FINAL PROGRESS REPORT

Submitted to

EARTHQUAKE AND WAR DAMAGE COMMISSION

on the project

'THE NEOTECTONICS OF THE RUAHINE AND MOHAKA FAULTS, BETWEEN THE MANAWATU GORGE AND PUKETITIRI'

December 1995

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ABSTRACT

New Zealand lies across the active IndoAustralian-Pacific plate boundary. Volcanic activity and earthquakes are a direct result of interaction between these two plates. The Wellington and Ruahine Faults are major strike-slip faults that have formed due to this interaction. These faults move sideways in a horizontal motion so that the area west of, and including the Central Ranges is moving northward while the East Coast of the southern North Island is moving southward. If earthquake activity is averaged out on a yearly basis, these two sections of the North Island move past each other at a rate of 5 to 7 mm (for the Wellington area) and up to 15 mm per year for the Dannevirke area. These rates of motion are high by world standards.

The purpose of this study was to establish a record of past earthquake events which would allow future estimates of fault behaviour to be made in the region between the Manawatu Gorge and the Napier-Taupo highway. Trenches have been excavated through these faults in mainly swampy environments. Within these trenches are layers of earthquake debris, deformation and layers of peat. The layers of peat have been radiocarbon dated to give the approximate ages of the underlying and overlying earthquake debris. In many areas through which the faults pass are terraces composed of gravel debris which has been washed down from the axial ranges. The ages of these terraces are known due to layers of dateable volcanic ash and wood preserved within. Some of these terraces have been offset by the fault. As the ages of these terraces is known it is then possible to tell how far the fault has moved in a given period of time.

The above studies have shown a record of at least 12 M>6.5 earthquake events recorded on the Wellington Fault in the Woodville-Dannevirke district, 9 of which occurred in the last 30,000 years. This is the longest record of earthquake events recorded within a fault trench in New Zealand. The last earthquake on the Wellington Fault took place about 300 years ago between Dannevirke and Wellington. Horizontal offsets in the Dannevirke area were in the range of 10m and in the Wellington area between 3 and 4 m. The estimated magnitude of this earthquake was between 7.4 and 8.4 which would have caused major destruction of all larger buildings and engineering structures. Earthquakes of this size are estimated to occur every 300 to 400 years between Dannevirke and Wellington and every 300 to 500 years from the Ohara Depression north to the Napier-Taupo Highway. The Ruahine Fault (which is a branch of the Wellington Fault) between the Ohara Depression and the Napier-Taupo Highway is estimated to produce a 7.5 to 8 magnitude earthquake every 400 to 500 years. Horizontal movement is expected to be in the range of 3 to 5.5m. Dates for the last earthquake on the

Ruahine Fault are not so accurate but it is possible that there have been up to 4 earthquakes on this fault since 1850 years before present.

Fortunately, except for the Wellington area these faults lie mostly on the eastern margin and within the axial ranges. They pass mainly through farmland, areas of forestry and the Ruahine Range. It is possible that some farm houses in close proximity to the faults will receive damage but structures built on the fault may be ruptured or buried if in the path of any earthquake-triggered landslides. The large magnitude earthquakes can be expected to produce severe shaking in the cities of Palmerston North, Napier and Hastings.

CHAPTER 1

INTRODUCTION

New Zealand lies uniquely astride the Pacific-Indo/Australian plate boundary. From the east the Pacific plate is being obliquely subducted under the Indo/Australian plate. The surface boundary contact between the two plates lies off the east coast of the North Island along the Hikurangi Trough (Fig 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 40 mm/yr (at Cook Strait) to 50 mm/yr in the Hawkes Bay (Walcott, 1978a). This convergent vector has been resolved into 25 km/my of dextral strike-slip parallel to the Hikurangi margin and 35 km/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 Indo-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 is 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 uplift usually to the west. This domain is referred to as the North Island Shear Belt (Ballance 1993, Beanland 1995) and is considered to be a continuation of the dextral South Island Alpine Fault (Walcott 1978a). Studies of Cretaceous-Cenozoic stratigraphy suggest that the North Island Shear Belt has been active from mid to late Tertiary times (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 Axial Tectonic belt (Berryman and Beanland, 1988).

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 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 Axial Tectonic 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 only concentrate on a fault zone when the fault is creeping. So far the only positively identified fault creep in New Zealand is occurring on the Ostler fault in the central South Island (Reyners, 1989).

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 (Fig, 1b). Just south of the Manawatu Gorge the fault bifurcates, the major westward splinter being named the Ruahine Fault. The Ruahine Fault continues north until it becomes hidden 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). 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 Indo-Australian plate following the Hawkes Bay (1931) and Wairoa (1932) earthquakes (Walcott 1978a). Between 1964 and 1987 earthquake studies suggest a change 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 Wellington and Ruahine faults both display a large amount of late Quaternary displacement (Marden 1984). Within the study area these faults are in close proximity to the major population centres of Palmerston North, Dannevirke, 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 both faults. This was achieved by analysis of the sedimentary records of deposits revealed within tenches excavated along recent fault traces. The earthquake deposits usually consist of freshly eroded materials from the newly exposed adjacent fault scarp that are rapidly deposited into the adjoining fault trench during fault rupture events. The record within these trenches provides an estimate of displacement and timing of individual surface faulting events. Information obtained by the above method will also help develop fault behaviour models and assessments for future seismic hazards. Maps of both faults and their neotectonic geological environs are provided together with full-size cross-sections of all trenches excavated.

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 (Fig 1b). This covers a significant length of faulting within 10 to 30 km of three major North Island cities.

PREVIOUS REGIONAL WORK ON THE WELLINGTON FAULT SYSTEM

As 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 thought the fault belonged to a system of faults that linked 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. Stevens (1956, 1957) and Wellman (1953) first described movement on the fault as being dextral strike-slip. 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). DSIR conducted 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 of Wellington Harbour were carried out in Evans Bay 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 5mm/yr. More recent work (Stirling 1992) on displaced Holocene beach ridges agree with this amount of horizontal movement.

Detailed research on the Wellington Fault further north of the Wellington-Hutt Valley segment has been more sporadic. The Wellington and Ruahine Fault traces have been mapped by Lillie (1953) and Kingma (1962). In more recent times three trenches have been excavated across the Wellington Fault in proximity to the study area near Pahiatua. Exposed in 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 mapped in detail by Marden (1984), who documented a maximum horizontal offset of 150m on a Porewan terrace offset by the Wellington Fault. Marden concluded that although exceptions occur it appears that the latest phase of vertical fault movement is upward to the east of the Wellington Fault trace. In the south of the study area at Ballantrae, Marden and Neall (1990) established a maximum 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 was published by Hubbard and Neall (1980) but these erosional periods have not been, directly correlated with paleoseismic events.

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 faults was published.

Further north, research in the Wakarara Range and the Ohara Depression was carried out by Erdman and Kelsey (1992). Here the faults were mapped but no dating of recent fault activity is recorded. A seismic hazard analysis of the Wellington Fault in this area was produced giving a return period for magnitude 7 earthquakes of 1000 years (Raub et al. 1987). Wood fragments from an offset deposit indicate that a surface rupture has occurred since 1165 yrs B P. 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 study 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

Active faulting visible on all aerial photographs of the study area has been interpreted and used to search for suitable trench sites. Trench sites were then selected after field observations. 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.

