WAKA FAULTS

Vertical offset at the microwave station appears to be in the region of 30m up to the east (Plate 54). It is also possible that there is 250m of dextral horizontal offset. However because the Te Pohue landslide is directly below these offset features it is possible that what appears to be horizontal offset may have been lost in the landslide, which was probably fault generated. This landslide appears to be complex and to have been generated both pre and post Taupo Tephra (1850 ± 10 yrs B.P.) C. Hannan pers comm. If a post-Taupo Tephra earthquake event did trigger landslide movement here then it would correlate to the event which formed the small scarp seen within the Wedd trench and the area adjacent to the Te Waka Fault.

Unfortunately there are no Holocene formations preserved across the fault in this section to give offset rates. Although offsets can be calculated from the limestone age it would give a false rate because most faulting especially in the Wedd trench area of the Te Waka splinter fault has occurred within the last 20,000 yrs. However a tentative vertical offset can be found using the 30m height difference found at Te Waka Trig. If the timing for this eastward uplift is the same as that in the Wedd trench to the south then the Waiohau Tephra found 1.20m above the top of the downthrown limestone at the trench base gives a minimum vertical offset rate of 2.5mm/yr. A tentative horizontal offset rate is calculated using the Waiohau Tephra date

found in the Wedd trench for faulting initiation and the minimum distance that blocks of nearby (600m north of the Wedd trench) Te Waka limestone have moved dextrally (approximately 60m) gives a minimum offset rate of 6mm/yr for the southern segment of the fault. This tentative horizontal offset rate is the same as that found at Hawkstone Station on the Wellington Fault. Events within the trenches are similar except that there are four separable earthquake events seen in the Wedd Trench over the last 11,000 yrs and 3 separable earthquake events seen at Hawkstone Station since 10,000 yrs B.P. Given the large horizontal offsets which have occurred at both trench sites since the inception of eastward uplift, it is likely that there were more earthquake events than are recorded in these trenches. It is thought that strike-slip faulting coupled with a low uplift rate has smeared such events making them inseparable.

CHAPTER 6

THE RUAHINE FAULT FROM THE MANAWATU GORGE TO THE KAWEKA FOREST

The Wellington Fault trace bifurcates just south of Kahuki (Marden 1984). The major westerly splinter is called the Ruahine Fault. One of the first outcrops on this fault can be seen in the north bank of Kahuki Stream. It is approximately 40m west of the Kahuki horst and graben system which is a duplex on the Wellington Fault. The outcrop is formed of fault gouge and is approximately 5m wide and 6m high. Between Kahuki and the Manawatu Gorge the fault separates Torlesse greywacke bedrock to the west from Plio-Pleistocene deposits to the east. This boundary can be traced through dense bush on Centre Road where it can be seen as a change in lithology, then be followed across a steep hillside just west of the Ballance Bridge (Figure 3, Plates 1 and 2).

MANAWATU GORGE TO OHARA DEPRESSION

The Ruahine Fault has no topographical expression between the northern side of the Manawatu Gorge and just 200m south of Saddle Road. A sinistral compressional sidestep is postulated only from the strike of the fault trace south of the gorge to the strike of the trace south of Saddle Road and from some crushed deformed Torlesse bedrock within the Te Apiti Stream (Marden 1984, Figure 3). Approximately 200m south of Saddle Road the fault trace is expressed only as a linear patch of swamp where it crosses through Tertiary rocks. North of Saddle Road the fault trace can be followed for 150m in a steep washed out ravine, otherwise the trace is not visible crossing the highly eroded Tertiary rocks of the Ruahine Anticline (Lillie 1953). The trace can be located again south of Wharite Road where it becomes the contact between Torlesse basement

and eastward-dipping Tertiary sediments suggesting uplift to the west (Marden 1984).

The fault crosses Wharite Road and from here on to the Ohara Depression traverses through steep land of Torlesse greywacke basement rock only. It passes to the east of Wharite Trig where it was mapped by Marden (1984) as a series of fault breccia zones. The trace then becomes less defined in the headwaters of Coppermine Creek. In the upper Mang-a-tua and Raparapawai catchments there are extensive zones of brecciated Torlesse rock corresponding to the fault trace. These could be collectively termed the Ruahine Fault Zone. North of the Raparapawai catchment the Ruahine Fault Zone crosses the sinuous crest of the Ruahine Range east of Maharahara Trig. Immediately east of the trig Marden (1984) describes two prominent sharply defined outcrops 50 to 75m long respectively and between 6 to 8m high with uplift being to the northwest. These well defined outcrops are unusual for this southern section of the fault trace. Farther north a number of streamlets are dextrally offset between 20 and 40m. However many of these streams lie within crushed zones and this apparent offset may be the result of fault influence on drainage patterns, as seen in the upper reaches of the Makawakawa catchment. Fault exposures of brecciated bedrock can be seen in cuttings on Takapairi Road. The fault then strikes northwards along the upper reaches of the Pohangina River. Torlesse basement greywacke has been sub-divided into 3 north-east trending belts here (Sporli, Bell, 1976 and Marden 1984). The fault zone bounds the Pohangina Melange and the Western Axial Belt and consists of up to three crush zones. Just north of Top Gorge Hut is a large bend in the river which may be caused by deposition of an old sedimentary fan which the trace is seen to cross. The fault zone then crosses the Pohangina Saddle and has been mapped as a dual trace up to Daphne Hut by Sporli and Bell (1976, Figure 31). North of the hut (1km) the fault zone crosses at ridge where it becomes difficult to follow both in the field and on aerial photographs. It is possible that the fault and the boundary of Pohangina Melange merge some distance past Stumpy No 2 trig, northward into the Ohara Depression where the Ruahine Fault trace merges with Cullens fault (Raub 1985, Figure 2).

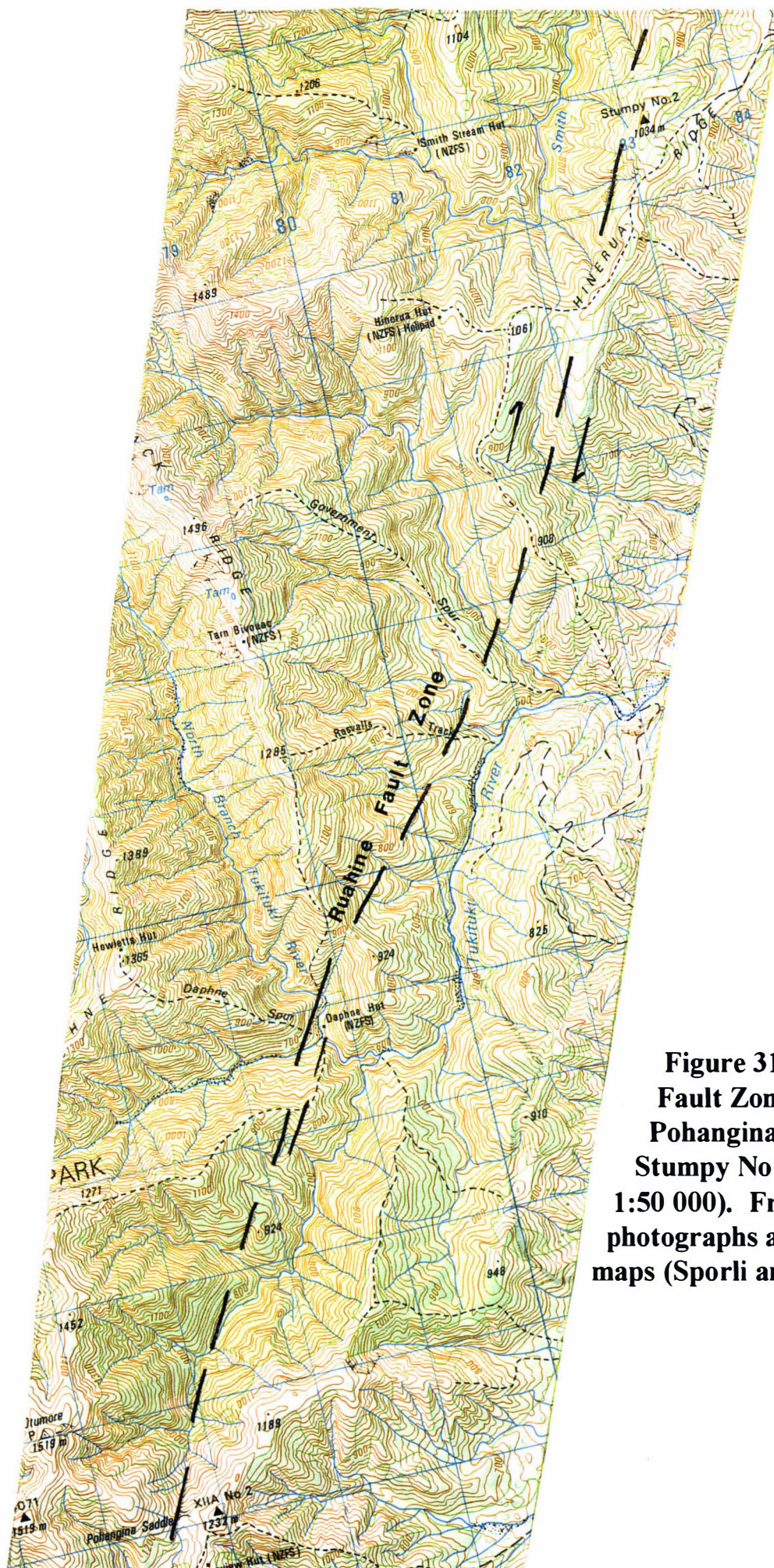


Figure 31. The Ruahine Fault Zone between the Pohangina Saddle and Stumpy No 2 (NZMS U22 1:50 000). From aerial photographs and existing maps (Sporli and Bell 1976)

THE OHARA DEPRESSION

From the Ohara Depression northward the character of the Ruahine Fault changes. The fault again becomes a contact fault between uplifted Torlesse bedrock of the Ruahine Range and downthrown Tertiary sediments within the Ohara Depression (Figure 2). Behind the airstrip on North Block Road a steep scarp is upthrown to the east. It is likely that this scarp is the result of a compressional left step in the fault. From the airstrip northward along the base of the Ruahine Range not far from the forest line are numerous shutter ridges, offset spurs and streams (Figure 21). The offsets are dextral and do not appear particularly recent; the bends in the streams and shoulders of the ridges are rounded and not sharp (Plate 56). This makes dextral horizontal offsets difficult to measure, but distances between 50 to 100m were measured. The difference in these offset distances is partly due to the differing age of the geomorphic features measured. The fault trace continues north bearing 030° through Gwavas Forest. South of Sentry Box the fault trace becomes more complex. Displaced greywacke is pushed out into the Ohara Depression along the Matapura (Figure 2) and a smaller unnamed fault. Both of these faults may be splays of the Ruahine Fault but their presence is inferred only from outcrops; they have no surface expression (Erdman and Kelsey 1992). There are offset spurs in the Sentry Box area but these were not measured because of the dense bush cover. North of Sentry Box a linear feature without offsets can be seen on aerial photographs. In the field this feature is an anticline running parallel to the fault for approximately 4km. Farther north and east of Herricks Trig, the latest vertical uplift is to the east. This trend continues northward across McIndoe flat to the Ngaruroro River with well defined steep fault scarps. McIndoe flat has a number of younger terraces 20m above the river level, which appear to be Holocene and Ohakean in age (Appendix 3). The youngest of these terraces is offset vertically by 0.5m to 0.8m and approximately 3m dextrally. Unfortunately the age of this terrace surface is unknown. All of the younger terraces in this area lack a loess covering and have a thin veneer of volcanic material, which may have been reworked. Here the main fault trace is seen to

bifurcate; the easterly splinter bears north of the Ngaruroro River directly toward The Lizard which is seen in the distance (Figure 26).

OHARA DEPRESSION TO THE KAWEKA FOREST

The *westerly* splinter of the Ruahine Fault bounds the Omahaki Depression to the east. This section then becomes the western boundary of the Mt Miroroa thrust fault (Figure 31a). There is a third poorly defined trace mapped by Brown (1980) which can be followed across the Omahaki Depression to the Miroroa thrust fault but this trace does not appear to have been active in recent times (Figures 26 and 31a).

The more *easterly* trace can be seen crossing Omahaki Road close to a sharp U-bend in the road where it appears as a break in slope where it traverses through Te Waka limestone. Farther north this fault trace traverses across the Lizard where Te Waka limestone is completely overturned (Beu 1995). The trace then passes west of the Blowhard onward through the Kaweka Forest to where it can be seen approximately 50m west of Lawrence Hut (Figure 31a).

There are some horizontal offsets seen in streamlets in the area but most faulting activity has been obscured by forestry works. There are 3 to 7km horizontal offsets mapped by Beu (1995) of the Te Waka limestone at this locality which would give tentative horizontal offsets between 0.15 to 3.5mm/yr over the last 2ma. There are no significant markers on the Ruahine Fault between the Manawatu Gorge and the Kaweka Forest to determine the total horizontal offset.

The central and northern portions of the Ruahine Range were uplifted along the Ruahine Fault, the highest peaks of which now reach elevations of over 1700m. Beu (1981) gives three lines of evidence for this uplift which began in early Castlecliffian time. He calculates a mean uplift rate for the Ruahine Range to be at least 1.3mm/yr.

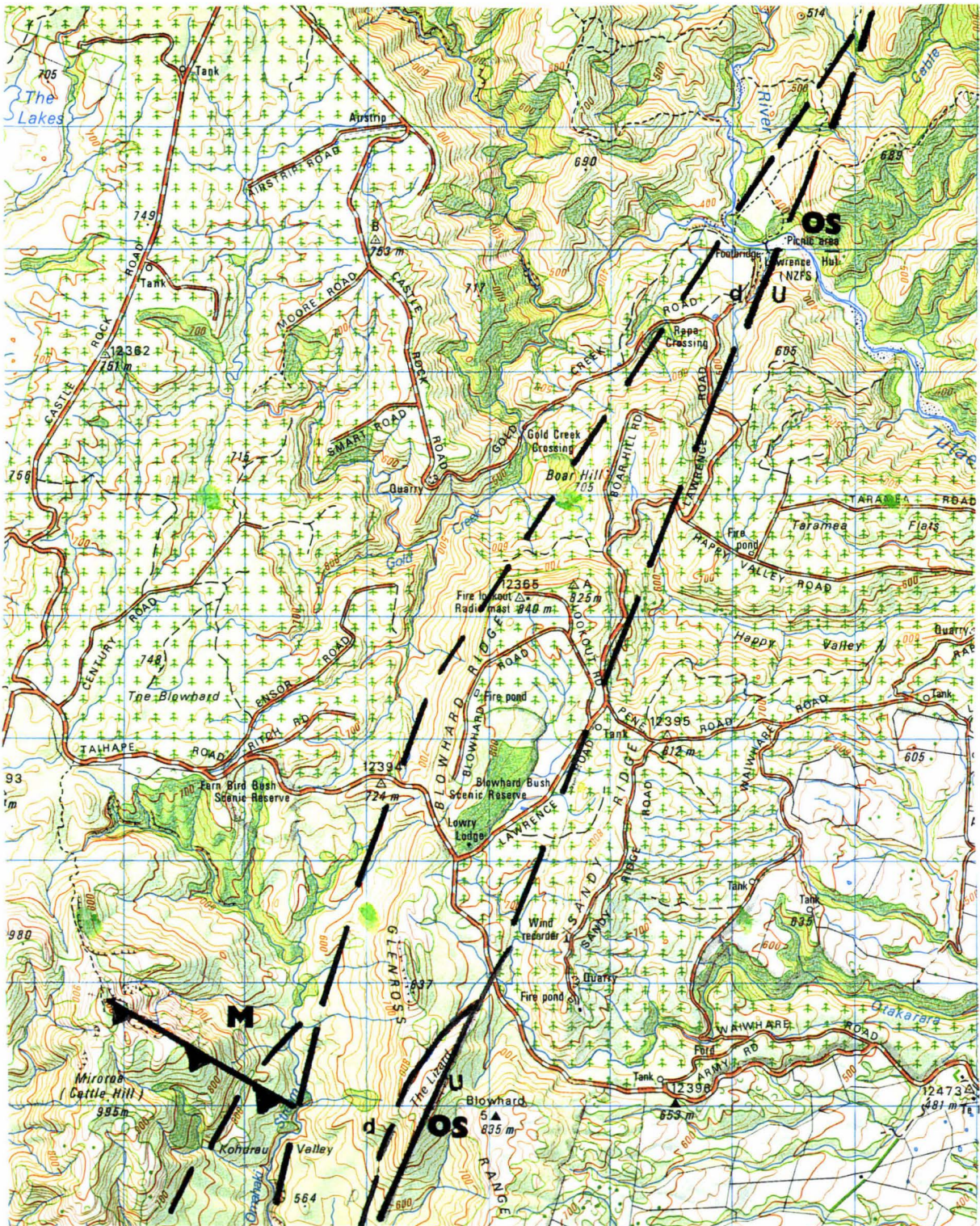


Figure 31a, Approximate locations of the split trace of the Ruahine Fault between The Lizard and Lawrence Hut, NZMS U20. The Fault trace was difficult to follow through this area due to forestry activity. M is the Miroroa thrust fault as mapped by Brown (1980) and OS are horizontal offsets, u and d are vertical offsets.

Strain Transfer Faults :Discussion

At the southern end of the Ohara Depression is the Cullens Fault (Raub 1985) starting close to the Wellington Fault and curving toward the Ruahine Fault. The northwestern part of this fault is mapped by Kingma et al. (1962) as being an extension of the Ruahine Fault. Linear features seen on aerial photographs from Daphne Hut by the North Branch of the Tukituki River across Stumpy No 2, toward offset ridges south of Cullens Trig (Figure 21). It is proposed here, that strain is transferred from the Wellington Fault to the Ruahine Fault via Cullens Fault. Offsets on the Ruahine Fault south of this area are minimal as described earlier in this chapter. Further the fault south of this area does not even appear on the Superior Oil Company's cross-section (1943) of the Ruahine Range. On the other hand the Wellington Fault in the Dannevirke area (south of Cullens Fault) has an average offset rate of 12mm/yr. In contrast north of Cullens Trig the Ruahine Fault has a more strongly marked trace (Plate 56) while horizontal activity on the Wellington Fault in the Ohara Depression drops off to 3 or 4.6 mm/yr (chapter 4).

North of Gwavas Forest, in the northern sector of the Ohara Depression is another compressional (left stepping) splinter fault diverging from the Wellington Fault, named the Big Hill Fault. At its southern end, this fault strikes northwest and has reverse motion (Erdman and Kelsey 1992; Cashman et al., 1992). This fault is also thought to transfer motion from the Wellington Fault to the Ruahine Fault causing the WNW to ENE trending folds between the Ruahine Range and Big Hill (Erdman and Kelsey 1992). The Big Hill Fault is also considered to be a part of the regional dextral strike-slip system.

If the Big Hill Fault is a transfer structure in recent times then it might be expected that the trace of the Wellington Fault would weaken after strain transfer showing less faulting activity. Correspondingly the Ruahine Fault trace should appear more eroded before strain transfer showing less faulting activity, in fact the opposite is true. The Wellington Fault trace **north** of the Big Hill Fault is prominent in the field and on aerial photographs with clearly defined offset spurs, shutter ridges, ponded

drainage and offset streams with uplift to the east (Plates 36, 37 38 and 40). The Ruahine Fault trace *south* of the Big Hill Fault also has clearly defined shutter ridges, ponded drainage and offset terraces with latest uplift being to the east. It is suggested here that transfer action on the Big Hill Fault would have occurred before the initiation of eastward uplift (pre-14,082 yrs B.P. see chapter 4). It is also possible that strain is transferred at depth, as the faults in the narrowest part of the Ohara Depression are only 3km apart and may meet at depth (3km). There is no doubt that strain is being, or was in the past transferred from one fault to the other. Farther north the Ruahine Fault is seen from trenching studies to be much more active than the Wellington Fault (see chapter 7). Both Cullens and the Big Hill fault exhibit typical characteristics of transfer faults (Twiss and Moores 1992). Firstly they lie at a high angle to the regional direction of displacement. Secondly they appear to connect the adjacent Wellington and Ruahine Faults.

CHAPTER 7

THE RUAHINE FAULT BETWEEN THE KAWEKA FOREST AND THE NAPIER-TAUPO HIGHWAY

The Ruahine Fault trace is difficult to follow through the Kaweka forest, but it can be seen as a thickly vegetated scarp (uplifted to the east) just west of Lawrence Hut. Sections of the fault trace can be seen from Lotkow Road along Gorge Stream (Figure 32) where offsets along the fault trace have been described by Beanland and Berryman (1987). From Lawrence Hut through the Black Birch Range to Baldy quarry on Whittle Road the fault passes through Torlesse greywacke basement. In this area the fault scarps are steep (up to 60°) and appear fresh (Plate 60). To the north of Baldy greywacke quarry the fault trace is the boundary between Torlesse greywacke to the west and Tertiary siltstone to the east for about 6km, with uplift being to the east (Frontispiece). From Baldy quarry north the trace is clear, sharp and straight; scarp angles are between 30° and 50° . The geology then changes again and the fault trace passes through greywacke basement until just south of the Napier-Taupo highway where it is delineated by an internally undeformed displaced block of Nukumaruan limestone on the Napier-Taupo highway.