Trenches were excavated across both the Wellington and Ruahine 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. By convention the northern wall of a trench is the one that is usually logged. However 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. All excavated trenches have been named in the text after the farm owner or manager. Data from these trenches 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 from an adjacent fault scarp immediately after a surface rupture. 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 relate to grid north in this thesis.

FAULT NOMENCLATURE

In 1912 a Cotton identified the west shore of the Wellington Harbour as a fault scarp of recent origin and in a later paper 1912b he named it the Wellington Fault. This nomenclature was extended further 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 name 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 had a regional tectonic significance. In this thesis the name Wellington Fault is used 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.

CHAPTER 2

REGIONAL GEOLOGY

This chapter discusses the relationship between the Wellington and Ruahine Faults and the effects these faults have on the regional geology in the areas through which they pass. Each area discussed has unique structural and faulting differences.

MANAWATU GORGE TO OHARA DEPRESSION

In this area the Wellington and Ruahine Faults with their different deformational styles exhibit much the same behaviour throughout their separate lengths.

Wellington Fault

The Wellington Fault is one of the major active dextral strike-slip faults of the North Island Shear Belt. Within the field area the trace of this fault shows signs of late Quaternary faulting activity throughout its length. In the south of the field area the western margin of the Dannevirke Basin is bounded by the Wellington Fault. Within the Basin are greywacke conglomerates which are considered to be early alluvial fan deposits from an uplifting Ruahine Range. As the oldest conglomerates are around 1 ma in age, the Range is inferred to have been uplifted rapidly since then (Beu et al., 1981). It is thought likely that this period of rapid uplift was largely controlled by faults bordering the range. In this area the westward uplift would have been largely controlled by the Wellington Fault.

The Dannevirke Basin lies on the eastward downthrown side of the Wellington Fault. Within the basin Castlecliffian deposits of the Mangatarata Formation have been folded and at the northern end of the basin faulted. These thrust faults and blind thrusts under the folds, are no more than 5km distant from the Wellington Fault and may be deformational features that connect with the fault at depth. The faults are considered by Melhuish (1990) to be inactive at present. This was based on field observations and the lack of seismicity in the area.

This early Quaternary deformation style appears to have changed and now the main activity on the fault is dextral strike-slip (Marden 1984). Westward late Quaternary uplift rates at Ballantrae are in the region of .76 to 1.23mm/yr (Marden and Neall 1990), however most Holocene upthrow along the fault is seen to be mainly to the east. The major tectonic deformation seen today is associated with Holocene faulting activity. This deformation is more localised and is confined within the fault trace and splay fault areas. Locally some sediments of Tertiary origin dip inward towards the fault, while the dips of the latest Ohakean terraces adjacent to the fault appear to be unchanged or only slightly deformed since their formation. These terraces dip eastward between 3 and 6°, however vertical and horizontal offsets are common.

The larger deformational features seen along the Wellington Fault trace between the Manawatu Gorge and Kumeti Road are two strike-slip duplexes. The larger of these duplexes is no more than 2 km in length and are zones of high fracture density with smaller en-eschelon faults defining the duplex structure (see chapter 3). Duplexes often but not necessarily form at compressional or extensional fault bends. 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 can take place by uplift around a contractional duplex or subsidence around an extensional complex (Woodcock and Fischer 1986). These two duplexes are found on Inglis' Farm at the end of Foleys Road and between Loveday and Fairbrother Roads.

Other deformational features are seen in splay or splinter faulting (Marden 1984). Very little deformation was seen between these splay faults and the main fault plane but this may be due to the lack of outcrops in an area of highly cultivated farmland. The third kind of deformation is confined to the fault trace itself in the form of tectonic and geomorphic landforms. The tectonic landforms are springs, sagponds, upthrown or downdropped scarps and breaks in slopes seen on steep hillsides along with duplexes, already mentioned. Geomorphic landforms are offset streams, ridges or spurs and river terraces. Older Holocene offsets for streams and terraces are in the region of 90 to 100m. All the above deformational features are seen all along the fault trace between the Manawatu Gorge to Kumeti Road. 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 basement of the Ruahine Range. In this area offsets on shutter ridges and spurs are also in the region of 100m. The edges on the spurs and ridges are clear and sharp even in shattered greywacke. It is possible that they are the same age as the offsets seen south of Kumeti Road. Unfortunately most papers written on the age and analysis of scarp profiles are for cohesionless materials and not basement rock so age estimates of these scarp profiles could not be made. There are a number of folding episodes recorded within the Torlesse basement rocks but these are ductile deformations and therefore not related to Quaternary faulting which appears to be brittle. It is possible for the main faults in this area to 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 (Sporli and Bell 1976).

Ruahine Fault

By contrast the Ruahine Fault seems to have been largely inactive between the Manawatu Gorge and Ohara Depression during Holocene times. In the south of the area the fault is the contact fault between Torlesse basement and Tertiary sediments (Marden 1984) and must have been active during Tertiary times. Seismic cross-sections of the Ruahine Range done 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 meters wide) show the locality of the fault (Marden 1984). There are a few offset streams and some influence on drainage patterns but little else. Marden (1984) reports that there are two sharply defined fault scarps of 50 and 75 m lengths where a walking track crosses the main range east of the Maharahara Trig. The height of these scarps is between 6 and 8 m with uplift being to the northwest. These scarps are the only evidence of possible Quaternary faulting through the length of the area mapped by Marden.

OHARA DEPRESSION

Both the Ruahine and Wellington Faults display evidence of having been active during Quaternary times. The Ohara Depression consists of two basement blocks, one block has been down-dropped between the Wellington and Ruahine Faults and is now covered with Tertiary 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 but elsewhere maintain their gentle, regional southwesterly dip. In this area the behaviour and deformational style of both faults are seen to be similar

Wellington Fault

Structural development of late Tertiary and Quaternary rocks show that the Wellington Fault has been active for a considerable period of time within the Ohara Depression. There are a number of folds between the Wakarara Monocline (Figure 2.) and the Wellington Fault in the Waipawa Reentrant zone and these are likely to be related to compressional deformation between these two structures. In this same area there is a large (500m) compressional left step in the Wellington Fault which also has folds within the compressional zone. The vergence of these folds is dextral corresponding with the sense of movement on the fault (Raub 1985). This compressional left step and associated deformation is possibly another strike-slip duplex in the early stage of evolution. Where the folds are between the fault limbs, continued faulting action and compression will eventually lead to the formation of horses.

River terraces in the Wakarara area indicate that upthrow on the Wellington Fault has reversed during the late Quaternary. Along the Mangataura Stream, terraces with estimated ages of c. 60 to 80,000 yrs are upthrown to the northwest, whereas younger terraces of c. 11,000 yrs are upthrown to the southeast (Raub et al. 1987). Further north on the west flank of Mt Mary is another syncline close to the fault which is probably associated with faulting activity and the uplifting 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 to almost vertical and it is possible that the Wakarara Monocline (located 1 km to the south east) may merge with the Wellington Fault in this area (Figure 2). A single natural exposure in the Wakarara area revealed offset units that were radiocarbon dated as indicating a surface rupture had occurred since 1165 +/- 50 yrs B P., (Raub et al. 1987).

Ruahine Fault

The Ruahine Fault lies between the younger downdropped late Tertiary sediments to the east and the upthrown Ruahine Range (Torlesse greywacke basement) to the west, showing that most of the uplift in the past was towards the west. However the most recent uplift on this fault especially in the northern section of the Depression is to the east, as confirmed by striations on the fault surface in Tarapeke Stream (Erdman and Kelsey 1992) and upthrown eastward scarps. Other deformation along the Ruahine Fault is in the Sentry Box area where the Matapuna Fault, (a possible splay of the Ruahine Fault) inferred from the upthrown greywacke basement to the east of the Ruahine Fault, (Figure 2) is on the same strike as folds in the Sentry Box limestone. These folds are likely to have formed as a response to movement on this fault.

Strain Transfer Faults: Discussion

In the southern end of the Ohara Depression is the Cullens Fault. It is mapped by Raub (1985) as 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. There are linear features seen on aerial photographs from Daphne Hut by the North Branch of the Tukituki River across Stumpy No 2 to offset ridges south of Cullens Trig. It is here suggested that strain is being transferred from the Wellington Fault to the Ruahine Fault via Cullens Fault. Offsets on the Ruahine Fault south of this area are almost non-existent and the fault south of this area does not even appear on some workers' maps. To the north of this area the Ruahine Fault has a strongly marked trace. On the other hand the

Wellington Fault in the Dannevirke area has an average offset rate of 10mm/yr, but in the Ohara Depression this rate drops to 3-4.6 mm/yr.

In the northern sector of the Ohara Depression is another fault branching from the Wellington fault called the Big Hill Fault. This fault is considered 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. The Big Hill Fault is considered to be a part of the regional dextral strike-slip system and at its southern end the fault strikes northwest and has reverse motion (Erdman and Kelsey 1992; Cashman et al., 1992). If this fault is a transfer structure in recent times then the trace of the Wellington Fault should weaken after transfer. Correspondingly the Ruahine Fault trace should be weaker before transfer, but in fact the opposite is true. The Wellington Fault trace north of the Big Hill Fault is noticeable in the field and on aerial photographs with offset spurs, shutter ridges, ponded drainage and offset streams with uplift to the east. The Ruahine Fault trace south of the Big Hill Fault also has shutter ridges, ponded drainage and offset terraces with the latest uplift being to the east. It would seem that if the Big Hill Fault is a transfer fault then this action occurred before the initiation of eastward uplift (prior to 14 082 yrs B P.). However it is also possible that strain is being transferred at depth, because the faults in the narrowest part of the Ohara Depression are only 3km apart and may meet deeper down in the crust. Whatever the relationship between the two faults, there is no doubt that strain is being transferred from one fault to the other. Further north, the Ruahine Fault is seen from trenching studies to be much more active than the Wellington Fault.

NGARURORO RIVER TO THE NAPIER-TAUPO HIGHWAY

In this area the regional geology is similar from the Ngaruroro River to the Napier-Taupo Highway. Trenching studies have shown that here the Ruahine Fault is more active in Holocene times than the Wellington Fault (see chapters 5 and 7). The deformation caused by the faults on the geology around them is similar. This area is also dominated by block faulting so that the major deformation is between the blocks rather than within blocks. In this part of Hawkes Bay one of the major lithologies through which the faults pass is the Te Aute Limestone Facies (Beu et al., 1980).

Wellington Fault

North of the Ngaruroro River Ohakean-aged terraces are offset by the Fault but they are not deformed except within the fault trace itself. Further north past the Fort, the regional east to southeastly dips of the limestone remain unchanged by the fault. Between the Ruahine and Wellington Faults the Limestone dips at 15° to the southwest and a similar dip is measured to the east of the Wellington Fault. The only major deformation is seen in the difference in the height of the limestone blocks. To the north of this area the fault traverses softer marine siliclastic rocks of Pliocene 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 Glenross Road at Willowford where there are ill defined offset ridges. On the Napier-Taihape Road, Waihua terraces (Grindley 1960) dip at 3° to the southeast which may have been their original depositional dip. It is possible that these terrace surfaces have not been deformed locally by fault action only displaced. Older rocks underlying the gravels close to the fault have been tilted toward the fault between 3 and 5°. Other deformation seen in this area is the result of slumping and landslides. Off Willowford Road there is a large slump and a landslide to the east on the north side of Tutaekuri River. Further north on Hawkstone Station is a landslide on the west side of the fault trace.

North of the Tutaekuri River the fault trace becomes much more pronounced as the trace again passes through harder Te Waka Limestone. At Mangatutu Station the limestone to the east of the fault dips southeast between 6 and 14°. To the west of the fault there is little exposure, but one outcrop almost right on top of the fault trace appears horizontal. There are indications that these limestone facies accumulated in an actively deforming tectonic regime. The limestone has intraformational and interformational unconformities with large along strike (100m to over 5km) and across strike (300m to over 1 km) variations in limestone thicknesses. Other indications of this deformation are seen in giant tabular cross-beds with sets 10 to 40 m thick (Kamp et al., 1988). This does not mean that the limestone was deformed by the Wellington and Ruahine Faults but rather by the action of the subduction zone during limestone formation in Tertiary times. Seismic profiles through the offshore Hikurangi margin show that similar deformation is still occurring today in late Quaternary sediments (Lewis 1980). The change in dip seen at Mangatutu is not necessarily due to fault activity. It is likely that this change occurred during formation of the limestone and is one of the giant cross beds already mentioned. However further north there is a change in dip across the southern end of the Te Waka Fault (see chapter 5) which is a major splinter of the Wellington Fault. This change in dip was not caused by the fault but continues across the fault trace. The change in dip is exposed east of the fault and appears to be the natural formation of another giant cross-bed. It is difficult to determine vertical and horizontal offsets especially over some distance due to the effects of the cross-beds and the unconformities within the limestone.

Other 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 is found again close to the trace of the Wellington Fault. This deformation may be an extension of the Ngatapa Syncline which further north is associated with deformation on the Wellington Fault (Cutten 1994).

Ruahine Fault

North of the Ngaruroro River the Ruahine Fault splinters into two or more traces. In the area around Mt Miriroa the regional faulting patten is complex. Here cross-cutting relationships between faults becomes ambiguous and relative chronologies difficult to establish (Brown 1980). This is probably because many outcrops are isolated from each other and the area between covered by heavily regenerating bush in some areas or destroyed by forestry activities. Most of this area is heavily criss-crossed with faults which trend northeast parallel to the Ruahine Fault. However there are a number of northwest-trending faults of which the Mt Miroroa thrust is the best known. Uplift on these northwest-trending faults is mainly to the south while uplift on the northeast- trending faults varies. The Ruahine Fault trace appears to be mainly upthrown to the east whereas the parallel Kaweka Fault is upthrown to the west. It is possible that the deformation between these two major fault zones is caused by these differences. The compressional trend for this area is to the northeast sub-parallel to the dominant fault trends (Brown 1980). On the northeastern slopes of Mt Miriroa, Torlesse greywacke basement has been thrust over Waitotaran siltstone. Brown (1980) reports that this thrust has developed due to dextral shear from the Ruahine Fault. Bedding on the Lizard splinter of the Ruahine Fault has been tilted up to 60°.

North of the Kaweka Forest the Ruahine Fault trace becomes a single strand once more and deformation caused by the fault seems to be confined to the fault trace. On the east side of the Davis 1 trench (see chapter 7) the Tertiary siltstone was heavily jointed but there was no regional patten seen elsewhere. Local deformation in this area is recorded by offset streams, spurs, shutter ridges and upthrow to the east. Further north of the Davis 1 trench uplift was to the west in a sissor-type geometry which changes again within a few kilometers. On the Napier-Taupo Highway the Ruahine Fault has offset a Miocene limestone and a section of Taupo Pumice Alluvium. Bedding within this limestone seems relatively undisturbed.