TRENCHING ON DAVIS' FARM

Davis' Farm is located at the end of Whittle Road near the Kaweka forest (figure 32). Two trenches were excavated in this area one either side of Baldy quarry (U20/092077). The quarry exposes basement greywacke with vertical bedding and some tight ductile folding which is thought to have occurred earlier in the depositional history of the greywacke. It is not considered to be a part of the deformation occurring on the Ruahine Fault during recent times. This locality was chosen for trenching because the fault trace appears very fresh, with little erosion of the fault scarp and abundant carbonaceous material was likely to be preserved in blocked drainage sections of the fault trace (Plate 57). Aerial photographs of this area show the fault trace as a perfectly straight line. The latest vertical

movements in this region show that uplift has shifted from the west side of the fault to the east probably within the last 20,000 yrs. Streamlets in the area have been displaced dextrally between 8 and 10m.

DAVIS 1 TRENCH

The site for this trench is located approximately 100m to the north of the quarry near the end of Whittle Road. This trench was excavated at right angles to the fault through a swampy ponded drainage site. It was 29m long and up to 5m deep, the trench walls were, marked with 1m string grid and logged at a scale of 1:20 (see map pocket volume 2). This trench was excavated below the lowest peat level (Figure 34) and after samples were retrieved, immediately backfilled up to the peat for stability. Only two metres of the south wall were logged due to trench wall collapse.

Stratigraphy

The *western* end of the excavated trench was composed of greywacke while the *eastern* end is composed of upthrown Tertiary siltstone of Kapitean age (Grindley, 1960). In the *central* section of the excavated trench were layers of terrestrial sediment. The base consisted of a silty grey unit with some wood, radiocarbon dated (NZ 8233) at 7778 ± 81 yrs B.P. Above this unit was a layer of peat containing some angular greywacke pebbles, the peat was radiocarbon dated (NZ 8231) at 5971 ± 78 yrs B.P. Overlying the gravelly peat is a lens of fine rounded gravel no more than 0.1m thick. Above this gravelly lens was more peat with some angular siltstone chips, a wood sample (NZ 8232) from the top of this unit was radiocarbon dated at 3623 ± 57 yrs B.P. On top of this peat was a layer of blue-grey rubble which is found in the south wall of the trench (Figure 35) and under the fold in the Waimihia Tephra (Figure 34, 13 and 14 vertical marks, Appendix 2). Overlying the peat and blue-grey rubble was a 0.19m thick layer of Waimihia Tephra. On top of this tephra was a 0.2m thick layer of peat above which is the Taupo Tephra. This tephra is 0.16m thick and consists of a fine white-grey ash layer at the base which is overlain by creamy coloured bedded layers of pumice with charcoal fragments. Overlying the tephra is a 3mm layer of peat, above which was a

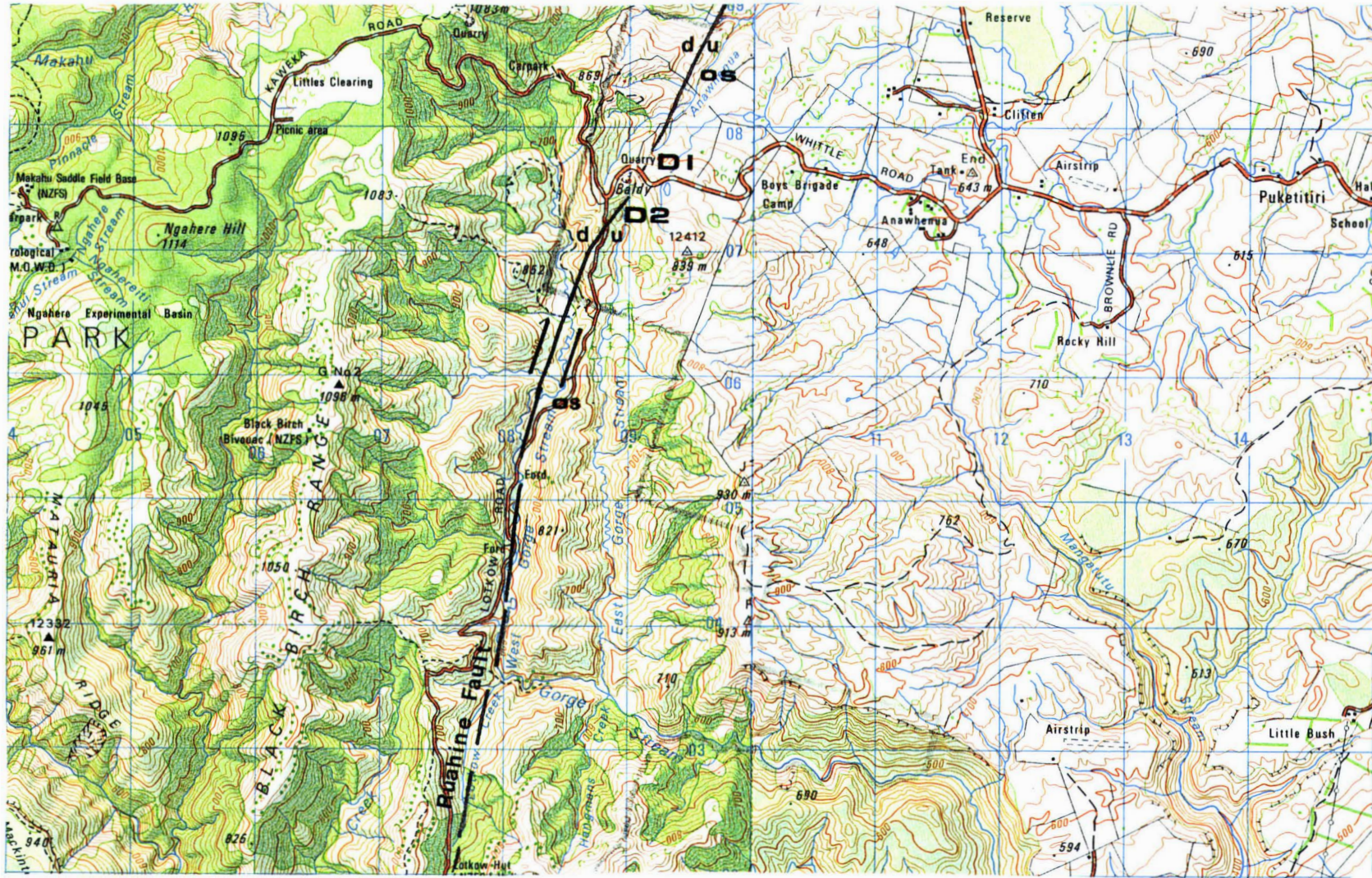


Figure 32. The Ruahine Fault between Lotkow Hut and Whittle Road (NZMS U20 and V20 1:50 000. D1 and D2 are the localities of the Davis 1 and 2 trench sites, OS are horizontal offsets and u d are vertical offsets. The latest upthrow in this area is to the east.

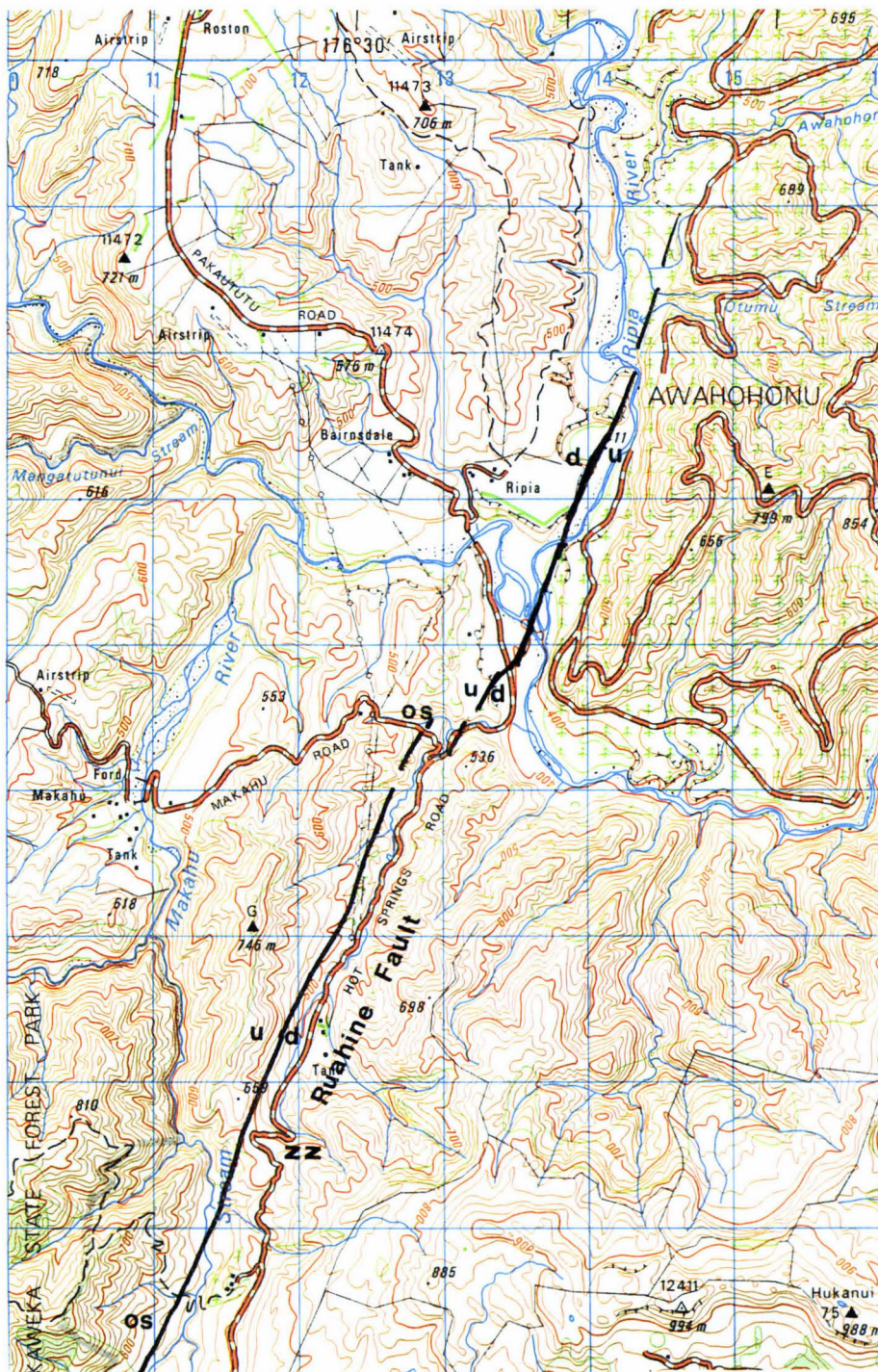


Figure 33. Locality map (NZMS, V 20 1:50 000) of the Ruahine Fault from Hot Springs Road to the Awahononu State Forest. ZZ is the zig zag in Hot Springs Road mentioned in the text, OS are offset streams and ridges marking horizontal movement and u d are the localities of vertical movement. There is a small sidestep in the fault close to the junction of Makahu and Hot Springs Roads.

second layer of blue-grey rubble composed of angular to rounded greywacke pebbles which make up 80% of the total unit. The 20% matrix in this unit consists mainly of reworked Taupo Tephra. The blue-grey rubble becomes sandier in texture toward the top of the unit. It is not found across the full length of the excavated trench but extends only to the 19m vertical mark (Figure 34) a wood sample from the base of this unit was radiocarbon dated (NZ 8230) at 1281 ± 63 yrs B.P. Above the rubble another peat unit has accumulated which is up to 1.5m thick. Within this peat and 0.5m from the surface is a layer of angular greywacke rubble. The sedimentary column for the south trench wall is exactly the same except that there is an additional layer of blue-grey rubble between the lowermost layer of peat and the Waimihia Tephra (Figure 35).

Structure indicative of faulting events

The main fault plane strikes at 015° and is situated between the peaty units in the trench and the eastward upthrown Tertiary siltstone. The dip ranges between vertical and 68° west; this variation may be caused by a down-dropped block of siltstone (Plate 58) the siltstone is crushed and broken at the contact. There are other possible fault surfaces where faulting and deformation occurs but these surfaces are not always visible due to the pliable nature of the sediment. For example there is a fold in the Waimihia Tephra the axis of which is aligned with a downthrown segment of the blue-grey rubble (Plate 59, Figure 32, vertical marks 13 and 14). Whilst there is no visible faulted planer surface along the edge of the downthrown block it is likely the fold was generated by movement here. Vertical offset for this event comes from the height of the fold in the Waimihia Tephra and the corresponding height of the downdropped blue-grey rubble which is about 0.6m. Within the uppermost peat layer and extending to the surface are two debris filled fissures at the 21 and 22 vertical marks. A third fissure filled with angular greywacke pebbles (clast supported) is found between the 9 and 10 vertical marks (Figure 34). These are thought to be evidence of the latest faulting event occurring on this segment of the Ruahine Fault.

Most of the trench sediments also have boudinage (pull-apart) structures; where Waimihia and Taupo Tephra units are disrupted (Figure 34). There are also layers of reverse stratigraphy where some blocks of tephra may

have been reworked by faulting or redeposited by storm events. These occur between the 25m vertical mark, where Waimihia Tephra is found on top of Taupo Tephra. At the 10m vertical mark Taupo and Waimihia Tephras are found 1m above other Waimihia and Taupo units in the trench. A scarp uphill and just to the southwest of the trench site is the probable erosional source for some rubble and blocks of redeposited tephras .

DAVIS 2 TRENCH

This trench is located some 500m south of Baldy quarry near the end of Whittle Road. Access to this site is from the forestry road to Lotkow Hut (Plate 60). The trench was excavated through basement greywacke and across the fault scarp. It was 12m long and up to 4m deep and it was logged at a scale of 1:20 (see map pocket volume 2).

Stratigraphy

This trench was excavated through shattered greywacke; both the floor and walls of the trench are composed of greywacke. Although the latest vertical fault movements are clearly upthrown to the east, no peats had accumulated in this section of the fault trench due to free drainage northwards within the fault trace. All the materials within the trench are derived either from the weathered greywacke or from tephras derived from the Taupo Volcanic Zone. At the bottom of the trench overlying the shattered greywacke bedrock is a unit of greywacke rubble consisting of angular cobbles and pebbles. Between the 1 to 4m vertical mark in the north trench wall is a unit of upthrust rubbly greywacke with some remnant bedding. Overlying the greywacke rubble is a unit of yellow-brown allophanic material containing a lens of Waiohau Tephra (north trench wall only) aged $11,850 \pm 60$ yrs B.P. (Froggatt and Lowe 1990). Above which (within the same yellow brown unit) is a dispersed layer of rhyolitic tephra. Over this is a dispersed 0.20m thick layer of Mangamate Tephra. Overlying the Mangamate Tephra is another dispersed layer of rhyolitic tephra. Above these tephras is more yellow-brown allophanic material containing some angular greywacke pebbles and carbonaceous material. Overlying this is the same yellow-brown allophanic material without the pebbles or

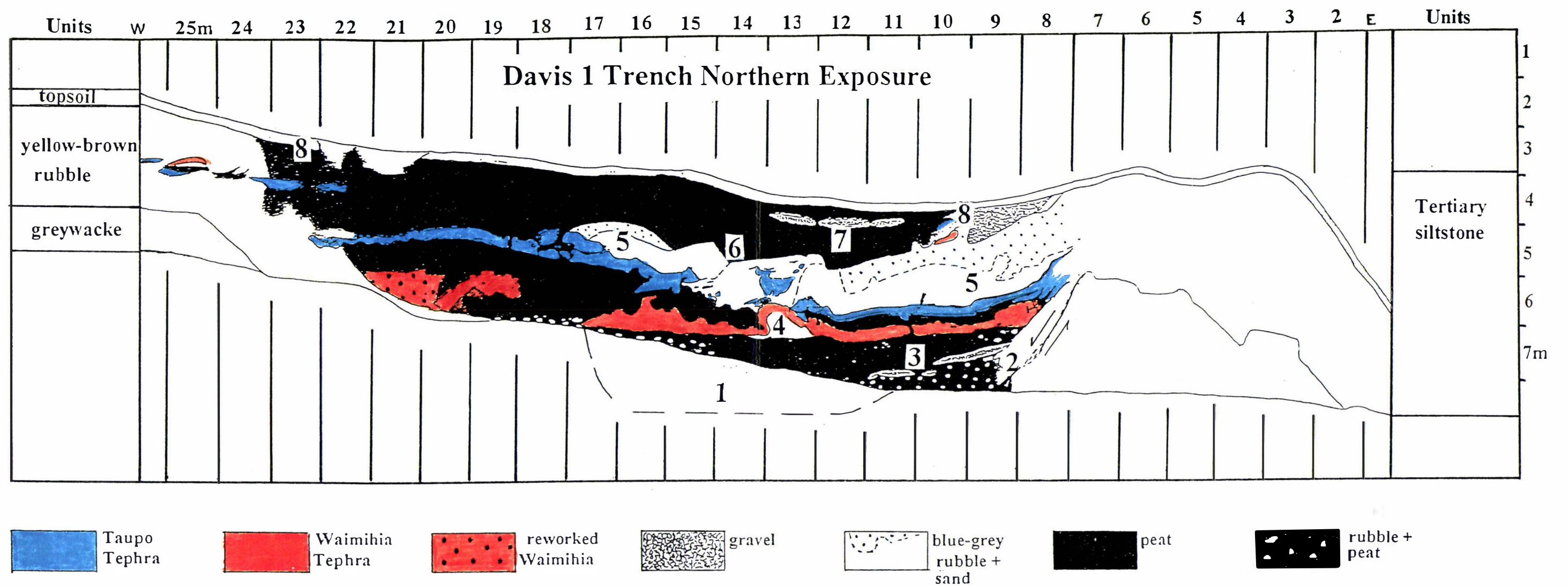


Figure 34. Cross section of the Davis 1 trench excavated across the Ruahine Fault at the end of Whittle Road, showing proposed sequence of earthquake event (numbers 1 to 8) and trench stratigraphy. Event 1 initiation of upward movement to the east pre (NZ8233) 7778 $\pm$ 81 yrs B.P. Event 2 dislocation of a siltstone block post (NZ8231) 5971 yrs $\pm$ 78 yrs B.P. Event 3 disruption of a gravel unit around (NZ8232) 3623 $\pm$ 57 yrs B.P. Event 4 an earthquake or storm deposits a blue-grey rubble into the trench pre Waimihia Tephra (3280 $\pm$ 20 B.P.). Event 5 an earthquake or storm event deposits more blue-grey rubble into the trench post Taupo Tephra (1850 $\pm$ 10 yrs B.P.). Event 6 offset and deformation of the blue-grey rubble, Waimihia and Taupo Tephra post 1850 $\pm$ 10 yrs B.P. Event 7 earthquake or storm deposits angular pebbles on top of the peat post (NZ8230) 1281 $\pm$ 63 yrs B.P. Event 8 creates earthquake fissures which are later filled with rubble.