Overall deformation along both Wellington and Ruahine Faults appears to be mainly confined to block faulting over geological time. Historically, large areas of uplift and subsidence are reported to be the major deformation which occurred during the Wairarapa (1855) and Hawkes Bay (1931) earthquakes.

CHAPTER 3

THE WELLINGTON FAULT BETWEEN THE MANAWATU GORGE AND KUMETI ROAD

The geology between the Manawatu Gorge and Kumeti Road consists mainly of Tertiary (marine) strata which unconformably overlie basement greywake. In some areas the Tertiary strata are covered by Quaternary river gravel terraces and Holocene river sediments (Marden, 1984). On the down-thrown (eastward) side of the fault these sediments are up to 2km thick (Hicks, 1983). Between the Manawatu Gorge and Kumeti Road, Tertiary and Quaternary sediments are found on both east and west sides of the fault. For the most part the Quaternary gravel river terraces dip gently eastward away from the fault. However the Tertiary strata both east and west of the fault dip inwards toward the fault between Saddle and Coppermine Roads. 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 Tertiary strata to the east of the fault.

The Wellington Fault trace is largely hidden where it emerges north of the Manawatu Gorge. The main causes of this are firstly coverage by both recent river sediments and secondly possible eastward block-sliding of Nukumaruan limestone. Part of the fault scarp and its associated springs are offset 200m to the east round the toe of the limestone (Marden, 1984). If the fault trace did continue straight through the Nukumaruan limestone its trace has been largely destroyed by quarrying. The fault trace is found immediately north of the limestone, where it shows a single eastward-facing scarp between 10 to 19m high. Holocene uplift is to the west where minimum rates of vertical offset are estimated at between 1.23 and 0.76mm/yr (Marden and Neall, 1990). The eastward-facing scarp continues northward until it is covered by Holocene sediments of Mangapapa Stream, 6 km north of Woodville (Figure 4).

INGLIS' FARM TRENCHES

On the eastern side of Mangapapa Stream the fault trace is seen as a small graben 28m in width. On the western side of this graben are two abandoned stream channels. 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 earthquakes on the Wellington Fault are likely to have a significant seismic hazard impact on the city. Secondly, the position and ages of Holocene or 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 on a scale of 1:20. Inglis 1 and 2 trenches were excavated through the recent sedimentary fan that overlies the southern portion of the faulted graben. No relevant coverbed stratigraphy or suitable carbonaceous material was obtained from these sites for dating purposes.

Inglis Site 3 Trench

The Inglis 3 trench was 38m long and up to 4m deep; it was dug through a ponded drainage site across the small graben. The trench footwall was mostly 10cm below the top of the unctuous clay unit. The lower depth of the unctuous clay was acertained by augering, Sample A from the base of the above clay unit was also retreieved in this manner. Between the horizontal 15m mark to the 9m mark the trench was excavated deeper to expose more of the main fault plane. The sediments exposed in the trench walls are divided into 6 genetic units (Figure 5).

Stratigraphy

The western wall of the graben is composed of grey Tertiary mudstone (upthrown to the west) and covered by Holocene bouldery gravels. The gravels are composed of rounded to sub-rounded greywacke boulders up to 36 cm across and are clast supported. These bouldery gravels are overlain by finer weakly layered gravels. These gravels contain rounded 1cm to 5cm clast-supported pebbles and cobbles with patches of yellow-brown weathering throughout. The same unit in the northern trench wall also contained thin layers of very fine gravel.

The central portion of the graben consists of fine sandy river gravels with clasts up to 2cm across, overlain by up to 2m of unctuous clay. Sedigraph and XRD analysis show the unctuous clay is likely to be composed of weathered and redeposited Tertiary mudstone. Wooden roots, branches and stumps, some in growth position and up to 15cm in diameter, were distributed throughout the unctuous clay. Overlying the unctuous 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 graben was composed of Ohakean river gravels. These contained clasts varying from 5cm to 13cm across that were highly oxidized. Overlying these gravels was a unit of yellow-brown silt loam.

Structure

The western wall of the graben is composed of uplifted Tertiary mudstone which forms the western boundary lithology of the main fault plane. The fault plane shows reverse movement and it strikes 038/85w. Horizontal movement on the main fault plane within the trench was not discernable. However strike-slip movement is inferred from drag structures seen in the unctuous clay and the different thicknesses of the bouldery gravels. Between the Tertiary mudstone to the west and the bouldery gravels to the east (on the main fault plane) was a 3-5cm thick layer of Tertiary mudstone mixed with carbonaceous material. Within this layer many cobbles, pebbles and some boulders were embedded. These gravels were rounded to sub-rounded and closely packed. There were no slickenslides visible but there was one clear groove made by a boulder trending 114^{o} with a plunge of 14^{o}. Measurements of boulder axes indicate that their short axes were (82 times out of the 100 counted pebbles, cobbles and boulders) at right-angles to the fault plane.

Immediately east of the main fault plane and underlying the bouldery gravel was a smaller mini-graben containing fault breccia. The average clast size of the breccia is > 1 to 3cm in diameter. The breccia, and the bouldery and cobbly gravels are overlain by layers of finer river gravels. These have been buckled and dragged down to the east of the main fault plane in what appears to be two successive faulting episodes. In the first episode the deposits were displaced downwards by 1.5m to the east. In the second episode the finer gravels were further displaced 90cm vertically.

In the centre of the fault graben is another fault striking parallel to the main fault and dipping 75^{o} to the west. This fault has displaced lenses of finer material within the bouldery gravel. It shows horizontal movement only, as 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 fault graben strikes 030/46W and displays normal fault movement. Here Ohakean gravels and a segment of unctuous clay have been dragged up 1.50m to the east.

Inglis Site 4 Trench

This is the oldest geological trench site on Inglis Farm, being located in a position adjoining what is thought to be a Porewan-aged gravel terrace (Marden, 1984). Unfortunately no distinct volcanic ash marker beds were found in the trench to give direct stratigraphic dates (Figure 6). The Inglis 4 trench is situated at the upper narrow end of the graben approximately 175m north of site 3. The trench was excavated at right angles across the graben and 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. On the east side of the trench are Porewan-aged or redeposited Porewan 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 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 within 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 in which another paleosol has formed containing carbonaceous material. The uppermost unit is yellow-brown silty clay loam covered by an organic topsoil with scattered pebbles and cobbles between 12 and 15cm thick.

Structure

This trench also exposes the western wall of the graben forming the main Wellington Fault trace striking 039/75w. Here there is a reverse component with the total upthrow of Tertiary against late Quatertary materials within the trench measured at 6m. At the bottom of the trench, 2.2 m east of the main fault plane, is a listric fault of upthrust Tertiary mudstone (Figure 6). This fault has deformed the three lower units of gravel and sediment but not the overlying units. The eastern wall of the trench is composed of Porewan or reworked Porewan gravels which have been displaced 1.2m upwards to the east. Within the trench are structural features where different paleosols have been thrust into either younger or older material. The lowermost structure is a wedge of yellow-brown silty clay loam (without pebbles) which appears to have been pushed obliquely into the Tertiary mudstone. The second structure is also a wedge of yellow-brown silty clay loam within the Porewan gravels. The boundaries of this structure were too diffuse to measure. The third structure was a wedge of Tertiary mudstone pushed horizontally into the fault trench sediments.