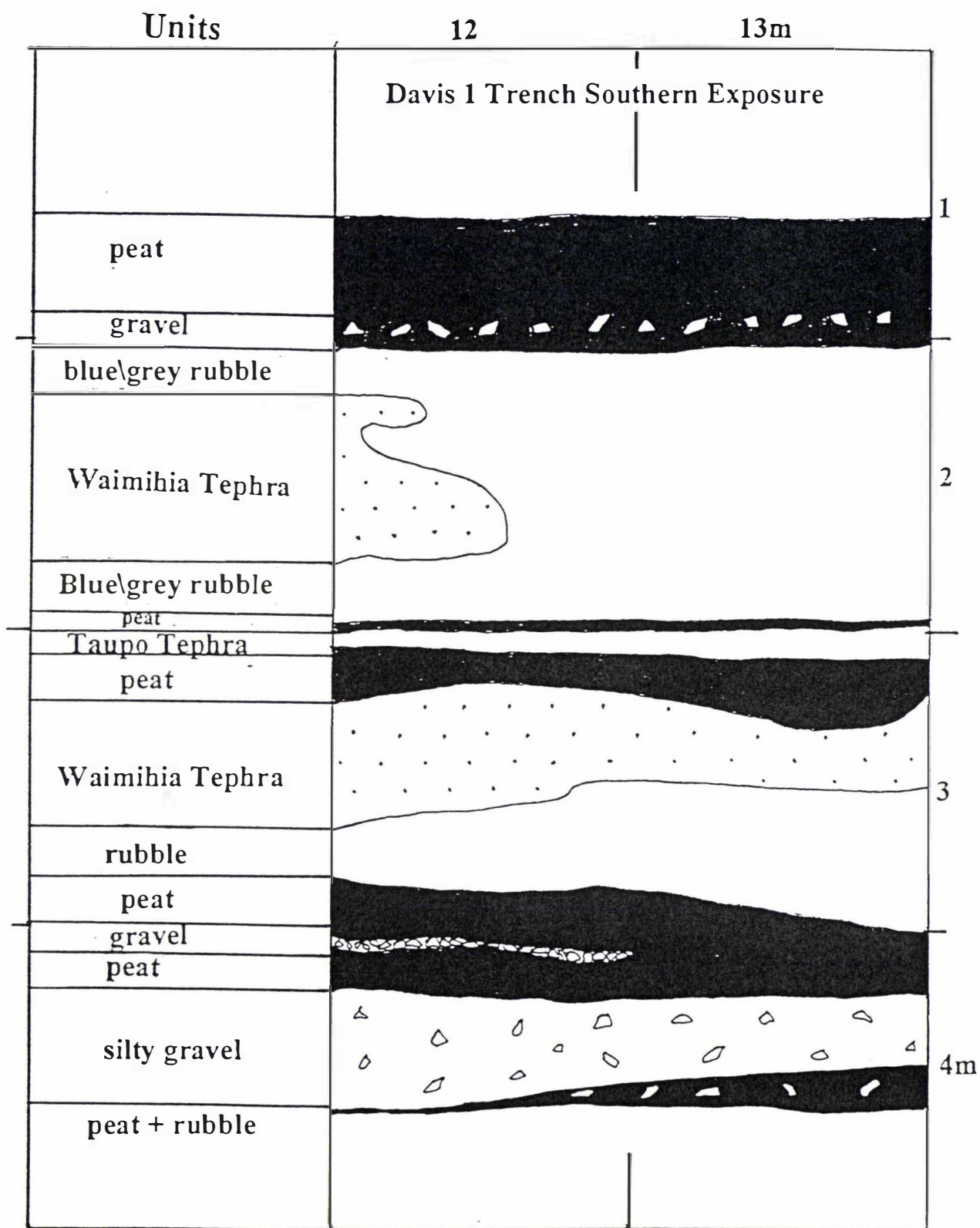
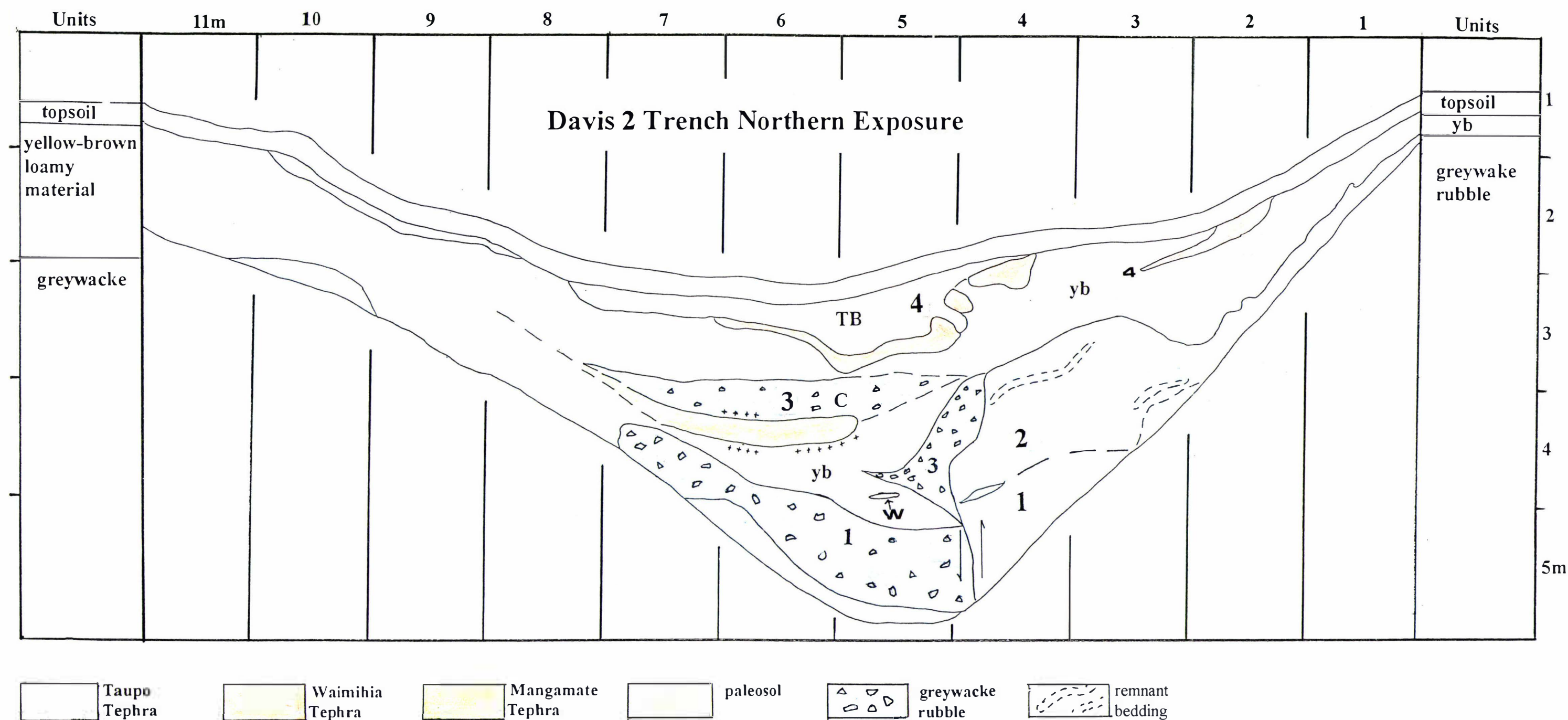
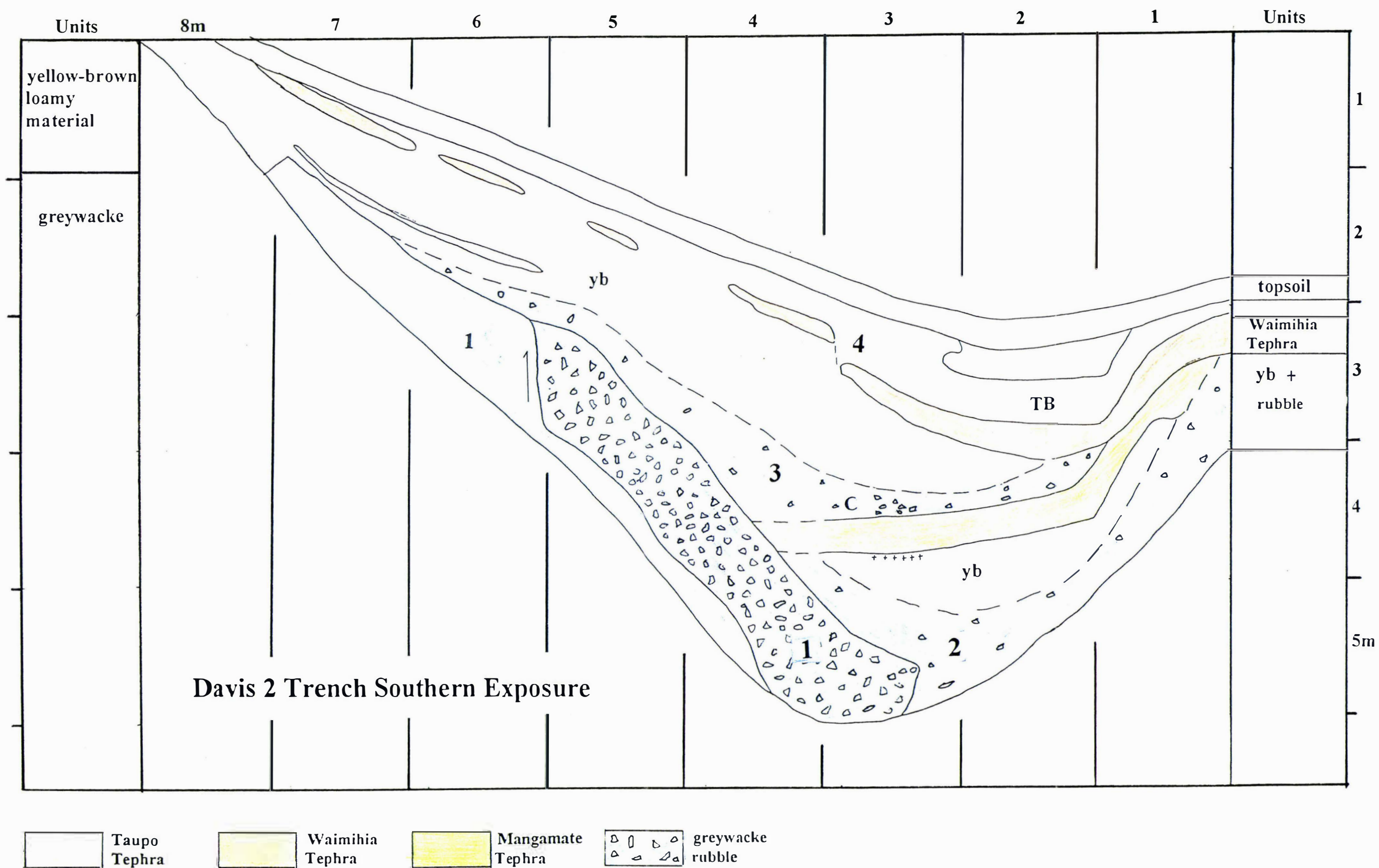


Figure 35. Cross section detail of the Davis 2 trench southern exposure showing stratigraphic sequences that are similar to those of the north wall of the trench.



TB = Taupo Tephra mixed with a subsoil, + = dispersed rhyolitic tephra, yb = yellow-brown loamy material, C = Carbonaceous material

Figure 36. Cross section of Davis 2 trench northern exposure south of the quarry on Whittle Road, showing stratigraphy and proposed sequence of earthquake events seen within the trench. Event 1 initiation of up to the east movement pre Waiohou Tephra (W) 11,850 +/- 60 yrs B.P., and deposition of colluvium into the trench. Event 2 further uplift to the east deposits more colluvium into the trench pre Mangamate tephra c.10,000 yrs B.P. Event 3 deposits colluvium into the trench on top of the Mangamate Tephra. Event 4 disrupts a paleosol and causes Taupo Tephra to be mixed with a subsoil Post 1,850 yrs B.P.



TB = Taupo Tephra mixed with a subsoil, + = dispersed rhyolitic tephra, yb = yellow-brown loamy material, C = Carbonaceous material

Figure 37. Cross section of Davis 2 trench southern exposure south of the quarry at Whittle Road, the proposed sequence of events 1 to 4 are the same as those found in the northern exposure of this trench.

carbonaceous material. On top of these units is a layer of Waimihia Tephra and then a layer of Taupo Tephra mixed within a B horizon subsoil. The uppermost unit is a 0.2 to 0.3m thick topsoil. The above units are the same for both the north and south trench walls; (Figures 36 and 37).

Structure indicative of faulting events

Within the north trench wall the greywacke has been uplifted by at least 2m to the east from the floor of the trench (Plate 61). This upthrown greywacke still contains some remnant bedding. The Mangamate, Waimihia and Taupo Tephra have all been truncated along with an adjacent paleosol seen on the north trench wall between the 2 to 3m vertical marks and in the south trench wall between the 6 and 7m vertical marks. In spite of the disruption of these features no planar fault surface was detected.

PROPOSED SEQUENCE OF EVENTS FOR DAVIS 1 AND 2 TRENCHES

Davis 1 Trench (Figure 34)

- The first faulting event in recent times (pre 7778 $\pm$ 81) would be the initiation of the upward movement to the east along this segment of the Ruahine Fault, to create a fault trench in which materials could accumulate.

There followed an interval where uplifted Tertiary siltstone is eroded into the trench. Wood from within the eroded siltstone gave a radiocarbon age (NZA 8233) of 7778 $\pm$ 81 yrs B.P. Drainage within the trench became blocked by the previous faulting event, causing peat to accumulate.

- The second earthquake event within the trench downdrops a large silt block on top of the peat (8-9m vertical mark). Wood from beneath this block has a radiocarbon age of (NZA 8231) 5971 $\pm$ 78 yrs B.P. There are angular greywacke pebbles within the peat which also indicate an earthquake event at this time.

Another time interval ensues where a thin lens of fine well rounded gravel is then deposited into the trench and up to 0.40m of peat accumulates. This peat contains wood fragments and siltstone chips.

- A third earthquake event occurs and the thin fine gravel lens is offset vertically up to the east by 0.17m. Wood from the top of this unit is radiocarbon dated (NZ 8232) at 3623 ± 57 yrs B.P.
- A fourth earthquake or storm event deposits a blue-grey rubble into the trench area. This unit is seen in the south trench wall (Figure 35) and under the fold in the Waimihia Tephra in the north trench wall (Figure 34). This event occurs post 3623 and pre-3280 $\pm$ yrs B.P. (Froggatt and Lowe 1990) which is when the deposition of the Waimihia Tephra occurred.

During the following time interval 0.19m of Waimihia Tephra is deposited into the trench at 3280 ± 20 yrs B.P. Then up to 0.2m of peat accumulates on top of the tephra, followed by the deposition of up to 0.16m of Taupo Tephra 1850 ± 10 yrs B.P. (Froggatt and Lowe 1990). Overlying the Taupo deposits is a further 3mm thick deposit of peat.

- A fifth earthquake and or storm event then deposits blue-grey rubble with 85% angular greywacke pebbles and plus reworked Taupo Tephra into the trench. Wood and peat at the base of this unit is dated (NZA 8230) at 1281 ± 63 yrs B.P.
- A sixth earthquake event then occurs when a 0.6m offset thrust fold is developed within the Waimihia Tephra. This corresponds with a 0.6m offset in the overlying blue-grey rubble. The overlying peat is also offset but some peat may have accumulated on the downthrown side of the offset at a latter date.
- After the above peat accumulates, a seventh earthquake or storm event deposits a layer of angular greywacke pebbles on top of the peat. A further 0.5m of peat then accumulates on top of these angular greywacke pebbles.

- An eighth earthquake event causes fissures (extending to the surface) to open in which rubble is deposited at the 9, 10m and 21, 22m vertical marks in the trench.

Davis 2 Trench (Figures 36 and 37)

- The first earthquake event preserved in this trench would have been the change in throw of the fault initiating the eastward upward movement prior to 11,850 yrs B.P. (i.e.- pre deposition of the Waiohau tephra).

During the interval between further faulting more greywacke rubble fell into the trench followed by the deposition of a yellow-brown allophanic unit enclosing a rhyolitic tephra. This tephra has a similar glass chemistry to those with an Okataina source and the most similar tephra known from this area is Waiohau Tephra (S. J. Cronin pers comm. 1994) dated at $11,850 \pm 60$ yrs B.P. (Froggatt and Lowe 1990).

- The second earthquake event is recorded by rubble in the north trench wall overlying the yellow-brown allophanic unit and further eastward uplift.

The above event is followed by an interval where more yellow-brown allophanic material is deposited into the trench. Above this is a dispersed rhyolitic tephra which is probably the Karapiti Tephra dated at $10,100 \pm 80$ yrs B.P. (Wilson 1993). Overlying the above units is the Mangamate Tephra aged c.10,000 yrs B.P. (Donoghue et al 1991). On top of the Mangamate Tephra is another dispersed rhyolitic tephra which may be Poronui Tephra dated at 9810 ± 50 yrs B.P. (Froggatt and Lowe, 1990).

- A third earthquake event post- 9810 ± 50 yrs B.P. truncates the above tephras with further uplift of the rubble on the eastern side of the trench. More rubble is then deposited into the trench on top of the disrupted tephra units.

Another time interval passes and more yellow-brown allophanic material is deposited into the trench. This is followed by the deposition of the Waimihia Tephra dated at 3280 ± 20 yrs B.P. (Froggatt and Lowe 1990).

More yellow-brown allophanic material is deposited followed by the Taupo Tephra dated at 1850 ± 10 yrs B.P. (Froggatt and Lowe 1990).

- A fourth faulting event occurs post-1850 yrs B.P. where the Waimihia Tephra is offset vertically 0.13m (in the south trench wall) and in the north trench wall Taupo Tephra is found in contact with and between pockets of Waimihia Tephra. This is suggestive of lateral fault smearing by strike-slip action. If this trench is correlated with the Davis 1 trench then there are several earthquake events represented here.

Correlation of earthquake events for Davis 1 and 2 is difficult because they were excavated through different lithological units. Davis 1 trench revealed a younger series of events preserved within peat layers with Davis 2 preserved mainly older earthquake events within older tephras. However together these two trenches reveal a history of earthquake activity over more than 11,000 years. Both trenches show that fault activity has occurred since the deposition of the Taupo Tephra (1850 yrs B.P.)

The Ruahine Fault Trace North Of Whittle Road

North of Davis 1 trench site the fault continues to be upthrown up to 12m to the east and offset horizontally by up to 10m in streams and 55m on shutter ridges. A fragment (0.08m) of greywacke rock found in the fault trench (unfortunately not in situ) had 2 sets of polished slickensides engraved on the surface. One set of slickensides had erased the limonite covering from the rock surface showing the greywacke beneath and the other angled at 10° away from and appearing to overlie the first, consisted of a highly polished surface. These surfaces serve to illustrate the oblique-slip nature of this section of the fault.

Eastward uplift continues northward for approximately 4km. Then there is a change in direction to westward uplift and the fault is seen as an eastward-facing break in slope north of the zigzag in Hot Springs Road (Figure 33, Plate 62). North of Makahu Road (just off the tar seal) is a stream with a 60m horizontal offset. The offset surface above the stream appears to be of Ohakean or early Holocene age because the next highest terrace remnant appears to be of Ratan age (based on the road cutting higher up on Hot Springs Road close to the zigzag (Hammond 1997).

However the offset stream and accompanying terrace surface may have evolved their present shapes as a result of what appears to be a right (extensional) step of 200m in the fault trace (Figure 33). At this locality Taupo ignimbrite (1850 yrs B.P.) onlaps or is faulted against Torlesse greywacke (Plate 63). On the north side of the offset stream where Taupo ignimbrite (1850 yrs B.P.) onlaps the terrace surface is a 0.90m vertical offset which is upthrown to the east. On the lower recent terrace surfaces the vertical offset is seen to be 2m (Plate 64). This latest 2m offset appears to be an exhumed surface exposed by the river and the 2m vertical offset is only in part, a recent faulting event and part of an older event or events. At the base of a nearby river outcrop are Ohakean river gravels overlain by fluvial material consisting of pebbly and cobbly gravels within a silty unit. This was overlain by Waimihia Tephra which in turn is overlain by more sediment and Taupo Ignimbrite. On top are recent river gravels, silt and topsoil. Thus the larger vertical offset on the lower terrace nearer the river is explained by the higher terrace being a younger pumice deposit of the Taupo Ignimbrite offset vertically at 0.9m. Further north up the Ripia River is another very recent terrace surface which is offset vertically 0.9m to the east. The fault trace could not be followed further, due to forestry activity in the Awahohonu State Forest.

The fault trace appears again on the Napier-Taupo Highway, here it is seen only as a boundary between Torlesse greywacke and an island of relatively undeformed Nukumaruan limestone (Plate 65) containing *Pellicaria* gastropods. Most of the trace has been eroded away at this locality but this is most likely due to farming, roading and forestry activities rather than a lack of faulting activity. In this area upthrow is still to the east and late Quaternary scarps and offsets can be seen north of the Napier-Taupo Highway near Tarawera (Beanland and Berryman 1987).

SUMMARY OF RECENT OFFSET FEATURES AND OFFSET RATES FOR THE RUAHINE FAULT

Vertical rates of upthrow to the east come from the base of the Davis 2 trench where tephra close to the trench base is dated at $11,850 \pm 60$ yrs B.P. and records an overall upthrow to the east of about 10m. This gives a

maximum vertical offset rate of 0.84mm/yr. A minimum vertical offset rate of 0.48 mm/yr is determined using the upthrow (0.9m) which has occurred since the Taupo Tephra was deposited.

Horizontal offsets are more difficult to determine as streamlets are offset up to 10m and spurs offset up to 55m. It is possible that this discrepancy formed after the Taupo eruption. New streamlets had to cut through the newly formed ignimbrite which covered the surface of this area (Hammond 1997) creating younger geomorphic landforms. This explanation is based on the thickness of ignimbrite found in the area and the similarity of the resulting offset rates for the 55m scarps and younger streams. For 10m of horizontal offset post-Taupo the rate is 5.4mm/yr. If the 55m horizontally offset scarp is used along with the age when eastward upthrow was first initiated (Davis 2 trench) then a rate of 4.64mm/yr is determined.

Beu (1995) has used Nukumaruan limestone facies for paleogeographic reconstructions giving a total horizontal offset for the Ruahine Fault of 20km, which can be resolved into 8mm/yr using the date Beu supplies for the onset of offset (2.5ma).

Table 4, A summary of faulting events from the Davis 1 and 2 trenches, for the Ruahine Fault. EQ are earthquake deformation events seen within the trenches but not dated.