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 has all the facets of an extensional strike-slip duplex (Woodcock and Fischer 1986, Twiss and Moores 1992). The duplex was formed by a double right-stepping extensional bend in the fault trace. The southern most bend has a change in direction of only 5° while the northern bend differs by 10° (Figure 7). This 5° bend may account for the narrowness of the graben. Reconstructed cross sectional paper cut-out models of the main units 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 (Figure 7). These structures are also fairly typical of dextral fault bends (Woodcock and Fischer, 1986, Twiss and Moores, 1992). The structures seen in the Inglis 4 trench serve to reinforce the above models. It is possible that the negative flower structures are individual horses within the pull-apart basin. These horses during intervals of faulting activity would move independently of each other due to the oblique nature of the strike-slip regime. The younging westerly trend of the normal faults within the Inglis 3 trench is also thought to be typical of the evolutionary stages in a pull-apart basin. In many such cases it has been observed that continual displacement leads to the basin being finally split by the youngest movement, a horizontal fault, which often, typically separates opposite sides of a basin from each other (Twiss and Moores, 1992). The youngest fault at Inglis 3 is a horizontal fault which separates the opposite sides of the basin as described above (Figure 5).

Inglis 3 Trench

Events within this trench have been correlated with nearby surface structures. It may be a coincidence that there are the same number of faulting events observed within the trench as there are offset features on the surface. 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 to the east. The Tertiary mudstone was then eroded into a sheltered basin forming the unctuous clay unit. A carbonaceous sample from the base of the clay gives an age of (NZA 3113) 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 over 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 event was post-4335 +/- 66 yrs B.P. It shifted the unctuous clay from its sheltered locality (behind the Ohakean gravel hill to the northwest) to a position which allowed the river to sweep into the basin depositing the bouldery river gravels. On top of these coarser gravels, thin (up to 40 cm) layers of pebbly, cobbly and very fine gravel were deposited. These gravels formed the Holocene 2 surface mapped by Marden (Figure 10).

3. During the third faulting event the Holocene 2 surface was uplifted and the Mangapapa Stream cut a channel through these deposits. This channel is 12.3m south of the Ohakean gravel hill. The centre of the pull-apart basin also dropped downwards at this time. This movement displaced the unctuous clay on the eastern side of the basin and the gravels on the main fault plane to the west.

4. A fourth faulting event caused the first channel to be abandoned and a second channel to form downstream. The offset between channels is 12.4m horizontal and approximately 1.8m vertical. This event may be correlated to offsets seen within the trench. Here the Holocene 2 surface is displaced a further 90cm, making a total vertical offset within the trench of 1.8m, the same vertical offset as that seen on the surface above between the two abandoned channels. The above faulting event or a buildup of river sediments then shifted the course of the Mangapapa Stream to the west abandoning the second river channel. A Holocene 3 surface was then deposited (Marden, 1984).The latest movements seen within the trench are dominantly horizontal.

5. The latest faulting event cuts through the central portion of the pull-apart basin and is visible from the top of the unctuous clay to the surface. The distance from the second abandoned river channel to the excavated trench's present position was 30.3m. Wood samples 40cm below the present topsoil and above the displaced Holocene 2 surface were dated (NZA 3696) at 211+/- 63 yrs B.P. Unfortunately the relationship between the silty sediment containing the above sample and the horizontal fault is unclear. Movement on this fault may thus have occurred either before or after the deposition of the silty sediment.

Finally a sedimentary fan was deposited over the southward part of the graben (trenches 1 and 2). As this fan does not seem to be offset by the fault, it is assumed that movement on the Wellington Fault has not occurred since the fan's deposition. It is possible that the youngest silty sediment found in the trench with an age of 211 +/-

63 yrs B P.was deposited at the same time as the above fan, giving a minimum age for the last fault movement.

Inglis Site 4

Measurements of the displaced Tertiary mudstone within this trench show that there is 6m of vertical offset, upthrown to the west along the western boundary fault. Deposits within the trench show a strong similarity to deposits on the higher Porewan gravel hillside to the east. It is significant that no appreciable amount of the uplifted Tertiary mudstone has been eroded 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 redeposition of Porewan gravels into the fault trench, while the Tertiary mudstone was 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 above gravels by faulting, along a listric fault within the trench 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 into the trench. A charcoal sample, in the upper eastern part of this unit gave a radiocarbon age (NZA 3071) of 29200 +/- 320 yrs B.P., postdating the former three events.

4. In this event, eastward uplift and deformation of the Porewan gravels occurs 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-29200 +/- 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 age (NZA 3114) of 10286 +/- 79yrs B.P. The 10286 yr age is likely to provide 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 there. The 9434 yr date from within the base of the unctuous clay provides a minimum date for this event.

5. A faulting or storm event caused the deposition of a lens of compact breccia into the fault trench. This breccia is not seen within other deposits in this area.

   A new soil then forms in finer silty materials above the compact breccia. It contained charcoal dated (NZA 3070) at 1105 +/- 65yrs B.P. in its upper part.

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.

   a) Subsequent to event 5, faulting has also deformed the Tertiary mudstone to the east of the main fault. This may be a purely horizontal movement because no vertical offset is seen here. It is possible that the last two events occurred simultaneously.

Summary of Faulting events seen on Inglis' Farm

The total late Quaternary 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. This 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. This gives an offset rate of 1.2 to 0.66 mm/yr depending on the inferred age of the Ohakean surfaces. This offset rate is similar to that calculated by Marden and Neall (1990). 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 is assumed that the clay 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 from the tree root at the top of the unctuous clay dated at 4335 +/- 66 yr B.P. The maximum offset can be measured from the base of the Ohakean gravel hill (beside the sheltered locality) to the Holocene 2 scarp on the eastern side of the fault. This distance is 65m which gives a maximum rate of 15mm /yr. The 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 the eastward-facing slope of an unstable hill composed mainly of Tertiary mudstone. Here only suggestions of a fault trace can be seen on aerial photographs. The fault trace is clearly visible again at 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 the road. At this locality a small stream is offset dextrally 53m. The fault scarp is composed of Tertiary mudstone fault gouge with angular to subrounded greywacke pebbles and is heavily eroded. Tertiary outcrops on the eastern side of the fault dip between 10 and 15° towards the fault plane. Outcrops on the western side of the fault also dip inward towards the fault. These are similar to the Tertiary sediments of the Saddle Road area (Lillie, 1953)

Approximately 500m north of Beagley Road is a pair of offset stream channels which angle across the Wellington Fault. The channels are part of the upper Mangapapa catchment system. 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. A trench was excavated at right-angles through the fossil stream bed. 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 on a scale of 1:20.