Faulting events	Davis 1 trench	Davis 2 Trench
10	EQ	
9	EQ or storm event	EQ?
8	post 1281	
7	post 1850	post 1850
6	pre 3280	
5	post 3623	
4	c. 5971	
3	pre 7778	post 9810
2		pre 10,100
1		pre 11,850

The above Table shows that there were at least 9 faulting events in roughly the last 12,000 yrs, and that 3 or 4 of these events occurred since the deposition of the Taupo Tephra 1850 yrs B.P. This is a much higher frequency of faulting events than that seen on the Wellington Fault in the same area.

CHAPTER 8

SUMMARY OF PALEOSEISMIC DATA FOUND IN EXCAVATED TRENCHES AND ALONG FAULT TRACES

This chapter summarises similar structural features indicative of faulting events and sedimentation rates found within excavated trench sites for the Wellington, Ruahine and Te Waka Faults. Fault scarp morphology is discussed and compared with similar studies overseas to give age estimations of the latest rupture faulting events. This gives a sense of timing for undated fault scarps on the Wellington, Ruahine and Te Waka Fault traces.

COMMON STRUCTURAL FEATURES INDICATIVE OF FAULTING EVENTS FOR EXCAVATED TRENCH SITES

There were a number of features indicative of faulting events which were common to all trench sites. In general there was a lack of faulted surfaces with slickensides. Data produced from excavated trench sites within New Zealand and overseas shows that this lack of faulted surfaces is common (Schwartz and Coppersmith 1984, Rockwell 1988, Beanland and Berryman 1990, Ikeda et al. 1991, Niemi and Hall 1992, Hull 1994). There were often visible lithological differences between truncated sediments with no discernible fault plane between them, e.g. in the Wedd trench (Te Waka Splinter Fault) Davis 1 and 2 trenches (Ruahine Fault) and Syme, McCool and the Inglis 4 trenches (Wellington Fault). It is possible that some of these expected fault planes were not present due to the amount of the allophane present within the terrestrial sediments. Soils containing allophane are sensitive and under physical disturbances such as ground shaking lose their inherent strength and flow (Oborn 1985). Trenches with fault planes but without slickensides were Trotter 1, Trotter 2 and Inglis 3. These trenches contained gravels, where the majority of clasts adjacent to the fault plane had their short axes aligned perpendicular to the fault plane. There were also

some exotic units that were not derived from sediments seen within the trench foot or hanging walls or from units found in the vicinity of the trench. These were the yellow-brown loam unit within the Syme trench (Plate 45) a displaced older peat block in McCool trench (Figure 24) and a breccia unit found in the Inglis 4 trench (Figure 6). These units are thought to have been carried along the fault plane surface by repeated strike-slip faulting with their vertical position depending on the obliquity of faulting in that area. Inglis 4 trench had the only horses (Ramsay and Huber 1987) or slices from the hanging or footwall that were directly thrust into other units (Plates 15, 16, 17 and 18).

Owing to the large dextral offsets (60m) seen at both Syme and Wedd trench sites and the small number of earthquake events seen within the excavated trenches (3 and 4 respectively). It is thought that a number of strike-slip events have been smeared together. Local vertical offsets at both of these sites over the last 10,000 years is small (c. 0.6mm/yr) and strike-slip events are difficult to separate in a vertical trench with high horizontal offsets. This can be seen in (Plate 43) where strong strike-slip activity has offset spurs with no major height differences at Hawkstone Station.

SEDIMENT ACCUMULATION RATES FOR EXCAVATED TRENCH SITES

The rate of sediment accumulation in the areas adjacent to the excavated trench sites serves to demonstrate that these were mainly depositional environments and thus preserve many faulting events. Additionally, a fault trace having such a high horizontal offset rate will record and preserve more earthquake events where sedimentary deposits are rapidly buried under earthquake-derived debris. Therefore, most events seen within the excavated trenches are considered to be the result of earthquake and not storm or erosional events. Sediment accumulation rates also serve as checks on radiocarbon dates and deduced rates of offset.

Excavated sites containing peat

From radiocarbon dates obtained in this study peat accumulation rates of 1mm per year (A S Palmer pers commun.) apply to most trench sites although swamps with sedges are reported to have a higher accumulation rate. Peat in the Trotter 1 trench took almost 3000 yrs for approximately 1.5m of peat to accumulate: in the Trotter 2 trench it took 1080 years for 1m of peat and 0.5m of silt and woody debris (approximately 1mm/yr). In the auger hole at the Paper Road site, 1.8m of peat and 1.95m of silty sandy sediment formed in the swamp in only 1746 years. However, peat is likely to have formed at the 1mm per year rate with the silty sandy units being deposited rapidly from the collapse of the adjacent hanging wall of the Wellington Fault (Plate 23). In view of this rate, it is proposed here that the horizontal offset rate of 14.3mm/yr for this section of the fault trace is reasonably accurate and may be a minimum.

In the Ohara Depression at McCool 1 trench 0.6m of peat accumulated over the last 1850 years and in McCool 3 trench up to 1m within the same time span. The Syme trench has up to 1m peat accumulation in 1400 years but only 0.40m since 1850 years B.P. The slower rate is probably due to changing drainage patterns from faulting activity. Davis 1 Trench also has variable rates ranging from up to 1m of peat accumulating at the wetter trench locations in 1400 years to 0.2m within the same time span for drier areas.

Sediment rates for sites without peat

Terrestrial sedimentary rates for trenches excavated within the fault trace minus peat are, Inglis 3 where 2m of unctuous clay accumulated over 5104 yrs. This clay was derived from the hanging wall of the Wellington fault scarp (Appendix 1). Up to 3m gravel was deposited in the same trench in 4335 years before present. The Inglis 4 trench has 6m of sediment which took more than 30,000 years to accumulate. The Wedd trench accumulated 3.5m of sediments in 12,000 years and the Davis 1 trench has approximately 4m of sedimentary units which were deposited over the same time period.

A natural exposure on the Wellington Fault recorded by Raub et al. (1987) in the Ohara Depression contained 2.5m of sediment which had accumulated in 1165 years. Another trench north of the Napier-Taupo Highway had an accumulation rate of 3m in 9,000 years (Hull 1983). Other trenches excavated by Beanland and Berryman (1990) south of the Manawatu Gorge at Pahiatua had accumulated sediments at a rate which roughly equalled 1m for every 1000 years. Trenches excavated farther south, closer to Wellington (Van Dissen et al. 1992) had sediment accumulation rates of 2 and 3m over a 9000 to 10,000 year period.

In general trench sites north of Wakarara (away from the Ruahine Range) in the Ohara Depression have lower sediment accumulation rates. However as these sites record most of the major tephra deposits over the last 12,000 years on the downthrown side of the fault, they must lie within depositional environments because severe erosional periods would have erased most of the fragile tephra layers.

FAULT SCARP MORPHOLOGY

A fault scarp has been defined as a tectonic landform coincident or roughly coincident with a fault plane that has dislocated the ground surface (Stewart and Hancock 1990). Initial faulting produces a steep scarp called a free face (Wallace 1977, Mayer 1984). The free face slope is related to the mechanical properties of the faulted materials and the dip of the fault plane at the surface. Scarp degradation usually starts with a gravity-driven phase leading to the destruction of the free face. The maximum angle of this debris slope is controlled largely by the angle of internal friction of the material and the angle of repose (usually 30° to 35°). Following this phase, usually 10 to 100 yrs (Avouac 1993) slower erosional processes such as rilling, overland flow, gravity and rain impacts become dominant (Figure 38a). The importance of each of these processes depends on the local lithologic and terrain conditions as well as more regional factors such as climate and faulting activity (Wallace 1977, Bucknam and Anderson 1979, Mayer 1984, Andrews and

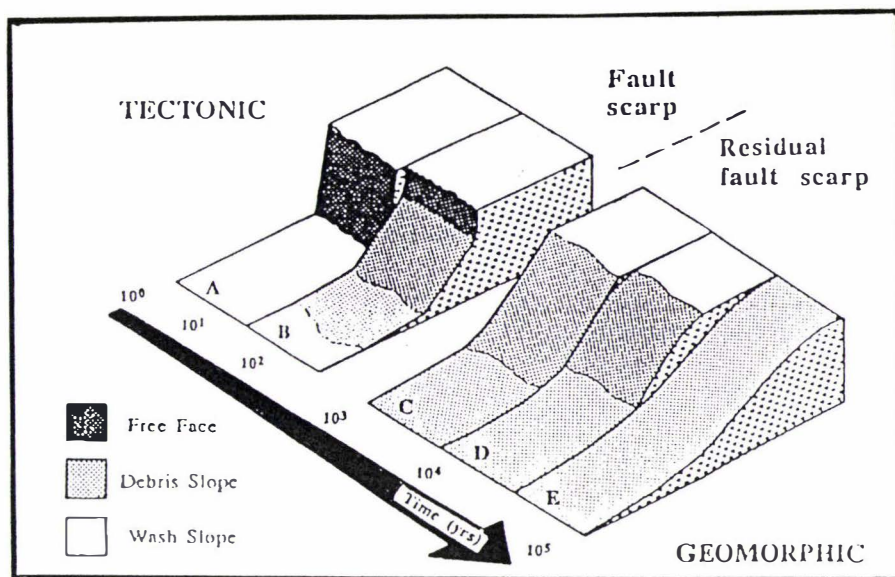
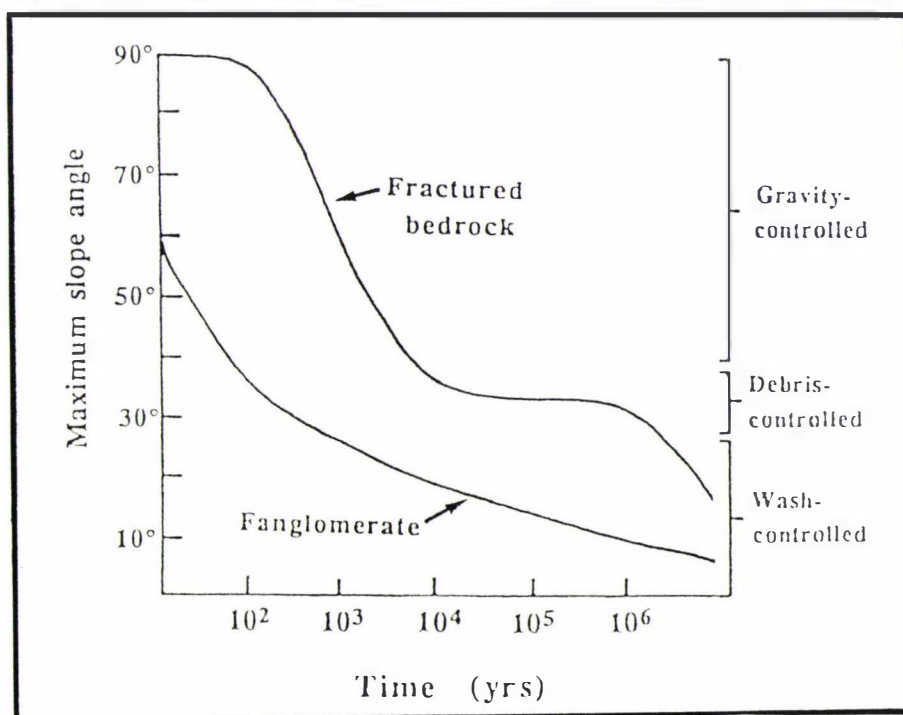


Figure 38a, Modification of a tectonic fault scarp to a residual fault scarp, most scarps belonging to the Wellington, Ruahine and Te Waka Faults had slopes of over 30° . Dated scarps had slope angles of 35° and fitted this diagram between categories B and C. Some scarps on the western edge of the Maniaroa Range and Te Waka Fault were category B only. Diagram modified from Stewart and Hancock (1990).

Figure 38b, Limits of maximum slope angle versus age of the fault scarp shows scarps in fractured bedrock are modified more slowly than scarps in fanglomerate. Bedrock scarps follow a similar sequence of gravity controlled, debris controlled and sheetwash controlled stages as well as decreasing slope angles but over longer periods of time. Modified from Stewart and Hancock (1990).



Hanks 1985, Avoulac 1993). Studies overseas have found that fault scarps in coarse-grained alluvium are steeper than those in fine-grained deposits (Mayer 1984, Stewart and Hancock 1990). For New Zealand conditions Hull (1990) reported that fault scarps having 4.6m of vertical separation from the 1931 Hawkes Bay earthquake were not well preserved in 1984 and only about 3km of fault trace could be confidently recognised.

Some faults in the study area strike through weakly consolidated sediments, these areas have more rounded fault scarps which may reflect a higher erosion rate, for example the area south of Willowford. In contrast areas of Torlesse greywacke bedrock (Plate 31) have a slower erosion rate. Studies overseas suggest that these bedrock surfaces are subject to a slope decline rate of only $0.036^{\circ}/\text{yr}$ (Stewart and Hancock 1990) and should not be compared to younger scarps of alluvial material (Figure 38b).

The free face of the hanging wall is not preserved anywhere on the Wellington or Ruahine Faults except at some bedrock localities (Plate 31) but the footwall face is often found more or less intact (Plate 23). In spite of the differences in climate between New Zealand and the Basin and Range areas of the United States of America, fault scarps with known ages on the Wellington and Ruahine Faults have similar slope-angle relationships to those overseas. Studies of fault-generated scarps overseas (Stewart and Hancock 1990) and in New Zealand (Cotton 1960) have shown that reverse fault scarps are usually more laterally discontinuous and more subject to erosion than normal fault generated scarps. However for most of their lengths (within the field area) the Wellington and Ruahine Faults have clear distinctive scarps with minor differences being due to different rock types. Normal fault scarp surfaces are usually better preserved (Plate 38) because there are no overhanging scarps which collapse quickly (Plate 23). All of the fault scarps observed in this study are the product of repeated faulting activity so the tops of these scarps are often more rounded because they have been exposed to erosional processes over a longer time period (Plate 23).

In the area between the Manawatu Gorge and Kumeti Road all the fault scarps in the trenched areas were fresh and had slopes of over 30° . The

latest age of these displaced surfaces was c.300 yrs B.P. (Figure 38a and b). If the reverse fault scarps with known ages in this area are compared with undated fault scarps between the Ohara Depression and the Napier-Taupo Highway, it can be seen that the ages of the scarps are comparable. This applies to the Wellington (Plates 38, 43, 44 and 47) Te Waka (Plates 52 and 55) and Ruahine Faults (Frontispiece, Plates 57 and 60). The above observation implies that both faults in the Ohara Depression and northward involve recent faulting with the latest events occurring between 300 to 400 yrs B.P.

CHAPTER 9

PALEOSEISMIC AND FUTURE HAZARDS FOR THE WELLINGTON AND RUAHINE FAULTS

This chapter discusses structure and fault deformation patterns which are seen along the Wellington and Ruahine Fault traces and within excavated trench sites. It also examines the effects that these structural and deformation patterns have had in the past, or may have in the future, on the geological landscape in terms of seismic hazards.

FAULT STRUCTURE, SEGMENTATION AND SURFACE RUPTURE

Faults are geometrically and mechanically segmented at a variety of scales. The ability of faults to rupture in lengths of tens to hundreds of kilometres represents a significant hazard. The term earthquake segment or fault segment here refers to those parts of a fault or faults that rupture as a unit during an earthquake (Machette et al. 1988). Primary surface rupture occurs during earthquake events when the fault rupture plane intersects the ground surface (Wells and Coppersmith 1994). Schwartz and Coppersmith (1984) first proposed that rupture on a given segment of a fault may be repeated many times with the same slip pattern characteristic to the segment. Since 1984 other earthquake researchers have agreed with this earlier study (Aki 1988, Bilham and King, 1988, Machette et al., 1988, Rockwell 1988 and Sanders, 1988). These workers have observed from paleoseismic studies that for many faults the amount of slip occurring at a given point on most faults is essentially the same during successive events. Therefore paleoseismic data, particularly the timing of past events, slip per event and slip distribution along the length of the fault are critical for defining persistent rupture segments, segment boundaries, scarp morphology and earthquake recurrence (Schwartz 1988).

Fault geometry is classified by Aki (1988) into two types. Type 1 has a straight trace with or without a slight bend and type 2 is a fault trace that is bent (10^0 or more) stepped or branched. Aki's studies found that type 1 geometry was an

earthquake starting point for 60% of real earthquake events studied and type 2 geometry a stopping point for 70% of real earthquake events studied.

PROPOSED RUPTURE SEGMENTS FOR THE WELLINGTON AND RUAHINE FAULTS

Fault segments have characteristic rupture patterns. Each segment interpreted in this study has been assigned independent behaviour for probabilistic hazard analysis.

Field observations of the Wellington and Ruahine Faults reveal that the faults do not deform the area through which they pass but rather act in response to the regional deformation within these structurally different areas. There are 4 main regionally different areas through which the faults pass. From south to north these are the region from Kahuki (south of the Manawatu Gorge) to the Ohara Depression, a region with prevalent strike-slip. The second is the Ohara Depression (a region with a dominant component of east-west compression). The third area is the region between the Ngaruroro and Tutaekuri Rivers, where compression has a north-northeast vector with a thrusting component. Brown (1980) maintains that strike-slip faulting action is here being translated into thrusting. The fourth area extends north from the Tutaekuri River to the Napier-Taupo Highway where strike slip and eastward uplift with a northerly tilt are the dominant components.

Wellington Fault

Kahuki-Dannevirke segment

The proposed southernmost segment in this study for the Wellington Fault is the Kahuki-Dannevirke Segment. This is based on the characteristic structural behaviour and timing of similar earthquake events which have occurred over the last 30,000 yrs B.P. between Kahuki and Dannevirke. Data for this proposal comes from trenching, offset studies, and fault structure within the area. The fault in this area acts similar to a type 1 fault (Aki 1988) where the fault trace is straight or has a slight bend of $<10^0$. The characteristic structural patterns for this segment are:

- There is minimal deformation along this section of the fault. Tertiary sediments are often pulled down (15°) close to the fault plane but this appears to be in response to drag from oblique strike-slip faulting. Younger sediments especially Porewan, Ratan and Ohakean river terraces show no folding and are undeformed except where they have been displaced vertically and horizontally at the fault trace.
- This segment of the fault has a greater en echelon pattern than seen elsewhere in the field area. Duplexes have formed where slip is transferred across the initial en echelon configuration between extensional and compressional steps in the fault trace. Strike-slip motion is prevalent in this area, and the average offset rate is 12mm/yr.
- Three large splinter faults seen as extensional features all branch to the north east between Coppermine and James Hill Roads (Marden 1984). This pattern of three closely spaced faults is only seen in this segment of the fault.
- Excavated trench sites on this segment of the fault trace have a history of faulting over 30,000 yrs B.P. Other sites farther north have a more punctuated history.
- Scarp morphology is of similar age (c. 300 yrs) and appearance, with some footwall free-face scarps being $>40^{\circ}$.
- The timing of faulting events is similar for this segment of the fault (Table 3). Vertical offset rates between Ballantrae and Trotter Farm are similar (Table 1) with the most recent uplift being up to the east.

It is possible that the southern part of the Kahuki- Dannevirke segment extends as far south as Wellington. Within this southern area data has been obtained by Lensen (1957) Beanland and Berryman (1990) and Van Dissen et al. (1992). Between Wellington and Dannevirke the fault trace is continuous but in the southern Tararua Range it is composed of two or more splays (Lensen 1957 and Van Dissen et al. 1992). Earthquake events on the fault from trenching studies outside the field area (Table 5) were located between Wellington and Kaitoke (Van Dissen et al. 1992) and at Pahiatua (Beanland and Berryman 1990) just south of the Manawatu Gorge. The timing of earthquake events along the entire segment from Wellington to Dannevirke appears similar for the last 3000 yrs. Not all the trenches at Pahiatua yielded c. 300 yr dates but as Wyss (1979) and Wells and Coppersmith (1994) observe, earthquakes commonly rupture only partially through to the surface in some areas over their sub-surface length. Unfortunately no earthquake event data has been obtained on the Wellington Fault between Kaitoke and Pahiatua.

If the Wellington-Dannevirke section is not a single fault segment then there must have been a number of rupture event earthquakes occurring at different localities on the Wellington Fault at similar times over the last 3000 yrs. If the Wellington-Dannevirke section consists of a single fault segment then it is a complex structure stretching for approximately 165km. It has slip rates ranging from 15mm/yr (max) in the north, to 5 to 7mm/yr (Van Dissen et al., 1992) in the south. A slip rate of 15mm/yr is very high by world standards (Allen et al. 1988). The northern sector between the Manawatu Gorge and Dannevirke has an average horizontal offset of 10m per earthquake. In contrast the southern section from Pahiatua to Wellington has an average horizontal offset of 3 to 4.7m (Berryman 1990). None of these figures are unusual; the San Francisco earthquake of 1906 ruptured along the San Andreas Fault over an area 450km long and 10m wide. North of San Francisco horizontal offsets were in the range of 4.9m to 5.5m whereas south of the city they were in the order of 1m (Niemi and Hall 1992).

It is possible that the Kahuki-Dannevirke segment of the Wellington Fault also extends as far north as the 500m compressional sidestep at Wakarara in the Ohara Depression.

Ohara Depression segment

The second proposed segment for the Wellington Fault is the Ohara Depression-Ngaruroro River Segment. Which is a type 2 stepped fault trace (Aki 1988). This segment begins south of Wakarara and ends at the Ngaruroro River in a region of east-west compression. Evidence for this segment includes:

- Tertiary sediments have been folded close to the fault trace and the Wakarara Monocline appears to merge with the fault. This can be seen on the south bank of the Ngaruroro River (Chapter 4).
- There is a 500m-wide left (compressional) step in the fault trace at Wakarara (Figure 21)
- Timing of faulting events in the south of the Depression (Raub 1985) are consistent with those found in the Big Hill (McCool) trenches. In the Wakarara area the latest earthquake rupture event occurred $\text{post-}1165 \pm 50$ yrs B.P. (Raub, Cutten and Hull 1987). In the Big Hill area at least two events have occurred post-Taupo Tephra deposition 1850 yrs B.P. A history of repeated faulting events from c. 14,000 yrs B.P. is recorded within the McCool 1 trench.

- Holocene horizontal offset rates for the Depression are 2.7 to 3.5mm/yr (Raub 1985) and for the Big Hill area are 4.9mm/yr.
- There are two left step (compressional) transfer splinter faults branching from the Wellington Fault in this segment, these are Cullens Fault (Raub 1985) and the Big Hill Fault (Erdman and Kelsey 1992).
- Fault scarp morphology in this area is similar to the southern segment with scarps being fresh and well defined ($\geq 30^\circ$) with the latest uplift being toward the east.

The Ngaruroro River to Tutaekuri River segment

This segment lies within a compressional regime but unlike the Ohara Depression compression has a more north-northeast vector. This area was not trenched and the largest horizontal offset (up to 150m) was a stream which was not dated. Key evidence for this segment is:

- The only dated horizontal offset rate of 3.3mm/yr for this segment comes from an Ohakean 2 terrace located on the north side of the Ngaruroro River.
- Fault scarps are generally more eroded in soft Tertiary marine sediments which south of Willowford Road dip gently inward toward the fault.
- Harder Tertiary limestone blocks have been uplifted and truncated close to the fault but are not folded.
- Between Willowford and the Tutaekuri River the area is covered by landslides and slumping features through which the fault trace is not visible.

Tutaekuri River to the Napier-Taupo Highway segment

In this area strike-slip is the dominant regime. The trace is generally straight and clear having a type 1 geometry.

- Fault scarps are fresh and steep with uplift being to the east, along the flank of the Maniaroa Range the scarps are steep with numerous landslides along its western face.
- This segment has one major splinter fault (Te Waka Fault) which is extensional with uplift to the east. This fault (from trenching studies) has similar timing of earthquake events and horizontal offset to the Wellington Fault.
- The Syme trench at Hawkstone Station in the Puketitiri area records at least one event post-Taupo Tephra deposition. There are only 3 faulting events recorded at this site with a history of over 11,000 yrs. Trenching studies in

the Mohaka River area (Hull 1983) show that at least two rupture events have occurred within the last 1900 yrs B.P.

- At Hawkstone Station the minimum horizontal offset rates are 6mm/yr with rates of up to 7.9mm/yr being recorded by Hull (1983) in the Mohaka River area north of the Napier-Taupo Highway.

Ruahine Fault

Kahuki-Southern Ruahine Range segment

The proposed southernmost segment for the Ruahine Fault is the Kahuki-Southern Ruahine Range segment. This segment covers the area between where the fault splinters from the Wellington Fault just south of the Manawatu Gorge through the Ruahine Range to Cullens Trig in the south of the Ohara Depression. This segment consists of multiple fault traces and crush zones with few horizontal offsets. There is only one locality where the fault shows possible evidence of Quaternary movement, close to Maharahara Trig (Marden 1984, see chapter 6).

Ohara Depression segment

The next proposed segment for the Ruahine Fault is the Ohara Depression-Ngaruroro River Segment and starts from a large compressional side-step west of Cullens trig. This is in contrast to the Kahuki-Ruahine Range segment with little recent offset. There is evidence of very recent offsets on this segment at McIndoe Flat on the south bank of the Ngaruroro River. Key evidence for this segment includes:

- The most recent uplift is toward the east. The fault trace has more rounded scarps in the south of the Depression. In the north the fault scarps are steep and fresh with slopes $\geq 35^\circ$.
- At Wakarara there is a large compressional (1.5km) sidestep which is a possible starting point for this segment.
- In this compressional zone some of the Tertiary sediments are folded parallel to the trace in close proximity to the fault.

Ngaruroro River to Tutaekuri River segment

This segment of the fault lies within a north to northeast compressional zone where strike-slip movement is translated into a thrusting regime. This is a type 2

regime (Aki 1988). The Ruahine Fault has a dual trace though out this area. The eastern trace across the flank of The Lizard has Tertiary sediments completely overturned (Beu 1995). The more western trace borders the Miroroa Thrust fault (Figure 31a).

- The most recent uplift is toward the east with fault scarps in general being poorly defined and difficult to follow both in the field and on aerial photographs.
- It is possible that the Kaweka Fault is a compressional splinter branching to the west, with uplift being toward the west.

The Tutaekuri River to the Napier-Taupo Highway segment

This segment represents a type 1 geometry having a single straight clear trace.

- In the Puketitiri area, the Davis 2 trench has evidence of at least one rupture event post-1850 yrs B.P. Up to four possible rupture events are seen in the Davis 1 trench post-1850 yrs B.P.
- Streams are offset horizontally between 8 and 10m; older ridges and an Ohakean terrace surface are offset horizontally by 55 and 60m respectively.
- Fault scarp morphology is fresh with slopes $>35^{\circ}$. A strong scissors-type geometry is evident, with uplift toward the east at the trench sites yet 4km south upthrow is toward the west.
- North of the Napier-Taupo Highway close to the Waipunga River, Beanland and Berryman (1987) consider that two fault rupture events may have occurred in the last 5000 yrs.
- The horizontal offset rate for this area ranges between 4.6 to 5.4mm/yr.

EARTHQUAKE MAGNITUDE AND INTENSITY MODELS

Recently in the United States of America, empirical formulae based on historical and modern earthquake data have been used to estimate earthquake magnitudes (Bonilla et al. 1984). A worldwide data base of earthquake source parameters have been used for these studies and models prepared. The first model is based on average displacement measurements which are calculated from net displacements recorded as near as possible along the entire surface rupture. Net displacements are used because the largest displacements typically occur along a limited reach of the rupture zone (Wells and Coppersmith 1994). A second model is based on the primary surface rupture length of a given fault segment.

This second model is complex and it is recognised that during a large release of strain, primary surface rupture segments on some faults can sometimes overlap (Ikeda et al. 1991 and Schwartz 1988). However, when segment or rupture overlap does occur other deformational features such as offset within these individual segments will still behave in a characteristic manner. In this study the first model is estimated using only net displacements. Calculations for the second model are based on the minimum possible length that an individual segment may rupture.

Wellington Fault

Models from the above sources have been used by Berryman (1990) to provide an estimate of the likely magnitude of an earthquake in the Lower Hutt-Wellington area. The first formula for displacement of strike-slip faults is:

$$M_S = 7.00 + 0.782 \log 10D$$

where M_S is the predicted surface-wave magnitude and D is a single event fault displacement in metres. The results predict a 7.4 to 7.5 magnitude earthquake for a single event with 3.4 to 4.7m offset. Using the same formula an earthquake event with an average single rupture of 10m (seen in Kahuki-Dannevirke segment) would produce a M_S earthquake of 7.8.

The second formula for strike-slip faults using length is:

$$M_S = 6.24 + 0.69 \log 10L$$

where L = rupture length in kilometres. This would produce an M_S earthquake of 7.3 over the 35km length of the Kahuki-Dannevirke Fault segment, which is the minimum distance for the rupture length in this area. The rupture length for this area however may extend as far north as the Ohara Depression or farther south toward Wellington.

The estimated magnitude for the Ohara Depression segment of the Wellington Fault is a little more difficult to determine accurately as there were fewer trenches excavated. In over 14,000 yrs of eastward uplift (McCool 1 trench) there has been over 66.9m of horizontal movement with up to 6 faulting events recorded within the trench. If all the events recorded within the trench are true rupture events then there is a minimum average offset of 10m per earthquake. These earthquakes would have magnitudes of M_S 7.8. Using the rupture length formula each average earthquake event would measure M_S 7.4.

As there were no trenches excavated in the Ngaruroro River to the Tutaekuri River segment only the proposed rupture length of 25km can be used and this gives an M_s value of 7.2.

The Tutaekuri River to Napier-Taupo Highway segment has a higher rate of horizontal movement than the Ohara Depression segment, with a minimum horizontal offset of 60m over 10,000 yrs. However the Syme trench appears to contain only 3 earthquake events over a similar period of time. It is possible that not all the strike-slip events are preserved here or that the events have been smeared together by the more dominate strike-slip action. Using the rupture length formula an average earthquake event of M_s 7.3 is obtained. This is a minimum value as it is not known how much farther this segment extends to the north of the field area.

The rupture length formula used for the Te Waka Splinter Fault, gives an average earthquake event of M_s 6.9. As there were only 4 faulting events recorded within the Wedd trench over a period of 11,000 yrs, no estimation of single offset events over this time period were made.

Ruahine Fault

The proposed southernmost segment for the Ruahine Fault (Kahuki-Ruahine Range segment) does not appear to have been active during Holocene times. The rupture length formula can be used here and an average earthquake event of M_s 7.5 obtained. The untreated Ohara Depression segment of the Ruahine Fault has a rupture length of 35km, an average earthquake event for this region would have a value of M_s 7.3. Likewise the segment between the Ngaruroro and Tutaekuri Rivers has a rupture length that would produce an average earthquake event of M_s 7.2.

Farther north on the Tutaekuri River to the Napier-Taupo Highway segment, where the Davis trenches are located, there are 10 possible fault rupture events recorded over 12,000 yrs with 55m and 60m of horizontal offset for similar aged features measured at different localities along the fault segment. An average horizontal earthquake movement for this section of the fault would be 5.5m and the predicted magnitude for a single offset is M_s 7.5, while the rupture length estimation would give a value of M_s 7.4. This latter value is thought to be a minimum as the northern extent of this segment is unknown. If the 3 earthquake events from the Davis 1 trench post-1850 yrs B.P. are used and a number of

horizontal stream offsets (of 10m, from up to 1km either side of the trench site) are assumed to have occurred since that time then, an average earthquake event of M_s 7.4 is found for the same locality.

It has been proposed by Wells and Coppersmith (1994) that the above estimated values of M_s earthquakes show no systematic difference to M (which is a direct measure of the amount of radiated energy) at values between 5.7 and 8.0.

The Modified Mercalli Scale as used in New Zealand (Eiby 1966, Appendix 4) lists an M_s 7 to 7.3 earthquake event as being, of a magnitude corresponding to the highest intensity reachable. Earthquakes with this magnitude are listed as disastrous where ground cracks badly, many buildings are destroyed, railway lines are bent and landslides occur on steep slopes. Earthquakes having a M_s 7.8 magnitude are listed (Eiby 1966, Appendix 4) as being "very disastrous where few buildings remain standing, bridges are destroyed and all services including railways, pipes and cables are out of action, there are also great landslides and floods".

SUMMARY OF TIMING AND EARTHQUAKE EVENTS FOR THE WELLINGTON AND RUAHINE FAULTS

A summary of faulting events for the proposed Kahuki-Dannevirke segment of the Wellington Fault is presented in Table 5. Complementary data from the Wellington area has been added, because faulting in this area may be part of the same segment. EQ represents an undated earthquake event where deformation is seen but has not been dated. Other earthquake events have been dated either post- or pre- the event in yrs B.P. Earthquake events from the Wellington-Lower Hutt area are from trenching studies of Van Dissen et al (1992). Earthquake events recorded in trenches at Pahiatua are from Beanland and Berryman (1990) see table 5.

Table 5 Summary of faulting events for the Kahuki-Dannevirke segment and possible southward extension of the Wellington Fault through to the Wellington area.

Van Dissen	Beanland & Berryman	Inglis 3 Trench	Inglis 4 Trench	Beagley Farm	Trotter 1 Trench	Trotter 2 Trench
c.300-400	c. 300	syn or pre 211	EQ	C.290	c. 257	c.257
c. 800	post 860	EQ	EQ			pre 257
	1010-1160	EQ	post 1105			c.960
c. 3840					pre 2090	post 3110
		post 4335		post 5324	pre 5000	EQ
					pre 6750	EQ
		pre 9434	post 10,286			pre 6780
					post 22,020	
			pre 29,200			
			EQ			
			EQ			

Table 6 Paleoseismic events from the Ohara Depression segment of the Wellington Fault. Dates are from trenching studies either post- or pre- the earthquake event in yrs B.P. EQ are earthquake deformational events seen within the trench but not dated. Raub et al. (1987) showed that there has been a surface rupture post 1165 ± 50 yrs B.P.

Mc Cool 1 Trench
EQ or storm event
pre 605 or storm event
c. 805
post 1850
pre 3280
4295 to 5206
pre 14082

Table 7 Summary of earthquake events for the Tutaekuri to Napier-Taupo Highway segment of the Wellington Fault and the Te Waka Splinter Fault located in the same area.

Syme Trench Wellington Fault	Wedd Trench (Te Waka Splinter Fault)
post 1850	post or c.1850
8770 to 10000	post 10000
pre 10100	pre 10000
	pre 11850

Table 8 Summary of earthquake events from trenching studies on the northern segment (Tutaekuri River to Napier-Taupo Highway) of the Ruahine Fault. EQ are earthquake deformation events recorded within the trenches but not dated.

Davis 1 Trench	Davis 2 Trench
EQ	
EQ or storm event	EQ?
post 1281	
post 1850	post 1850
pre 3280 or storm	
post 3623	
c.5971	
pre 778	post 9810
	pre 10,000
	pre 11,850

GROUND SHAKING AND LANDSLIDES

This section discusses potential hazards associated with future earthquake events occurring on the Wellington and Ruahine Faults.

Ground shaking

A large region can be shaken during an earthquake event. The Napier earthquake was felt over most of New Zealand (Hull 1990). The severity of shaking at any site within the region will depend on the earthquake magnitude and the depth of the earthquake focus. Other factors include the distance of the site from the epicentre, and the nature of the local site geology and physiography. These factors control the felt intensity, ground acceleration, velocity displacement and duration of the earthquake. Structures sited across or very close to the Wellington and Ruahine Faults are likely to be at risk from ground rupture and direct displacement both vertically and horizontally. Within the field area the only dwellings located on or very close to the faults are farm houses. Those situated directly on the faults will be torn apart by any fault displacement. A number of farmhouses have been built on the upthrown scarp of the Wellington Fault adjacent to the fault trace, where there is a better view of the surrounding countryside. However most farmhouses are single storey dwellings and are well constructed. Farmhouses located at some distance from the fault may survive with only cracked concrete slabs. Older buildings will lose their chimneys and

may be displaced from their foundations but there should be little loss of life due to building collapse unless houses are situated on or beside oversteep hillsides where landslides can occur. The main danger to the cities of Palmerston North, Dannevirke, Napier and Hastings will be from ground failure. During strong ground shaking, areas having clay-free sands and silts, fill and ground water within 10m can temporarily lose their inherent strength and behave as viscous fluids (liquefaction). Structures situated on these materials can settle or be torn apart as the ground spreads laterally and flows. This can be accentuated in the ground shaking of sensitive soils containing clays and young unconsolidated tuffs and ignimbrite. Such materials are common in Hawkes Bay. The disturbance of a sensitive clay leads to non-recoverable rupture and subsequent breakdown of the soil fabric causing a loss of undrained strength, excessive settlement, subsidence of the ground surface and slope instability (Oborn 1985).

There are a number of cities located in close proximity to the Wellington and Ruahine Faults adjacent to the field area that would suffer extensive damage through large magnitude earthquakes on these faults. For example, the 1931 Napier earthquake (M_s 7.8) resulted in major damage through ground shaking to both Napier and Hastings cities with the loss of 256 lives. The calculated epicentre for this earthquake was located 32km northwest of the city, not far from Patoka (close to the Wellington Fault, but not directly associated with it). Local historians recorded little damage at this locality, the major ground shaking being felt in Napier and Hastings. In Waipawa and Waipukurau (75km to the south of the epicentre) ground shaking resulted in the collapse of some buildings and all chimneys.

Table 9, Major towns and cities located on younger unconsolidated sediments and fill materials which are in close proximity to the Wellington and Ruahine Faults, at risk through ground shaking.

Town or City	Approximate distance from Wellington and Ruahine Faults
Fielding	< 20km
Palmerston North	13km
Woodville	<6km
Dannevirke	10-15km
Waipukurau	32-38km
Waipawa	32-38km
Havelock North	45km
Hastings	40-45km
Napier	40-45km

Landslides

Earthquake shaking can dislodge rock and debris on steep slopes, triggering rock falls and slides. Valley slopes adjacent to the Wellington and Ruahine Faults are steep (especially within the Ruahine Range) and have an average gradient of 30° . Slopes of 40° to 50° are common especially where the fault traces cross stream channels. Within the field area a large number of slumps occur adjacent to the fault traces or within a zone of fault-brecciated bedrock. There are two types of landslides associated with the faults. These are primary slides directly associated with fault traces and secondary slumps caused indirectly by faulting activity. Marden (1984) estimated that 25% of rock slumps within the southern Ruahine Range occurred in association with major fault traces and that most other rock slumps were the result of gravitational forces acting on fault disrupted bedrock. He estimated that 58% of all earth slumps in the area occur on the traces of known faults (Marden 1984).

The Manawatu Gorge is an area susceptible to landslide hazard because large portions of the gorge walls are composed of unstable bedrock overlain by loose scree. A large magnitude earthquake in the area would activate major landslides. At risk from landslides are the engineering works of the state highway located on the south wall of the gorge and the railway to Napier on the north gorge wall (Plate 2). At the east end of the gorge is a large block of Nukumaruan limestone. The Wellington Fault trace is not seen crossing the limestone but rather is mapped by Marden (1984) around the toe of the limestone. Nowhere else on the trace of the Wellington Fault does the fault detour around such a large block of rock. Aerial photographs (Plates 4 and 5) and field mapping yield little trace of the fault through the hard limestone. It is here proposed that the limestone represents a large glide block that moved 200m eastwards, covering the fault scarp during one of the last earthquake events. Evidence of movement within the limestone include a buckled syncline above and south of the present quarry face and a small anticline seen within a weakly aligned gravel lens (Plate 6). There is a railway tunnel within this limestone through which passenger trains pass twice a day (Plate 3).

There is a large earth slump covering the fault trace at Willowford and another north of the Tutaekuri River where a linear feature (a possible extensional splinter of the Wellington Fault) can be traced on aerial photographs crossing the river to the head scarp of the slump. This slump has been dated at c. 900 yrs B. P. (V.E. Neall pers comm.) which possibly dates the post-1850 yrs B.P. earthquake event

seen in the Syme trench at Hawkstone Station. There is evidence for there being a faulting event recorded in the McCool 1 trench at c. 805 yrs B.P. There is another large earth slump on Hawkstone Station which has not been dated. This slump has numerous small landslide ponds and peat-filled hollows and is located to the west of the fault trace. Along the steeply upthrown western slopes of the Maniaroa Range are numerous landslides located along the Wellington Fault trace (Plates 44, 46 and 48).

A landslide at Te Pohue that blocked drainage to create a lake is sourced directly from the hillside which is the northern limit of the Te Waka Splinter Fault. Timing for this event comes from the Wedd trench located on the southern section of the Te Waka Splinter Fault which shows evidence of earthquake activity post 1850 yrs B.P. Other evidence for an earthquake event at this time comes from trenching studies near the Hautapu River (a tributary of the Mohaka river) where Hull (1983) reports two fault movements on the adjoining Wellington Fault which occurred in the last 1900 yrs B.P. One of these earthquakes occurred c. 1200 yrs B.P. and caused large landslides in the Mohaka River at Maungataniwha.

Landslide debris often creates blocked drainage and the formation of lakes. A major triggering mechanism for many of these landslide-dammed lakes are earthquakes (Lowe and Green 1987). Eleven small lakes were formed by landslides caused by the Buller earthquake of 1929 (Adams 1981). Lake Ngatapa was formed during the 1931 Hawkes Bay Earthquake when a landslide dammed a tributary of the Mohaka River. The lake was 2km long and up to 25m deep. At the time it was thought to be permanent, however it was washed out during a major flood in 1938 (Adams 1981). Lake Waikaremoana is one of the largest landslide-dammed lakes in the North Island and was possibly triggered by an earthquake on the Wellington Fault some 2200 yrs B.P. however there are no earthquake events recorded at this time in either Syme or Wedd trenches. On the northeast side of Lake Waikaremoana is another large landslide covering 53 km². Lake Waikareiti is one of many ponds filling hollows in the debris. This landslide is radiocarbon dated at 11,500 yrs B.P. (Ward 1995). There is a pre-10,100 earthquake event date for the Wellington Fault from the Syme trench at Hawkstone Station. It is possible that this landslide event could be correlated with the earthquake event seen in the Syme trench although this site is located some 60km south of the lake. To date the formation and failure of landslide-dammed lakes have caused little damage in New Zealand, although they are a significant geologic hazard (Adams 1981). There are a number of possible

sites for future landslide-dammed lakes to be created close to over steepened slopes on the Ruahine and Wellington Faults especially on the Ngaruroro River, which could cause severe flooding on the plains down stream.