Stratigraphy for the Beagley Farm trench

The lowermost unit within the trench (Figure 13) is a grey Tertiary mudstone similar to that found in the Inglis trenches. Above the mudstone, in the centre of the stream bed, are subrounded bouldery gravels, matrix supported. A wood sample was retrieved from the top of the mudstone unit. The sample was found in growth position and was thought to have been overwhelmed by gravels brought down by the then, active stream. It gave a radiocarbon age (NZA 82290) 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. In between the north and south banks is a B horizon of yellow-brown loamy material containing some dispersed pebbles and cobbles, regarded as subsequent channel infill material following stream abandonment. A wood sample, 60cm below the top of this unit was radiocarbon dated at (Wk 3151) 290 +/- 50 yrs B.P. Overlying all the above units is the present topsoil which is 20cm 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 flows across the Wellington Fault, cutting through Tertiary mudstone and draining into the Mangapapa Stream (Figure 12). 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 moves again, the original channel is abandoned and a second stream channel on the eastern side of the fault (b) is cut parallel to the first but 30m further north. The number of earthquakes that make up the 30m offset are unknown. Shortly after these events or even during these events the dry stream channel would have begun to infill and the wood sample Wk 3151 290 +/- 50 yrs B.P. was deposited. Another faulting event or events created a 26.5m dogleg in the active stream (c). There is no clear evidence that sample Wk 3151 was deposited before or after these last events.

The Trotter trenches some 8 km to the north of this site have 5 faulting events recorded in the last 5000 yrs. If this records all the major earthquakes in the above trenches then each earthquake event must have involved an average horizontal displacement of 10m.

The overall horizontal offset rate for the Beagley Road area is 10.6 mm\yr, as measured from the total 56.5 m offset of both streams and the date of the wood in growth position.

From Beagley Road, the Wellington Fault trace continues northward trending 040°. Just before the fault crosses Coppermine Road there is a 93m offset along a small stream which has been dammed by the farmer and is now a small lake. In this area the latest series of vertical displacements appear to be mainly up to the east. However this is complex due to slumping and erosion on displaced hillsides. Between Oxford Road, just north of Woodville, and Coppermine Road, four splinter faults strike northeast 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. These faults all show vertical uplift predominantly to the northwest and displace Pleistocene marine strata and/or late Quaternary alluvial terraces. 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-eschelon* steps. In this area strike-slip faulting activity has dislocated surfaces which form shutter ridges. These ridges in some localities have blocked narrow gullies to form ponded drainage sites. This area can be reached via Top Grass Road and a paper road used by farmers whose properties adjoin the road (Figure 14). The offset at one of these ponded drainage sites along this northward curve is 50m. A carbonaceous sample was obtained by augering, from the base of this swamp.

Stratigraphy within the auger hole

Above the underlying Tertiary mudstone was a thin sandy silt unit from which a radiocarbon dated sample (NZA 5365) was obtained 3.75m below the swamp surface. On top of this unit was a log (perhaps dislodged by faulting). Above the log was 1.5m of peat covered by 30cm of sandy silt; this was overlain by 30cm of peat. Overlying the peat was a unit of fine sand on top of which was the uppermost unit of mud about 1m thick.

Sample (NZA 5365) was obtained from 3.75m below the swamp surface at a point 25m across the total horizontal offset of the ponded drainage site. An AMS date of the recovered carbonaceous material gave an age of 1746 +/- 78 yrs B.P.

PROPOSED SEQUENCE OF EVENTS FOR THE PAPER ROAD SITE

Earthquake events would have moved the shutter ridge across the gully far enough for a swamp to begin to form. Streams which form dog legs along the base of shutter ridges from such movement usually form a swampy area between the ridge and the stream. The ridge may have had to move more than 25m before the swamp began to form *i.e.*, where the sample was located, but not necessarily the whole 50m seen today. A horizontal offset rate can be obtained by using the age of the sample and the 25m distance the ridge had to move from the sample locality to its present day position, of 14.3 mm/yr. This is probably a maximum rate estimate.

The Wellington Fault trace can be seen just south of Loveday Road with uplift being most recently to the east. However adjacent to the Raparapawai Stream all traces of the fault have been destroyed or buried under the most recent stream terraces.

On the northward side of the Raparapawai Stream the fault trace splits into two segments that continue northward until they meet again at the end of Fairbrother Road, where Trotter farm is located at T24/ 609059 (Figure 14).

TROTTER FARM TRENCHES

Three trenches were excavated on Trotter's Farm (Figure 14). The first two were located on the downdroped eastward and westward limbs of a complex duplex structure on the Wellington Fault (Figure 18). The third trench was dug through an offset fossil stream channel which yielded no datable material. Vertical profiles of Trotter 1 and 2 trenches were logged on a scale of 1:20.

Trotter 1 Trench

This trench was excavated at right angles through the western fault forming the dual Wellington Fault Zone at this locality. The trench exposed an eastward-facing scarp within an Ohakean gravel terrace to the west and an adjoining peat swamp downthrown to the east. We interpret the Ohakean gravels were down faulted to the east and were then later covered by swamp sediments. The excavated trench was 12 m long and up to 3.4 m deep.

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 baes to within 1.4m of the surface making a total minimum thickness of 4.5m. Above the peat is a 1m thick horizontal layer of silt covered by 40cm of peat to the swamp surface.

The north and south walls of the trench were somewhat different, containing dipping layers of rubble within the peat. The lowermost unit was 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 is 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.

Structure

The fault plane in this trench dips eastward at 26° and strikes north at 074°. Pebbly sediments within this trench have a dip of 23°. Other sediments are all horizontal except where the peat unit appears to have been dragged upward by fault movement (Figure 15).

Trotter 2 Trench

This trench was excavated perpendicular to the eastern fault forming the dual Wellington Fault Zone at this locality. The trench exposed a westward-facing scarp within an Ohakean gravel terrace to the east and adjoining peat swamp to the west. The trench was 10m long and up to 5m deep. All four trench walls were logged on a scale of 1:20.

The eastern trench wall was composed entirely of Ohakean gravels. At the trench base were layers of silt up to 50cm deep between the gravel units. These layers were composed of grey silty carbonaceous clay and carbonaceous sandy silt, some containing wood. The gravels showed a weak horizontal layering and were mostly angular to subangular clast-supported pebbles and cobbles. The upper gravels were heavily oxidized, the lower reduced; the line between the two was 3.6m above 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 80cm-thick peat unit, above which was a thin layer of carbonaceous silt. On top of this was a grey silt unit some 25cm thick. Further above was river gravel, containing sub-angular to rounded pebbles, on which was developed a thin topsoil.

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 pebbly silty unit with some wood (continuous with the west and north trench walls). Overlying this was a 1m thick continuous unit of peat. On top of the peat was the continuous layer of carbonaceous silt, above which was a lens of solid wood and woody debris. Overlying the wood was another lens of fine sandy gravel. Above this was another continuous unit of grey silt over which were weakly aligned river gravels consisting of rounded to sub-rounded greywake pebbles which were clast supported and fairly well sorted .

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 . 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. Above these lenses was the continuous peat layer up to 1m thick. Overlying the peat was a continuous unit of carbonaceous silt which lenses out to the east. Above this was the grey silt unit and above the silt on the west end of the trench wall are the weaky aligned, rounded river pebbles. The upper unit on the eastern end of the trench consisted of a mixture of pebbly, cobbly and silty colluvium.

Structure

The Ohakean gravels of the east trench wall strike parallel to the fault with the gravel terrace surface dipping gently away from the fault at 3° toward the east. Sediments deposited within the west trench wall dip 10° to the west. The main fault plane seen within the north wall of the trench strikes northward 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. The sediments in the upper part of the trench immediatly west of the main fault plane have a change in dip to those at the trench base. These dip west at only 10° while those in the upper trench dip west up to 35°.

PROPOSED CORRELATED SEQUENCE 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) are deposited down slope into the trench sites as earthquake-derived erosional events. At the time of these earthquakes New Zealand would have been heavily forested and thus colluvial deposits would have only formed after severe environmental changes. These were most likely cyclonic storms or earthquakes. Wood debris and rounded pebbly river gravels are more likely brought in to the trenches during storm events.