CHAPTER 10

DISCUSSION AND CONCLUSIONS

This chapter discusses the effects the subducting Pacific Plate has on the North Island Shear Belt and in particular the Wellington and Ruahine Faults in terms of paleoseismic events and future earthquake hazard and prediction. Conclusions are drawn from the above relationships and the results of trench and field studies.

SUBDUCTION ZONE TECTONICS AND PREDICTIONS OF FUTURE EARTHQUAKE EVENTS

The North Island Dextral Fault Belt forms the westernmost part of the emergent plate boundary zone. Within this area are two main active dextral strike-slip faults and many associated faults. These faults have formed in response to oblique relative motion of the converging Pacific and Australian plates. The two major faults are the Wellington and Wairarapa Faults which are thought to extend to the surface of the subducting plate (Ballance 1975, Lamb and Vella 1987). If this is correct then the eastern North Island is a floating microplate bounded by the active dextral faults to the west and the subducting plate to the east. It has been designated by Ballance (1975) as the Hawkes Bay Crustal Microplate. This microplate is quite thin in places where the gently dipping subduction zone is only at a depth of 10 to 30km below the plate's surface (Kamp 1988). The history of faulting along the North Island dextral Fault Belt is quite complex. It has been suggested by a number of authors (Cole and Lewis 1981, Ballance et al., 1982, and Cutten 1994) that the current plate deformation zone (Hikurangi Margin) evolved by rotation of accretionary elements from an original northwest trending subduction zone which lay parallel to and east of Northland and Coromandel. The older elements of this prism were associated with subduction of a re-entrant of the Pacific Plate in mid-Tertiary times. The prism became separated from the northwest trending volcanic arc by dextral strike-slip movement along curved faults east of the Axial Ranges. This accounts for the paradox of a 22ma accretionary margin lying adjacent to a 2ma arc of the Taupo Volcanic Zone (Ballance et al., 1982). On the other hand Beanland (1995) has proposed that the currently active dextral faulting began in the Pliocene 4 to 2ma and that the North Island Dextral Fault Belt developed from Miocene to Pliocene

reverse faults in the inner forearc of the Hikurangi Margin. Plate reconstruction by Beanland (1995) shows that there was no requirement for earlier shear belts in the Hikurangi Margin. The difference in distance between the old volcanic arc and the new one is taken up by back-arc spreading and increased rates of plate rotation.

Subducting Plate Segmentation

As there have been no large interplate earthquakes with recurring intervals along the Hikurangi Margin and within the North Island Dextral Fault Belt since European settlement in 1840, determination of repeated long-term patterns was difficult (Reyners 1983). Reyners (1983) obtained seismic information of recurring earthquake patterns from other subduction zones having longer historical records namely the Nankai Trough to the east of Japan. Paleoseismic studies of recurring earthquakes in this area revealed a pattern of interplate seismicity with high levels of seismic activity in areas adjacent to rupture zones before a great interplate event. Postseismic activity was found to be high in marginal zones which border the preseismically active area. This seismic model was applied by Reyners (1983) to the few known interplate earthquake events which have occurred in New Zealand since the turn of the century. His study revealed similar results and showed evidence for plate segmentation due to the locking and unlocking of the plate interface.

The Wairarapa earthquake of 1855 is thought to have unlocked the plate interface to the south between Cape Turnagain and Wellington. Recent episodes of compression within this area are thought to be the result of the subducted plate and the overlying Hawkes Bay microplate becoming temporarily locked together again (Walcott 1978 and Reyners 1983). It has been suggested by Walcott (1978) that the 1931 Hawkes Bay earthquake ended the compressive phase in the northern section of the field area resulting in the decoupling of the overlying and underlying lithospheres between the Cape Turnagain area and Mahia Peninsula to the north. Earthquake activity north of Cape Turnagain was interpreted as relaxation in the subducted plate following the unloading or unlocking of the plate interface by the 1931 and 1932 earthquakes. The locking and unlocking of sections of the plate interface is manifest by segmentation or tearing (down-dip strike-slip faulting) in the plane of the subducting plate. These tears in the plate may not represent individual faults but rather zones of weakness developed over many cycles (Reyners 1983).

It is suggested here that lateral segmentation between the locked and unlocked plate interface and the increasing southward obliquity of the subducting plate is responsible for the differing kinds of strike-slip activity seen along the 4 proposed segments of the Wellington and Ruahine Faults within the field area. The southern Kahuki-Dannevirke Fault segment borders the locked plate interface, while the central fault segments of the Ohara Depression and Ngaruroro-Tutaekuri Rivers lie between the locked and unlocked plate interface. The northern fault segment (Tutaekuri River to Napier-Taupo Highway) lies within the presently unlocked regime. The proposed segments of the Wellington and Ruahine Faults are smaller than the plate segments and are thought to represent different structural regions of greater and lesser strain between locked and unlocked plate interface segments.

It is thought that down-dip tears may extend to the shallow part of the subducted plate (Reyners 1989). It has been suggested (Reyners 1989) that some segments or tears in the plate are major features and have surface manifestations, especially the tear which is traced between the Mangleton area (in the Ohara Depression) and northeast of Mt Ruapehu. It is of interest that both areas through which the proposed tears pass have major structural features. Within the field area Reyners' (1989) map of the proposed lateral tear or plate segments shows the southernmost tear as traceable through the Manawatu Gorge area. Farther north the next tear can be traced through the Ohara Depression area. If down-dip tears in the subducting plate are close to the microplate surface and have surface manifestations, then it is possible that the east-west compression of the Ohara Depression and north-east compressional vector of the Ngaruroro-Tutaekuri River segments are directly related to the underlying tear structures. The compression vectors of the Ohara Depression are compatible with a west-north-west direction of a down dip tear where softer younger sediments are being pushed and folded against the Axial Ruahine Range (Figures 2 and 21). Strain transfer from the Wellington to Ruahine Fault can also be accommodated by a west-north-west movement vector. Likewise just south of the Manawatu Gorge area the Ruahine Fault bifurcates from the Wellington Fault in a compressional left step with a more westerly component. There is a further compressional left step on the Ruahine Fault within the Manawatu Gorge (Figure 3). The Ngaruroro-Tutaekuri River Fault segment has a rotational northeast compressional vector with overturned sediments and complex faulting compatible with an area lying between the locked and unlocked plate interface.

It seems likely that all earthquake activity within the North Island Dextral Fault Belt is related and may occur in cycles due to the locking and unlocking of plate segments where strain accumulates in an area and is subsequently unloaded after an earthquake event. Some of this cyclic activity is seen in trenching and field work as part of this study on the Wellington and Ruahine Faults with earthquake events alternating between the Wellington and Ruahine Faults. In the Ohara Depression, Holocene faulting activity on the Wellington Fault slows and yet for the Ruahine Fault increases which is consistent with a transfer of strain from one fault to the other. Strain transfer either occurs at depth where the faults are close together or along transfer faults within the Ohara Depression. In support of this, current work suggests that rupture on one fault can increase the stress concentration on adjacent or associated faults (Berryman and Beanland 1987). In all cases Robinson and Benites (1995) assert that the interaction of faults significantly increases the probability of multiple large events within a short time, as compared to the case where each fault is considered in isolation. This has major implications for the area from Dannevirke south to Wellington. Dates for the latest 2 faulting events are much the same between Dannevirke to Kahuki and Kahuki to Wellington (see table 5). Berryman (1990) has predicted a future M_s 7.1 to 7.8 earthquake for the Wellington area and predictions for the Kahuki-Dannevirke segment (this study) are M_s 7.4 to 7.8. If both are separate segments this implies at least 2 devastating earthquake events will occur on average within c. 50 yrs with significant shaking occurring in both areas. Fault scarp morphology (Figure 38) and trenching studies predict that the Ohara Depression segment of the Wellington Fault will rupture within approximately 100 years of the more southern fault segment.

Recent uplift

The recent trace of the Wellington Fault is upthrown mainly to the southeast. This general trend extends from Wellington Harbour to just north of the Napier-Taupo Highway (Lewis 1989, Marden 1984, Berryman 1990, Raub, Cutten and Hull, 1987). The timing for this change in throw is estimated by Berryman (1990) for the Wellington area to have occurred about 14,000 years ago. For the Ohara Depression segment of the Wellington Fault, Raub et al. (1987) estimated eastward uplift to have been initiated between 60,000 and 11,000 yrs B.P. (Table 10). From McCool 1 trench the timing for this event is c. 14,082 yrs B.P. Eastward uplift for the Ngaruroro to Tutaekuri River segment is pre-10,000 yrs B.P. For the Tutaekuri to Napier-Taupo Highway segment of the

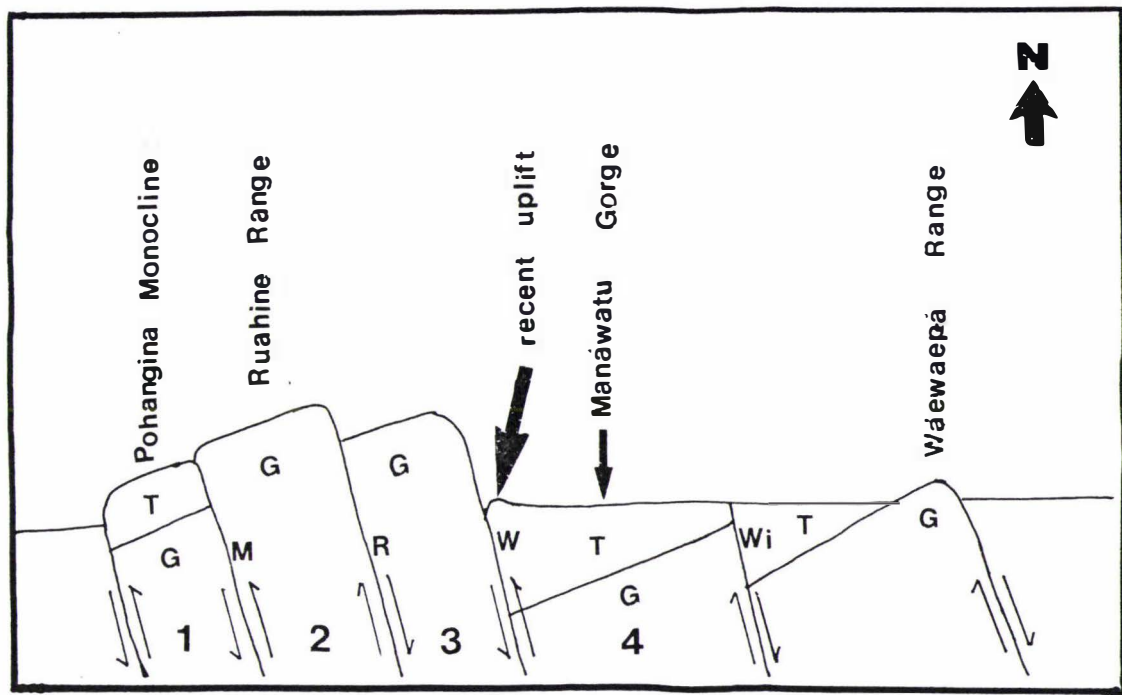


Figure 39, Above, cartoon cross-section diagram of the Wellington Fault between Woodville and Dannevirke showing the proposed eastward block uplift of the Ruahine Ranges along established faults. The arrow marks the locality of the new phase of eastward uplift as the Hikurangi margin expands eastward. Blocks 1,2,and 3 have been uplifted and Block 4 is just beginning to be uplifted. T=Tertiary sediments and G=Torlesse greywacke, M=Mokohine Fault (Marden 1984) W=Wellington Fault and R=Ruahine Fault Wi is the Wairarapa Fault.

Wellington Fault this movement was initiated just prior to 10,100 yrs B.P. (from the Syme trench at Hawkstone Station).

The Ruahine Fault between Pahiatua and the Ohara Depression is upthrown to the northwest. However between the Ohara Depression and the Napier-Taupo Highway the latest Quaternary upthrow is also mainly to the southeast. For this segment of the Ruahine Fault (and maybe for the region as a whole) the base of the downthrown side of the fault trench (Davis 2) was dated prior to 11,850 yrs B.P. providing a reliable date for the time of the actual onset of eastward uplift.

What is not known, is whether this change in throw for both Wellington and Ruahine Faults is the result of long term changes within the subduction zone or whether it is merely a short term aberration. There is some evidence for a permanent change of throw and this comes from seismic reflection profiles showing the structure of the growing accretionary prism. Here thick sediments within a 25 km-wide deformation front is propagating eastward by accretionary outgrowth of the overriding plate (Davey et al. 1986). If the accretionary prism can propagate eastward, then it is likely that the Range Front (Ruahine Range) is also growing and migrating eastward (Figure 39) because the Range front is considered to be a part of the continuing evolution of the presently active subduction system (Van Der Lingen and Pettinga 1980). It is possible that the next area to be uplifted is the greywacke block located beneath the Dannevirke area which in time will become the most eastern section of the range front bounded by the Wellington Fault to the west and the Wairarapa Fault to the east.

Table 10. Summary of timing for the onset of eastward uplift on the proposed segments for the Wellington and Ruahine Faults within the field area. The Ruahine Fault in the Ohara Depression segment is thought to have similar timing to the Wellington Fault based on fault scarp morphology.

proposed segment	date for the Wellington fault	date for the Ruahine Fault
Kahuki -Dannevirke	most trenches were excavated in duplex structures	uplift is toward the northwest
Ohara Depression	c. 14,082	similar to Wellington Fault
Ngaruroro River -Tutaekuri River	pre 10,000	unknown
Tutaekuri River-Napier Taupo Highway	prior to 10,100	just prior to 11,850

HORIZONTAL OFFSET RATES AND HISTORY OF STRIKE-SLIP FAULTING FOR THE WELLINGTON AND RUAHINE FAULTS

The structural history of the Hikurangi Margin shows that the strain regime has changed markedly from Mio-Pliocene to Pleistocene times. Rotation of the Hikurangi Forearc increased the obliquity between the direction of relative plate motion and Mio-Pliocene movement of reverse faults (Beanland 1995). Reverse faulting on the North Island Dextral Fault Belt ceased and was succeeded by dextral strike-slip faulting in the late Pleistocene (Kelsey et al. 1995).

Paleogeographic reconstructions of the North Island Dextral Fault Belt by Beu (1995) suggest a total possible strike-slip offset of 110km over the last 2.5ma. This reconstruction is based on restoring Nukumaruan Limestone formations in the Hawkes Bay area to their original postulated depositional sites. Beu (1995) has estimated the Wellington Fault as having 40 km of horizontal offset over 2.5ma giving an average rate of 16mm/yr. The same reconstruction for the Ruahine Fault totals 20km giving a horizontal offset rate of 8mm/yr. Horizontal offset rates from this study for the Wellington Fault vary throughout the field area from a minimum 3.3mm to 12mm/yr over the last 10,000 years (Table 11). The horizontal offset rate for the Ruahine Fault (this study) is 4.6 to 5.6mm/yr over the last 1850 years (Table 12).

Long term relative plate motion vectors across the Australian-Pacific plate boundary by DeMets et al. (1990) give velocity rates for the Hawkes Bay area of 40 to 45mm/yr. This resolves into approximately 28 to 30mm/yr margin-parallel relative motion, with late Quaternary slip rates on the North Island Dextral Fault Belt accounting for 75% of this motion (Beanland 1995). These rates of motion for the whole Dextral Fault Belt are calculated to decrease farther north to 5.0mm/yr in Hawkes Bay (Beanland 1995). However this study finds that although horizontal movement does decrease farther north on the Wellington Fault it increases on the Ruahine Fault. Altogether rates of motion northward do not change markedly, rather they are more widely spread. The Tutaekuri River to Napier-Taupo Highway segment has a combined total of at least 18mm/yr for the Wellington, Ruahine and Te Waka Faults, which still accounts for almost 75% margin parallel plate motion. Further, other trenching studies by Hull (1983) on the Wellington Fault north of the Napier-Taupo Highway near the Hautapu River had tentative horizontal offset rates of 7.9mm/yr.

Table 11. Horizontal and vertical offset rates for the Wellington Fault segments based on trenching studies and field observations. The long term rate by Beu (1994) for the uplift of the Ruahine Range is labelled (GD1) and (GD2) is the uplift rate for Mt Miroroa (Beu 1976). Horizontal offset rates by Beu (1995) using paleogeographic reconstructions for the whole length of the Wellington Fault total 16mm/yr.

segment	horizontal offset rate	vertical offset rate
Kahuki to Dannevirke	12mm/yr average	0.66 to 1.23mm/yr (GD1) 1.3mm/yr
Ohara Depression	3.76 to 4.75	0.28mm/yr
Ngaruroro River -Tutaekuri River	3.3mm/yr	(GD2) 0.6mm/yr
Tutaekuri River to Napier-Taupo Highway	6mm/yr	0.6mm/yr
Te Waka Splinter Fault	6mm/yr	0.6 to 2.5mm/yr

Table 12. Horizontal and vertical offset rates for the Ruahine Fault. This data is only estimated for the northernmost segment where trenches were excavated through the fault. The horizontal rates are based on streams which were offset since 1850 yrs B.P. The vertical rate is based on late Quaternary movements up to the east (which began just prior to 11,850 yrs B.P.). Horizontal offset rates by Beu (1995) for the whole length of the Ruahine Fault based on paleogeographic reconstructions total 8mm/yr.

segment	horizontal rates	vertical offset
Tutaekuri River to Napier Taupo Highway	4.6 to 5.6mm/yr	0.48 to 0.84mm/yr

Changing strike-slip rates for the Wellington and Ruahine Faults

The structural history of the Hikurangi Forearc shows (Kelsey et al. 1995) that the pattern of strain partitioning has changed over time as a response to more than 10° of clockwise rotation over the southern sector of the margin over the last 1ma. Knuepfer (1992) reports that variations in slip rate in the northeast part of the South Island during the late Quaternary are the result of episodic variations in slip across the plate boundary. These variations are thought to occur over 5000

40,000 years. Trenching in this study shows that, within the last 2000 years earthquakes appear to have been occurring more frequently. This may be (partly) because the more recent events are better preserved within the trench sites. In general strike-slip motion appears to be on the increase. In the Dannevirke area there is a Porewan hill (aged 70 to 80,000 yrs B.P.) that has been cut in half by strike-slip activity on the Wellington Fault. The horizontal offset is 150m (Marden 1984) giving an offset rate of 2.1mm/yr. Horizontal offset rates for younger Ohakean terrace scarps in the Dannevirke area average 12mm/yr or 100m. Some erosion would account in part for this discrepancy in offset rates. For the horizontal offset rate to have remained constant the Porewan terrace would have had to lose approximately 600m of lateral river channel erosion since it was formed. This seems highly unlikely. On this basis it is concluded that horizontal offset rates have increased toward the present.

There are also indications that the interaction between the Australian and Pacific plates may be different to that first thought. New work by Webb and Anderson (1995) finds that slip vectors derived from interplate thrust events are rotated away from the plate relative motion direction toward arc-normal. This implies a large amount of partitioning slip between convergence on the plate interface and transcurrent movement which is presumably accommodated on the North Island Dextral Fault Belt. Surveys of the Wellington-Wairarapa GPS network by Darby and Beavan (1995) suggest that the relative velocity across the region is one third to one half of the relative velocity between the plates. Modelling by these authors shows distribution of this deformation is occurring along the Wellington and Wairarapa Faults which have the greatest late Quaternary slip rates.

SUMMARY OF PALEOSEISMIC ACTIVITY FOR THE WELLINGTON AND RUAHINE FAULTS

This study has established a framework within which the frequency of large magnitude earthquakes in the region can be estimated from past events. Further trenching is required on dextral strike-slip faults of the North Island Dextral Fault Belt before a complete record for the last 30,000 years can be obtained. It is not a question of if a large earthquake event will occur on the Wellington and Ruahine Faults but when, one will occur. If the frequency of earthquakes is examined for the Wellington Fault, it can be seen that a large surface rupture

earthquake occurs every 300 to 500 years for the two southern segments and at least every 1000 years for the more northern segments (Table 13).

Table 13. A summary of estimated paleoseismic activity for the Wellington Fault within the field area. Dates are given in years before present (B.P.).

rupture segment	Kahuki Dannevirke	Ohara Depression	Ngaruroro River -Tutaekuri River	Tutaekuri River to Napier-Taupo Highway
single average horizontal offset	10m	10m	?	?
timing of event	every 200-300 yrs within the last 1000	every 200?-500 yrs within the last 1000	?	Every 1000 ?
earthquake magnitude	Ms 7.3-7.8	Ms 7.3- 7.8	Ms7.2	Ms 7.3

The Ruahine Fault has ruptured on average every 500 yrs over the last 1850 yrs B.P. (Table 14).