A summary of events on the fault interpreted from the Trotter 1 and 2 trenches is as follows:

1. The first earthquake event occurred post the formation of the Ohakean gravels. At this site the gravels contain the sample dated (Wk 3146) at 22020 +/- 150 yrs B P., but the terrane was probably not offset until 10-12000 yrs B P., when terrace aggradation in the region ceased (Marden and Neall 1990). This event

offset the Ohakean terrace up to the west at the Trotter 1 site (Figure 19a) and up to the east at the Trotter 2 site.

An interval between faulting events occurred and the woody peat accumulated in both trenches.

2. A second earthquake event deposited gravel into Trotter 1 trench on top of a peat unit prior to 6080 +/- 60 yrs B P., based on sample Wk 3145 located just above the gravel in the Trotter 1 trench. As sample Wk 3145 was found close to the top of the gravel unit it can be assumed that if there was an earthquake event at this time it must have occurred c. 6100 yrs B P. However there is no record of faulting activity in any of the other trenches between 6000 and 9000 yrs B P.

   There is then an interval where more peat accumulates in the Trotter 1 trench followed by the deposition of a pebbly silty unit with some wood (Trotter 2 trench) and a silty pebbly unit (Trotter 1). It is possible that the deposition of these silty pebbly units in both trenches is a storm event.

3. A third earthquake event occurred; 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.

   This is followed by an interval where a lens of carbonaceous silt and some pebbles is deposited and preserved on the north wall of Trotter 2.

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

   There followed an interval where peat accumulates in both trenches beginning in Trotter 2 at 3110 +/- 60 yrs B.P. This date (sample Wk 3148) is 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 average conditions would take c. 1000 yrs to accumulate (based on a common peat accumulation rate of 1mm/yr, A.S. Palmer pers. comm.).

5. A fifth earthquake event occurs and the peat in the Trotter 1 trench is deformed and dragged 80cm up to the west (Figure 15). Coarse colluvial woody debris is

deposited in the south wall of Trotter 2. Wood from the woody debris is dated at 2030 +/- 50 yrs B.P. (sample Wk 3149).

There follows an interval, where up to 1m of grey silt is deposited in both trenches post-2090 +/- 50 yrs B.P., based on sample Wk 3143 located at the base of the silt in Trotter 1.

6. A sixth earthquake occurs and all the upper units in Trotter 2 are dragged upward and buckled. This is probably due to a compressional strike-slip event. This event was dated from a wood sample (Wk 3150) which was located at the top of the tilted grey silt unit and dated at 960 +/- 50 yrs B.P.

   This is followed by an interval where rounded and well sorted river pebbles are washed into the trench in 3 layers during a storm event.

7. These gravels are then tilted during a seventh earthquake event.

   More weakly aligned horizontal gravels are then deposited into the trench (Trotter 2) during a storm event. A wood sample from within these gravels was radiocarbon dated at (Wk 8228) 257 +/- 44 yrs B P. The older sediments (especially the 1m thick upper peat unit) show some evidence of periodic erosion where the tops of the beds have been truncated in the Trotter 2 trench (Figures 16 and 17).

8. An eighth earthquake event causes colluvium to fall downslope into both Trotter 1 and 2 trenches, post 257 +/- yrs B P..

Wellington Fault Structure in the Trotter Farm Area

Between Loveday Road and Fairbrother Road the Wellington fault forms a duplex which on the surface lookes like 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 and 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 as described by Marden (1984). Further 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 through an Ohakean gravel terrace. This terrace surface is presumed to have been formed close to 10000 yrs B.P. (Figures 19a and 19b). This assumption is supported by a date for these terraces from the Trotter 2 trench in which the lower part of the gravels is dated at 22020 +/- 150 yrs B.P. The upper terrace surface is some 10m above this point and is therefore consistent with the above assumption. The total vertical offset comes from the Trotter 1 trench where the Ohakean terrace surface is upthrown to the west 5.15 m above the trench surface. Added to this is the thickness of the sediments (5.9 m) within the trench on the downthrown side of the fault. As the Ohakean gravel surface was not found on the downthrown side, a minimum vertical offset rate for this area was estimated at 1.14 mm/yr.

The Wellington Fault is upthrown to the east along the top of Fairbrother Road. Upthrow is also to the east, north of the Oruakeretaki Stream. At Bakers Road only 1km to the north, a Porewan-aged hill (Marden 1984) is upthrown to the west and offset horizontally 150m. Tertiary sediments and a 20cm-thick layer of ash to the west of the fault dips 10° to 15° away from the fault; however this block of sediments may not be in place. Dips of other Tertiary and Quaternary sediments in the area are difficult to determine due to lack of outcrop. 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 the Otamaraho Stream, less than 2km north of Kumeti Road, the Wellington Fault strikes through greywacke terrain, with this lithology both to the east and west of the fault.

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 29000 years of faulting activity. There are up to 12 faulting events recorded in these trenches. Most of the evidence for these faulting events is based on deformation seen within the trenches. Some of these events are based solely on colluvium presumed to have fallen into the trench during faulting activity. The major periods of storm-induced erosion seen within New Zealand in the last 1,800 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 that are based on colluvial deposits that fall within the above time periods. However these erosional events do not extend back very far in time. Further back in time, there are major erosional events that took place in the West Tamaki catchment of the Ruahine Range (Hubbard and Neall 1980). These events 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 events may have been 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 known event with no date, other events are dated either post- or pre- the event in yrs B.P.

Inglis Farm		Beagley Farm	Trotter Farm	
Trench 3	*Trench 4*	*Offset Stream Trench*	*Trench 1*	*Trench 2*
211	EQ	290	post 257	post 257
EQ	EQ			pre 257
EQ	post 1105			960
			pre 2090	post 3110
post 4335				EQ
		post 5342	pre 5000	EQ
			pre 6750	pre 6080
pre 9434	post 10286			
			post 22020	
	pre 29200			
	EQ			
	EQ			

Table 2: Summary of horizontal offset rates seen on surface features along the Wellington Fault between Manawatu Gorge and Kumeti Road.

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

Table 3: Vertical offset rates along the trace of the Wellington Fault between Manawatu Gorge and Kumeti Road.

Ballantrae	Inglis Farm	Trotter Farm
0.76 to 1.23 mm/yr	0.66 to 1.2mm /yr	1.14 mm/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 Jurrasic age (Kingma, 1958). Basement greywacke in the Ruahine Range has been subdivided into 3 northeast-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 10 to 50cm thick. Thicker ridge-forming sandstone beds are found east of the fault in the West Tamaki, Mangatewainui, Makaretu and Tukituki river catchments. Bedding planes within the Kashmir belt in the above areas are mostly 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 plane. Within this crush zone remnant bedding can be found in places. The fault trace appears prominently on aerial photographs where it crosses the Apiti Saddle. There are also dextral offsets of 80 to 100m on small streams just south of the Saddle. 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 the Wellington Fault trace is another linear feature seen on aerial photographs. This feature 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 of this feature in the field due to heavy regenerating bush in the region. It is however possible that this lineation is the boundary between the Kashmir Belt and the Pohangina Melange belt. Where the Wellington Fault crosses the Moorcock Saddle there are a series of springs along and parallel to the fault trace. The fault trace can then be followed along the westward side of the Moorcock Stream (Figure 20) where there is a series of classical offset shutter ridges and spurs. Horizontal offset on one of these shutter ridges was measured at 100m with uplift toward the northwest. At the end of Mill Road there are spectacular exposures in the greywacke but the fault trace is less clear.