Table 14. A summary of paleoseismic activity for the only segment trenched on the Ruahine Fault. Fault scarp morphology between the northern Ohara Depression and Ngaruroro River suggests a similar faulting history to the trenched area (Figure 39a and b).

rupture segment	Tutaekuri River to Napier-Taupo Highway
earthquake magnitude	Ms 7.4-7.5
single average horizontal offset	5.5m
timing of events	approx once every 500yrs over the last 1850yrs

FUTURE WORK

Wellington Fault

Future work in the study area will need to be directed at delineating fault segments more firmly to enable more accurate rupture predictions. To accomplish this, trenching will need to be carried out between Kaitoke and Pahiatua. Information from trenching studies in this area will establish firmly the southern extent of the Kahuki-Dannevirke rupture segment.

To accurately predict the timing of earthquake events in the North Island all the strike-slip faults of the North Island Dextral Fault Belt need to be trenched. There is an absence of earthquake events in the paleoseismic record in the Dannevirke area, for example between c. 6,000 and c. 10,000 yrs B.P. Is this because there were no earthquakes at this time or were there rupture events on other strike-slip faults within the North Island Dextral Fault Belt at this time? Hence the general activity pattern of the Dextral Fault Belt needs to be more clearly established. This may reveal areas of higher strain and establish the locality for the next faulting event. There have been a number of trenches recently excavated elsewhere on North Island Shear Belt faults. Dates from these excavations could be used to establish fault scarp ages and allow comparisons with dated scarps (composed of similar sediments) from this study. A model for North Island fault scarps could be established.

If the limestone block at the east end of the Manawatu Gorge represents a block landslide (preliminary investigation suggests that it is) it represents a significant hazard to road and rail transport in the area. Drilling through the toe of the limestone may help to establish if any movement had occurred and when it took place. There are a number of landslides in the Willowford area that could be dated. This would establish timing for earthquake events within the Ngaruroro-Tutaekuri segment of the Wellington Fault. Lakes in the area, created by landslides could be dated and these dates correlated with data from trench sites to confirm earthquake events.

Fault creep is considered a mode of slip which is an inhibiting factor in the accumulation of elastic strain and the generation of earthquakes (Wallace 1970). As this inhibiting factor would have major implications for earthquake prediction in the area, verification of this phenomenon or lack of it is important. GPS surveys in the Ohara Depression (in the Gull Road area) might confirm reports from a farmer who maintain that galvanised pipes across the Wellington Fault have been pulled-apart twice since 1960.

Ruahine Fault

Trenching studies should be carried out across the Ruahine Fault south of the Manawatu Gorge and north of the gorge at Ballantrae to establish how active the fault has been in the Dannevirke area during late Quaternary time. Further trenching needs to be carried out on the Ohara Depression segment to confirm

rates of offset, timing of events and earthquake magnitude. There are suitable sites for trenching studies on Big Hill Station in the Ohara Depression.

Within the Hawkes Bay area the behaviour of the subduction zone needs further work in terms of plate evolution. There are numerous papers about Forearc Uplift and structure of the accretionary wedge but no basic understanding of faulting processes within the subduction zone as a whole, how one earthquake event is related to another and its impact on the human environment in terms of hazards. This study shows that there is a long history of faulting activity within the Hawkes Bay area. It is only a matter of time before a large (M_s 7+) earthquake occurs on either the Wellington or Ruahine Fault zones, which calls for careful consideration when planning any future engineering works major buildings or town planning.

APPENDICES 1-5

APPENDIX 1

SEDIGRAPH AND XRD ANALYSIS OF COMPARISONS BETWEEN
TERTIARY MUDSTONE UNCTUOUS CLAY AND SHELF MATERIAL

SEDIGRAPH S100 V3.02

Sample type: Tertiary mud-clay

Analysis temp: 34.7 deg C

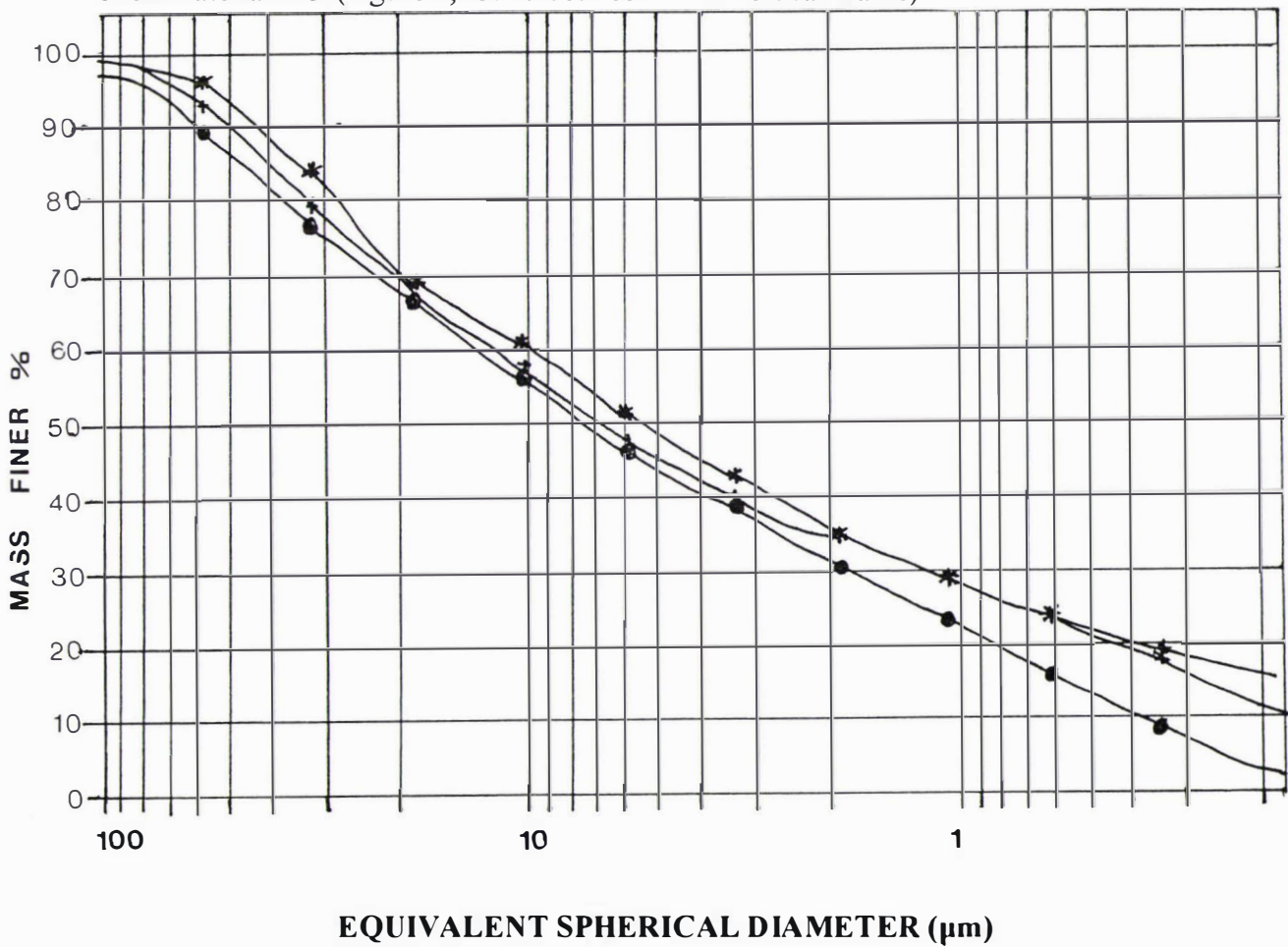
Liquid type: water

Baseline/Full scale 114/93 Kilocounts/sec

Tertiary mudstone = + (Figure 5, found between 5-8m vertical marks)

Unctuous clay = * (Figure 5, found between 12-30m vertical marks)

Shelf material = ● (Figure 5, found between 8-9m vertical marks)



APPENDIX 1 CONTINUED

XRD ANALYSIS

The Following XRD analysis of Tertiary Mudstone (5-8m vertical mark), Shelf Material (8-9m vertical mark) and Unctuous clay (12-30m vertical marks) samples, showed that these materials were all from the same source. The major difference being that the fresher less weathered Tertiary Mudstone and Shelf Material both contained albite which had weathered to sericite in the older more eroded Unctuous clay unit.

Identified Phases: Tertiary Mudstone Inglis 3 Trench (found between the 5 and 8m vertical marks, Figure 5).

JPDS# Si ML/X At% Identity....

5-0490D 133 12/1 131 Silicon Oxide / Quartz, low = SiO₂

lerr: 150 derr: 2.0 Background: 1 dmax/min: 25.64/1.469

20-0554C 37 13/* 24 *Sodium Aluminium Silicate / Albite, low = NaAlSi₃O₈

Identified Phases: Unknown Shelf Material Inglis 3 Trench (located between the 8 and 9m vertical marks, see Figure 5)

JCPDS# Si ML/X At% Identity....

5-0490D 159 12/1 119 Silicon Oxide / Quartz, low SiO₂

lerr: 50/150 derr: 2.0 Background: 1 dmax/min: 25.64/1.469

9-0466* 81 12/9 48 *Sodium Aluminium Silicate / Albite, low = NaAlSi₃O₈

Identified Phases: Unctuous Clay Inglis 3 Trench (found between the 12 and 30m vertical marks, Figure 5).

JCPDS# Si ML/X AT% Identity....

5-0494D 184 11/0 94 Silicon Oxide / Quartz, low = SiO₂

lerr: 50,150 derr: 2.0 Background: 2 dmax/min: 25.64/1.469

2-0056D 49 7/8 4,1 Potassium Aluminium Silicate Hydroxide /
Sericite=KAl₂Si₃AlO₁₀(OH)₂

lerr: 50,150 derr: 2.0 Background: 2 dmax/min: 25.64/1.469

APPENDIX 2

TEPHRAS FOUND WITHIN EXCAVATED TRENCHES

The following tephra have been found within excavated trench sites and are listed from youngest to oldest. “Tephra” is a collective term for all the unconsolidated, primary pyroclastic products of a volcanic eruption (Froggatt and Lowe 1990).

TAUPO TEPHRA

This tephra was erupted from the Taupo Volcanic Centre 1850 ± 10 yrs B.P. and consists of three units. This sequence is clearly seen within the Wedd trench on the Te Waka Splinter Fault. The lowermost layer consists of coarse ash and pumice called Hatepe Ash. This is overlain by a fine to very fine layer named Rotongaio Ash which is in turn covered by the coarser Taupo lapilli (Eden et al. 1993). Taupo lapilli are distinguished in the field from other tephra because their vesicles (gas release chambers) are elongate V.E. Neall, pers comm.

Taupo Ignimbrite was distinguished from airfall Taupo deposits on the following criteria:

- lack of shower bedding
- a lack of particle sorting, clasts ranging from boulders to ash
- charred logs and small pieces of charcoal are common especially near the base of the deposits and
- rip-up clasts of soil were sometimes found near the base of deposits

Deposits of Taupo Tephra were found in McCool, Davis, Wedd and Syme trenches.

Remnant deposits of Taupo Ignimbrite were found along the Ruahine Fault Trace in the Puketitiri area and at the Te Waka Trig (Hammond 1998).

WAIMIHIA TEPHRA

This tephra is present as a macroscopic layer, found at a number of localities throughout Hawkes Bay. It has a loose coarse sugary texture (looking like rice bubbles with much the same colour) which is diagnostic. It is composed of an orthopyroxene-dominated mineralogy consistent with derivation from

the Taupo Volcanic Centre, and was erupted 3280 ± 20 yrs B.P. (Froggatt and Lowe 1990).

MANGAMATE TEPHRA

The Mangamate Formation comprises 6 andesitic tephras erupted from Mt Tongariro c.10,000 yrs B.P. (Donoghue et al. 1991). In the field this tephra is often seen as a discontinuous layer of yellowish grey to dark greyish yellow spheroidal balls usually less than 30mm in diameter composed of fine ash.

KARAPITI TEPHRA

This Tephra was erupted from the Taupo Volcanic centre 10,100 yrs B.P. (Wilson 1993). This ash has a sandy texture (greyish white) and was found at the base of the Syme Trench (Figure 29). This sample was identified on the basis of its glass chemistry and stratigraphic location (S. Cronin pers comm. 1994).

Ferromagnesian mineralogy

Opx 75%

Cpx 20%

Tm 4.5%

Hb 0.5%

WAIIOHAU TEPHRA

The Waiohau Tephra was erupted from the Okataina Volcanic Centre $11,850 \pm$ yrs B.P. (Froggatt and Lowe 1990). This ash was found in small pockets 0.6m from the base of the Wedd trench (Figure 30) and 1m from the base of the Davis 2 trench (Figure 36). The ash has a greyish white colour with a sandy texture. This tephra was identified on the basis of its distinctive glass chemistry (Okataina source) and stratigraphic location (S. Cronin pers comm. 1994).

Ferromagnesian mineralogy

Davis 2 trench

Opx 65%

Cpx 9%

Tm 25%

Hb 1%

Wedd Trench

Opx 64%

Cpx 15%

Tm 17%

Hb 4%

APPENDIX 3

MAJOR AGGRADATIONAL TERRACES OFFSET BY THE WELLINGTON AND RUAHINE FAULTS

Along the eastern edge of the Ruahine and Kaweka Ranges are aggradational (Milne 1973) river terraces which formed in response to major late Quaternary climatic changes. These terraces are composed of alluvial gravels and sediments derived from Mesozoic greywacke sandstone-argillite principally in the main axial ranges. Limestone, sandstone and mudstone derived from the softer Neogene hill country sequences is a minor component along with volcanic alluvium. Blanketing the terrace gravels are rhyolitic and andesitic tephras with some overbank sediments and loess. Coverbeds on younger surfaces are often thin (<0.5m) hence the soils developed therein are often stony in character (Hammond 1998).

Ohakean Terraces

These are the broadest and some of the most laterally extensive surfaces in the Hawkes Bay district (Hammond 1998). Typically these terraces comprise a Nukumaruan mudstone or sandstone swath which is overlain by greywacke aggradation gravels with silt and clay lenses (seen in the Trotter 2 trench). This is the youngest (lowest) well defined aggradational terrace surface usually closest to river banks and is often composed of three distinct treads (Figure 27). The Ohakean terrace subsets are Ohakean 1 (Oh1) Ohakean 2 (Oh 2) and Ohakean 3 (Oh3) from the highest (oldest) to lowest (youngest) respectively. Risers separating these terraces are usually <3m in height decreasing in a downstream direction. The greatest height difference is between the Oh1 and Oh2 terraces with the latter having the broadest tread, followed by Oh2 and Oh3 (Hammond 1998).

Ohakean terraces in the area adjacent to the southern Ruahine Range have been mapped and dated by Marden (1984) at 25,000 to 10,000 yrs B.P. for all three terrace surfaces. Oh1 is 25,000 to pre 13,300 yrs B.P. Oh 2 pre13,300 to 13,000 yrs B.P. and Oh3 from 13,000 to 10,000 yrs B.P.

Ratan Terraces

These terrace surfaces are generally much higher ($\geq 20\text{m}$) than Ohakean terrace surfaces and are located farther away from river banks. These terraces generally have a thicker loess cover. They have been mapped by Marden (1984) on the eastern flanks of the southern Ruahine Range where they are interpreted to have been deposited between 30,000 to 40,000 years B.P.

Porewan Terraces

These gravel terraces are the highest (oldest) encountered in this study and are therefore not so well preserved. They have been mapped on the eastern flank of the southern Ruahine range by Marden (1994) where they are interpreted to have formed between 70,000 and 80,000 years B.P.

APPENDIX 4

SCALE OF EARTHQUAKE INTENSITIES WITH APPROXIMATE CORRESPONDING MAGNITUDES

Modified Mercalli Scale as used in New Zealand (Eiby 1966)

<i>Intensity</i>	<i>description of characteristic effects</i>	<i>Maximum acceleration of the ground</i>	<i>Magnitude corre- sponding to highest intensity reached (M_s)</i>
I	<i>Instrumental</i> : detected only by seismographs	14	
II	<i>Feeble</i> : noticed only by sensitive people	25	3.5
III	<i>Slight</i> : like the vibrations due to a passing lorry: felt by people at rest, especially on upper floors	50	to 4.2
IV	<i>Moerate</i> : felt by people while walking; rocking if loose objects, including standing vehicles	100	4.3 to
V	<i>Rather strong</i> : felt generally; most sleepers are wakened and bells ring	250	4.8
IV	<i>Strong</i> : trees sway and all suspended objects swing, damage by overturning and falling of loose objects	500	4.9-5.4
VII	<i>Very strong</i> : general alarm, walls crack, plaster falls	1000	5.5-6.1
VIII	<i>Destructive</i> : car drivers seriously disturbed masonry fissured, chimneys fall, poorly constructed buildings damaged	2500	6.2
IX	<i>Ruinous</i> : some houses collapse where ground begins to crack and pipes break open	5000	to 6.9
X	<i>Disastrous</i> : ground cracks badly, many buildings destroyed and railway lines bent, landslides on steep slopes	7500	7-7.3

XI	<i>Very disastrous:</i> few buildings remain standing, bridges destroyed, all services (railways, pipes, and cables) out of action, great landslides and floods	7.4-8.1
	9800	
XII	<i>Catastrophic:</i> total destruction, objects thrown into air, ground rises and falls in waves	>8.1 (maximum known=8.9)

APPENDIX 5

SUMMARY OF RADIOCARBON AND AMS SAMPLES

Location	Lab no	NZ fossil record no	Radiocarbon age (yrs B.P.)	Sample material
Inglis 3 trench	NZA 3698	T24/f121	211 +/- 63	charcoal
Inglis 3 trench	NZA 8001	T24/f111	4335 +/- 66	wood
Inglis 3 trench	NZA 3113	T24/f105	9434 +/- 77	charcoal
Inglis 4 trench	NZA 3070	T24/f109	1105 +/- 65	charcoal
Inglis 4 trench	NZA 3114	T24/f110	10286 +/- 79	charcoal
Inglis 4 trench	NZA 3071	T24/f108	29200 +/- 320	charcoal
Beagley trench	Wk3151	T24/F22	290 +/- 50	wood
Beagley trench	NZ 8229	T24/f128	5324 +/- 61	wood
Paper Road	NZA 5365	T24/f129	1746 +/- 78	peat
Trotter 1 trench	Wk 3143	T23/f46	2090 +/- 50	wood
Trotter 1 trench	Wk 3144	T23/f48	5000 +/- 60	wood
Trotter 1 trench	Wk 3145	T23/49	6080 +/- 60	wood
Trotter 2 trench	NZA 8228	T23/f51	257 +/- 44	wood
Trotter 2 trench	Wk 3140	T24/f55	960 +/- 50	wood
Trotter 2 trench	Wk 3149	T24/f54	2030 +/- 50	wood
Trotter 2 trench	Wk 3148	T24/f53	3110 +/- 60	wood
Trotter 2 trench	Wk 3147	T24/f52	6750 +/- 60	wood
Trotter 2 trench	Wk 3146	T24/f50	22020 +/- 150	wood
McCool 1 trench	NZ 8291	U21/f79	605 +/- 35	peat
McCool 1 trench	NZ 8293	U21/f80	805 +/- 58	wood
McCool 1 trench	NZ 8288	U21/f76	5206 +/- 81	peat
McCool 1 trench	NZ 8289	U21/f77	4295 +/- 56	wood
McCool 1 trench	NZ 8290	U21/f78	6561 +/- 79	peat
McCool 1 trench	NZ 8287	U21/f75	14082 +/- 156	wood
Syme trench	NZA 4557	U20/f	8770 +/- 120	charcoal
Davis 1 trench	NZ 8230	U20/f140	1281 +/- 63	peat
Davis 1 trench	NZ 8231	U20/f141	5971 +/- 78	wood
Davis 1 trench	NZ 8232	U20/f142	3623 +/- 57	wood
Davis 1 trench	NZ 8233	U20/f143	7778 +/- 81	wood

REFERENCES

- Adams J. 1981: Earthquake-dammed lakes in New Zealand. *Geology* **9** 215-219
- Adkin, G.L. 1947: The Tararua Range as a unit of the geological structure of New Zealand. *Trans. Roy. Soc. New Zealand*. **77**: 260-272
- 1954: Late Pleistocene and recent faulting in the Otaki-Poriua, Dalefield-Waipoua districts of south Wellington, North Island, New Zealand. *Trans. Roy. Soc. New Zealand*. **81**: 501-519.
- Aki K., 1988: Geometric features of a fault zone related to the nucleation and termination of an earthquake Rupture. *USGS proceedings of workshop Open-File Report 89-315* 1-7
- Allen C., Zhuoli L., Hong Q., Xueze W., Hauwei Z., Weishi H., 1988: Segmentation and recent rupture history of the Xianshuihe Fault, Southern China. *USGS proceedings of workshop Open-File Report 89-315* 10-30
- Andrews D.J. and Hanks T.C. 1985: Scarp Degraded by Linear Diffusion: Inverse Solution for Age. *Journal of Geophysical Research*, Vol 90, No B12 10.193-10.208.
- Arabasz, W.J. and Lowry, M.A. 1980: Microseismicity in the Tararua-Wairarapa area: depth-varying stresses and shallow seismicity in the southern North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. **23**: 141-154
- Avouac J. 1993: Analysis of Scarp Profiles: Evaluation of Errors in Morphologic Dating. *Journal of Geophysical Research*, Vol 98 NO B4 6745-6754.
- Ballance P.F. 1976: Evolution of the upper Cenozoic Magmatic Arc and Plate Boundary in Northern New Zealand. *Earth and Planetary Science Letters* **28** 356-370
- 1993: The New Zealand Neogene Forearc Basins. *South Pacific Sedimentary Basins. Sedimentary Basins of the World eds Ballance P.F.* . 177-193
- Ballance, P.F. Pettinga, J.R. and Webb, C. 1982: A model of the Cenozoic evolution of northwestern New Zealand and adjacent areas of the southwest Pacific. *Tectonophysics*, **87** 37-48
- Beanland, S and Berryman, K. 1990: Paleoseismicity of the Wellington Fault north-east of the Tararua Ranges. *Geol. Soc of New Zealand*. **93**: 42-46.
- 1987: Ruahine fault reconnaissance. *New Zealand Geological Survey. EDS 109*.
- Beanland S. 1995: Role of the North Island Shear Belt in the Hikurangi Margin. *Symposium, Subduction systems and Processes in New Zealand N Z Geophysical Soc.*

Bell, J.M. 1908: The Physiography of the Port Nicholson Harbour, New Zealand. *Rep. A'sian. Ass. Adv Sci.* 11: 438-349.

✓ Berryman, K. 1990: Late Quaternary movement on the Wellington Fault in the Upper Hutt area, New Zealand. *New Zealand Journal of Geology and Geophysics.* 33: 257-

Berryman, K. and Beanland, S. 1988: Ongoing deformation of New Zealand: rates of tectonic movement from Geological evidence. *New Zealand Geological Survey Transactions, Vol 15. No 1/GEN*

Beu A.G. 1994: Late Neogene Limestone of Eastern North Island (Sheet2) *unpublished map.*

-----1995: Pliocene Limestones And Their Scallops, Lithostratigraphy, Pectinid Biostratigraphy And Paleogeography Of Eastern North Island , Late Neogene Limestone. *Institute of Geological & Nuclear Sciences Limited*

✓ Beu A. G., Browne G.H., and Grant-Taylor T.L. 1980: New *Chlamys delicatula* localities in the central North Island and the uplift of the Ruahine Range. *New Zealand Journal of Geology and Geophysics* vol 24 127-132

Beu A G , Grant-Taylor T.L., Hornibrook N. 1977: Nukumaruan records of the Subantarctic Scallop *Chlamys Delicatula* and Crab *Jacquintia Edwardsii* in central Hawkes Bay. *N Z Journal of Geology and Geophysics* Vol 20 2 217-248

----- 1980: The Te Aute Limestone Facies Poverty Bay to Northern Wairarapa. *Miscellaneous Series Map 13 . N Z Geological Survey DSIR*

Beu A.G. 1995: Pliocene Limestones And Their Scallops: Lithostratigraphy, Pectinid Biostratigraphy And Paleogeography of Eastern North Island Late Neogene Limestone. *Institute of Geological and Nuclear Sciences. Monograph 10.*

Bilham R., King., 1988: Slip distribution on oblique segments of the San Andreas Fault, California: observations and theory. *USGS proceedings of workshop Open-File Report 89-315* 81-93

✓ Blakely R.J. 1981: Downstream river management to erosion processes in the south-eastern Ruahine Range. *Erosion in the Ruahines, International conference on soils with variable charge ed Neall V.E. Massey University.*

Bonilla, M.G., Mark, R.K. and Leinkaemper, J.J. 1984 Statistical relations among earthquake magnitude, surface rupture length and surface fault displacement. *Bulletin of the Seismological Society of America.* 74: 2379-2411.

Browne G.H. 1980: The Geology of the Kuripapango-Blowhard District, Western Hawkes Bay. *MSc thesis Auckland University*

✗ Bucknam R.C. and Anderson R.E. 1979: Estimation of fault-scarp ages from a scarp-height-slope-angle relationship. *Geology* vol 7 ,11-14.

Carter, L., Lewis, K.B., and Davey, F. 1988 Faults in the Cook Strait and their bearing on the Structure of central New Zealand. *New Zealand Journal of Geology and Geophysics*. 31: 431-446.

Cashman, S.M., Kelsey, H.M., Erdman, C.F., Cutten, H., and Berryman, K.R. 1992: Strain partitioning between structural domains in the Forearc of the Hikurangi subduction zone, New Zealand. *Tectonics*, 11, no2: 242-257.

Cole, J.W. and Lewis, K.B. 1981: Evolution of the Taupo-Hikurangi subduction system. *Tectonophysics*, 72 1-21

Cotton, C.A. 1912b: Recent and sub-recent movements of uplift and subsidence near Wellington, New Zealand. *Scot. geogr Mag*, 28: 306-312.

----- 1950: Tectonic scarps and fault valleys. *Bull. Geological Society of America*. 61: 717-757.

Crozier M.J. and Pillans B.J. Geomorphic events and landform response in South-Eastern Taranaki, New Zealand. *Science Hydrology Geomorphology* 471-487

Cutten H.N.C. 1994: Geology of the middle reaches of the Mohaka River. *Institute of Geological Sciences Ltd Sheet V19 BD*

Darby D., Beavan J., Welsch W., and Hollmann R. 1995: The emergence of a deformation signal from GPS surveys of the Wellington and Wairarapa regions. *Symposium, Subduction Systems and Processes in New Zealand. N Z Geophysical Soc.*

Darby D. J. 1994: Monitoring strain on the Wellington Fault at Te Marua during 1993. *Institute of Geological and Nuclear Sciences Report 94/8*

DeMets C., Gordon R.G., Argus D.F. and Stein S. 1990 : Current Plate Motions. *Geophys. J.* 101: 425-478

Davey F.J., Hampton M., Childs J., Fisher M.A., Lewis K., Pettinga J.R. 1986: Structure of a growing accretionary prism, Hikurangi Margin, New Zealand. *Geology* vol 14 663-666

Donoghue, S.L., Stewart, R.B. and Palmer, A.S. 1991: Morphology and chemistry of olivine phenocrysts of Mangamate Tephra, Tongariro Volcanic Centre, New Zealand. *Journal of the Royal Society of New Zealand, Vol 21 No 3* 225-236.

Drummond R.G. 1968: Landslide in the Tuititiki River. *Soil and Water* 22-23

Eden D.N., Froggatt P.C., Trustrum N.A., Page M.J. 1993: A multiple-source Holocene tephra sequence from Lake Tutira Hawkes Bay, New Zealand. *NZ Journal of Geology and Geophysics* vol 36: 233-242

Eiby G.A. 1966: The Modified Mercalli Scale of Earthquake Intensity and its use in New Zealand. *NZ Journal of Geology and Geophysics* vol 9: 122-129

Erdman, C.R. and Kelsey, H.M. 1992: Pliocene and Pleistocene stratigraphy and Tectonics, Ohara Depression and Wakarara Range, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. 35: 117-192

Feldmeyer A.E., Jones B.C., Firth C.W. Knight J 1943: Geology of the Palmerston North-Wanganui Basin. *The Superior Oil Company, N Z Geological survey Report 171*

Froggatt, P.C. and Lowe D.J. 1990: A review of late Quaternary silicic and some other tephra formations from New Zealand: their stratigraphy, nomenclature, distribution, volume and age. *New Zealand Journal of Geology and Geophysics Vol 33* 89-109

Froggatt P.C. and Howorth R. 1980: Uniformity of vertical faulting for the last 7000 years at lake Poukawa, Hawkes Bay, New Zealand. *N Z Journal of Geology and Geophysics* 23, 493-497

Grant P.J. 1985: Major periods of erosion and alluvial sedimentation in New Zealand during the late Holocene. *Journal of the Royal Soc. of N Z.* vol 15, 1 67-121

Grant-Taylor, T.L., Adams, R.D., Hatherton, T., Milne, J.D.G., Northey, R.D. and Stephenson, W.R. 1974: Microzoning for Earthquake effects in Wellington. *New Zealand Department of Scientific and Industrial Research. Bull 213.*

Grapes, R.H., Hardy, E.F. and Wellman. 1984: The Wellington Mohaka and Wairarapa faults. *Publication of Geology Department, Victoria University of Wellington.*

Grapes R.H. 1993: Sir Charles Lyell and the 1855 Wairarapa Earthquake. *News Letter Geological Soc of N Z* 102

----- 1991: Aggradation surfaces and implications for displacement rates along the Wairarapa Fault Southern North Island, New Zealand. *Journal of Soil Science, Hydrology and Geomorphology* 453-469

Grindly, C.W. 1960: Sheet 8 Taupo, Geological Map of New Zealand 1:250000. *Department of Scientific and Industrial Research.*

Hall, W.E. 1946: Notes on the Later Geologic History of the Wellington Peninsula. *New Zealand Journal of Science and Technology*. B27: 427-30.

Hammnd A. 1988: Late Quaternary landscape evolution of western Hawke's Bay, North Island, New Zealand. *PhD Thesis held at Massey University.*

Hatcher R.D. 1990: Structural Geology. *Merril Publishing. Bell & Howell Information Co.*

Hicks, S. 1983: Ribbon Tectonics. *S Hicks Wellington.*

Hubbard C.B. and Neall V E. 1980: A reconstruction of late Quaternary erosional events in the West Tamaki River catchment, southern Ruahine Range, North Island, New Zealand. *N Z Journal of Geology and Geophysics vol 23* 587-593

Hull A. G. 1983: Trenching of the Mohaka Fault near Hautapu River, Hawkes Bay. *Immediate Report N.Z. Geological Survey 968/31 /831*

-----1990: Tectonics of the 1931 Hawkes Bay earthquake. *New Zealand Journal of Geology and Geophysics Vol 33: 309-320*

-----1994 past Earthquake Timinh and Magnitude along the Inglewood Fault, Taranaki, New Zealand. *Bulletin of thr New Zealand Society for earthquake Engineering: Vol27 No 2 155-161.*

Ikeda Y., Suzuki Y., Herece E., Saroglu F., Isikara A.M., Honkura Y. 1991: Geological evidence for the last two faulting events on the North Anatolian Fault zone in the Mudurnu Valley, Western Turkey. *Tectonophysics 93 335-345*

Kamp P.J., Harmsen F., Nelson C., and Boyle S., 1988: Barnacle dominated limestone with giant cross-beds in a non tropical, tide swept, Pliocene Forarcf seaway Hawkes Bay, New Zealand. *Sedimentary Geology 60 173-195*

Kamp P.J. 1988: Tectonic geomorphology of the Hikurangi Margin: surface manifestations of different modes of subduction. *Z. Geomorph N.F.55-67*

Kelsey H.M. Cashman S.M. Beanland S Berryman K.R., 1995: Structural evolution along the inner forearc of the obliquely convergent Hikurangi Margin. *Tectonics vol 14 no1 1-18*

Kingma, J.T. 1962: Sheet 11 Dannevirke. Geological Map of New Zealand. 1:250000. *Department of Scientific and Industrial Research.*

----- 1958: Geology of the Wakarara Range, Central Hawkes Bay. *N Z Journal of Geology and Geophysics 1 76-91*

Knuepfer P. L. K. 1992: Temporal variations in latest Quaternary Slip across the Australian-Pacific Plate Boundry, Northeastern South Island, New Zealand. *Tectonics vol11 no 3 449-464.*

Lamb, S.H. and Vella, P. 1986: The last million years of deformation in part of the New Zealand plate-boundry zone. *Journal of Structural Geology, Vol9 No. 7 877-891.*

Lensen, G.J. 1957: The Wellington Fault from Cook Strait to Manawatu Gorge. *New Zealand Journal of Geology and Geophysics. 1: 176-196*

Leslie W.C. and Hollingsworth R. J. S. 1972: Exploration in the East Coast Basin, New Zealand. *Beaver Exploration, The Area Journnal 39-44*

Lewis, K.B. 1989: A reversal of throw and change of trend on the Wellington Fault in Wellington Harbour. *New Zealand Journal of Geology and Geophysics. 32: 293-298*

-----1980: Quaternary sedimentation on the Hikurangi oblique-subduction and transform margin, New Zealand. *Sedimentation in oblique-slip Mobile Zones eds Ballance P. F. and Reading H G. Spec. Publ. inst. Ass. Sediment. 4 : 171-189*

- Lewis, K.B. and Mildenhall, D.C. 1985: The late Quaternary seismic, sedimentary and palynological stratigraphy beneath Evans Bay, Wellington Harbour. *New Zealand Journal of Geology and Geophysics*. 28: 129-153.
- Lillie, A.R. 1953: The Geology of the Dannevirke Subdivision. *New Zealand Geological Survey. Bull 46*.
- Lowe D.J., and Green J.D., 1987: Origins and development of lakes. *Inland Waters of N Z DSIR Bull 241* 1-57
- Machette M. Personius S., Nelson A., Schwartz D., Lund W., 1988: Segmentation models and Holocene movement history of the Wasatch fault zone, Utah. *USGS Proceedings of workshop Open-File Report 89-315* 229-245
- Marden, M. 1984: Geology and the relationship to erosion in the southern Ruahine Range, North Island New Zealand. *PhD thesis, Massey University*.
- Marden, M. and Neall, V.E. 1990: Dated Ohakean terraces offset by the Wellington Fault, near Woodville, New Zealand. *New Zealand Journal of Geology and Geophysics*. 33: 449-453.
- Mayer L. 1984: Dating Quaternary Fault Scarps formed in Alluvium Using Morphologic Parameters. *Quaternary Research* 22, 300-313
- McKay, A. 1892: On the geology of the Marlborough and Nelson. *New Zealand Geology. Report. Geol. Explor., 1890-91* 21: 1-28.
- McSaveney M. J. and Hull A.G. 1995: A 7000-year record of great earthquakes at Turakirae Head, Wellington. *Symposium, Subduction Systems and Processes in New Zealand, NZ Geophysical Soc*
- Milne, J.D.C. 1973: Map and sections of river terraces in the Rangitikei Basin North Island, New Zealand. N.Z. Soil Survey Report 4. *Department of Scientific and Industrial Research*.
- Miyauchi T., Ota Y., Hull A. 1989: Holocene marine terraces and tectonic uplift in the Waimarama coastal plain, eastern North Island, New Zealand. *N Z Journal of Geology and Geophysics* vol 32 437-442
- Niemi T., and Hall T., 1992: Late Holocene slip rate and recurrence of great earthquakes on the San Andreas Fault in Northern California. *Geology* v 20 195-198
- Oborn L.E 1985: Identification and Evaluation of Geotechnical Hazards. *Philosophy and methods of Investigation used in New Zealand* 19.1-19.11
- Officers of the Geological Survey. 1966: Active Earth Deformation. *New Zealand Geological Survey. Report 89*.
- Pillans B. J. 1994: Direct Marine-Terrestrial Correlations. *Quaternary Science Reviews* V13

Ramsay, J.G. and Huber, M.I. 1987: The techniques of modern structural geology. Vol 2: Folds and Fractures. *Academic Press INC*.

✓ Raub, M.L. 1985: The Neotectonic evolution of the Wakarara Area, Southern Hawkes Bay, New Zealand. *MSc thesis, Auckland University*.

Raub, M.L., Cutten, H.N., and Hull, A.G. 1987: Seismotectonic hazard analysis of the Mohaka Fault, North Island, New Zealand. *National Society for Earthquake Engineering, Proceedings Vol 3*.

Reyners M. 1983: Lateral segmentation of the subducted plate at the Hikurangi Margin, New Zealand: Seismological evidence. *Tectonophysics* 96 203-223.

Reyners, M. 1989: New Zealand seismicity 1964-87: an interpretation. *New Zealand Journal of Geology and Geophysics*. 32: 307-315.

Rockwall T. 1988: Behaviour of individual fault segments along the Elsinore-Laguna Salada Fault zone southern California and northern Baja California: implications for the characteristic earthquake model. *USGS Proceedings of workshop Open-File Report 89-315* 289-308

Robinson R. and Benites R. 1995: The risk of multiple large earthquakes in the Wellington Region due to elastic interactions. *Symposium, Subduction systems and processes in New Zealand. NZ Geophysical Soc.*

Sanders C.O. 1988: Fault Segmentation and occurrence in the strike-slip San Jacinto Fault Zone California. *USGS proceedings of workshop Open -File Report 89-315* 325-345

Schwartz D.P. 1988: Paleoseismicity, Persistence of Segments and Temporal Clustering of large Earthquakes: examples from the San Andreas, Wasatch and Lost River Fault Zones. *USGS Open File Report 89-315 p* 361-375

Schwartz D.P. and Coppersmith K.J. 1984: Fault Behaviour and Characteristic Earthquakes: Examples From Wasatch and San Andreas Fault Zones. *Journal of Geophysical Research* Vol 89 no B7 5681-5698

✓ Sporli, K.B. and Bell, A.B. 1976: Torlesse Melange and coherent sequences, Eastern Ruahine Range, North Island, New Zealand, *New Zealand Journal of Geology and Geophysics*. 19 no 4: 427-447.

Sporli, K.B. 1988: Tectonic Controls on Cenozoic Sedimentation in the North Island. *Energy Exploration and Exploitation Vol 6 No 2* 104-116.

_____ 1990 : (Field Trip Guide) Tukituki - Wakarara Area, Ruahine Range. *Geological Society of New Zealand INC Annual Conference Napier*. 171-188

Stevens, G.R. 1956: Stratigraphy of the Hutt Valley, New Zealand. *New Zealand Journal of Science and Technology*, B38: 201-235.

----- 1957: Geomorphology of the Hutt Valley, New Zealand. *New Zealand Journal of Science and Technology*, B38: 297-327.

Stewart I. J. and Hancock P.L. 1990: What is a fault scarp? *Episodes* vol 13 NO 4.

Stirling, W. 1992: Holocene beach ridges displaced by the Wellington Fault in Lower Hutt New Zealand. *New Zealand Journal of Geology and Geophysics*. 35: 447-453.

Twiss, R.J. and Moores, E.M. 1992: Structural Geology. *W.H. Freeman and Company* : New York.

Van Der Lingen G.J. and Pettinga J.R. 1980: The Makara Basin: a miocene slope-basin along the New Zealand sector of the Australian-Pacific obliquely convergent plate boundary. *Sedimentation in oblique-slip mobile zones* Eds Ballance and Reading. *Spec Publ int. Ass. Sediment* 4 191-215

Van Dissen, R.J., Berryman, K.R., Pettinga, J.R., and Hill, N.L. 1992: Paleoseismicity of the Wellington-Hutt Valley segment of the Wellington Fault, North Island, New Zealand. *New Zealand Journal of Geology and Geophysics*. 35: 165-176.

Walcott, R.I. 1978: Geodetic strains and large earthquakes in the Axial Tectonic Belt of North Island, New Zealand. *Journal of Geophysical Research*. 83: 4419-4429.

Wallace B. E. 1977: Profiles and ages of young fault scarps, north-central Nevada. *Geological Society of America* Vol 88 1267-1281

Wallace R.E. 1970: Earthquake Recurrence Intervals on the San Andreas Fault. *Geological Soc of America Bull* V 81. p 2875-2890

Ward C. 1995: The Waikareiti Landslide, Te Urewera National Park. *Programme and Abstracts. Geological Society of N Z Miscellaneous Publication* 81A

Webb T.H. and Anderson H. 1995: Seismotectonics of the Hikurangi Margin and North Island, New Zealand. *Programs and Abstracts Symposium 1995 N.Z. Geophysical Soc*

Wellman, H.W. 1948: Tararua Range summit height accordance. *New Zealand Journal of Science and Technology*

----- 1953: Data for the study of recent and late Pleistocene faulting in the South Island of New Zealand. *New Zealand Journal of Science and Technology*, B34: 270-288

Wells D and Coppersmith K. 1994: New empirical relationships among Magnitude, Rupture Length, Rupture Width Rupture Area, and Surface Displacement. *Bull Seismological Soc of America* Vol 28 4 974-1002.

Wilson C. J. N. 1993: Stratigraphy, chronology, styles and dynamics of late Quaternary eruptions from Taupo volcano, New Zealand. *Phil trans R Soc. Lond* 343, 205-306

Woodcock, N.H. and Fischer, M. 1986: Strike-slip duplexes. *Journal of Structural Geology*, 8: 725-735.

Wyss M. 1979: Estimating maximum expectable magnitude of earthquakes from fault dimensions. *Geology*; v 7 336-340