North of the Tukituki River at Alder Road the most recent uplift is to the east, the height is variable and may represent only a few faulting episodes. On the Oakley property at the head of Alder Road (Figure 20) a small ridge parallel to the fault trench has been upthrown to the east between 2 and 3m high. The fault trace (bearing

034o) appears clear and distinct in this area. Offset shutter ridges are very noticeable especially when seen from a distance. Horizontal offset ridges were measured at 60 and 100m, the smaller offset probably represents a younger geomorphic feature.

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 has been infilled by 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 35o. However close to the Wellington fault the Kereru Limestone has been folded into a syncline. At Wakarara the Wellington Fault trace is more eroded and 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 (Raub, 1985). Raub's map of the area also shows a 450m offset in the basement greywacke on the fault trace.

Further north, the Wellington Fault trace bears 036o crossing an old 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 90o angle and had been pulled apart "due to stretching across the fault plane". The house is located on the eastward upthrown side of the fault trace (Figure 22). Fences in the area had not been affected but these are more flexible fixtures. Such reports may indicate that a small amount of creep is taking place both vertically and/or horizontally.

Further north the Big Hill fault diverges in a northwesterly direction from the Wellington Fault. These 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. The deformation consists of folding of 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 22o. 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).

TRENCHING ON MCCOOL 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 Big Hill greywacke basement to the west and Tertiary sediments to the east. Blocked drainage, offset spurs and streams show that the latest episodes of vertical faulting to be up to the east. On McCool farm at the end of Nelson Road three trenches were excavated across or close to the Wellington Fault trace.

McCool 1 trench

This trench was 16m long and up to 4.5m deep. It was excavated perpendicular across the fault through a blocked drainage site at U21/010746 (Figure 22). The trench walls were cleaned and marked with a 1m string grid and logged on a scale of 1:20.

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-aged gravels from dates on 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 14082 +/- 156 yrs B.P. This carbonaceous silt unit thinned and wedged out to the west. Above the carbonaceous silt was a silty sandy 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, one dispersed tephra, two distinct tephras, patches of peat and carbonaceous silt close to the fault plane and two more tephras (FIgures 23 and 24). The uppermost tephra layer is thought to be from the 1850 yrs B P. Taupo eruption, the one below almost certainly Waimihia Tephra (Froggatt and Lowe 1990). The above are overlain by peat containing a thin layer of fine sandy gravel and a layer of angular pebbles which was seen in the north trench wall only.

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

Structure

The fault plane within the trench strikes 020o and was vertical. Tephras between the 9 and 10m (south trench wall, Figure 24) are dragged downward 1.6m while the same tephras at 9 and 10m (north trench wall, figure 23) are only disrupted. Above these tephras and close to the fault plane (020/v) are displaced lenses of peat that are older than the fragments of peat and wood found in the layers below. These clearly have been dragged upwards into the fault zone. There are no tephras found on the upthrown side of the fault.

McCool 2 Trench

This trench was situated east of the Wellington Fault. It was 16m long and less than 2m deep and was logged on a scale of 1:40. The trench was excavated through the younger of two paleo-overflow channels from a lake formed along the fault trace by upthrow to the east.

Stratigraphy

The lowermost unit consisted of a pebbly and cobbly gravel which was mainly clast supported; the matrix consisted of a coarse sand. The south wall of the trench was composed of a thick loess pan which had been cut through by the, then active overflow channel. This unit contained some carbonaceous material which was not submitted for dating. Above the pebbly cobbly gravel unit and abutting the loess pan were sediments deposited by the overflow stream. These consisted of silty oxidized 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 arrival soil because there were orange burn marks within the soil. Covering these units was the present topsoil which was 20cm thick.

This trench was excavated in the hope that more conclusive material for dating the horizontal offset of the paleo channels might be provided.

McCool 3 Trench

This trench was 13m long and up to 4m deep. The sides were cleaned and logged on a scale of 1:20. The trench was excavated through a swampy area across the fault trace. However the main fault plane was either further to the east within the upthrown hill or the behaviour of the fault differs in this area. The former is considered to be the most likely. Only 8m of the south trench wall was logged as the rest was destroyed by slumping. Although there was swamp and peat on the surface of this trench area, the sediments below were remarkably dry and no datable material was found.

Stratigraphy

The base of the trench on the downthrown (westward) side of the fault consisted of a grey-brown sandy silt. On the upthrown side of the trench was an angular gravel consisting of cobbles and pebbles with a coarse sand matrix. Above both of these units is a colluvial pan consisting of silty sand and patches of gravel, some of which was in layers, the rest dispersed throughout the trench walls. The Taupo Tephra from the 1850 yrs B.P. eruption was found at the base of the peat unit on the downthrown side of the fault only. On the upthrown (eastward) drier side of the fault the upper unit consisted of topsoil formed within gravel.

Structure

The fault plane is not apparent in the upper part of this trench (Figure 25). This is possibly due to not having excavated across the main fault plane at this locality. However a fault plane was found at the base of the trench about 55cm wide. This may be subsidiary to the main fault plane. The north trench wall (Figure 25) has a horizontal gravel unit that is bent vertically downward parallel to the fault scarp. The south trench wall shows thrusting of one gravel unit above another.

PROPOSED SEQUENCE OF EVENTS FOR McCOOL FARM

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

1. Initiation of uplift to the east. A minimum age for this first earthquake was given by the carbonaceous silt above the offset gravels found at the base of the trench (Figure 24).

   A time interval then follows in which a brown carbonaceous silt unit with wood dated (NZ8287) at 14,082 +/- 156 yrs B. P. is deposited. After this the lower grey/brown sandy silty loam units are deposited.

2. A second earthquake event is recorded by the carbonaceous silt unit being deformed and 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 with more carbonaceous silt, peat, tephras and blue/grey sandy silty loam deposited into the trench.

3. A third earthquake event is recorded by all the above units being deformed. This event occurred post-deposition of the tephras. Clearly the peat above the tephras has been displaced by strike slip faulting because it is older (NZ8290) 6561 +/- 79 yrs B.P.,than the units it overlies.

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

4. A fourth earthquake event is recorded by the above tephras being displaced and a wood sample (NZ8293) dated at 805 +/- 58 yrs B. P. is folded between the sandy silty loam and the gravel unit.

   An interval of peat then 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, but this could also be a depositional feature. This event is dated by sample (NZ8291) at 605 +/- 35 yrs B.P., froma sample of the underlying peat.

   Another interval follows with more peat accumulation.

6. A sixth earthquake or storm event is recorded where angular greywacke pebbles are deposited into the trench. This unit is seen in the north trench wall only and there is no deformation associated with this event.

   A further interval of time is recorded to the present when more peat accumulates.

Other deformation in the adjoining area along the fault includes offset streams, spurs and upright bedding. South of McCool 1 trench a streamlet had been offset by 53m.

To the north of the trench site there are offset spurs but the fault trace in places has been destroyed 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 20cm thick. Below this to the base of the hole at 1.6m was a sandy clayey fault gouge.

Further north, Tertiary bedding appears to be vertical close to the fault trace. Bedding close to the fault on the south bank of the Ngaruroro River is tilted at 70o. These bedding planes are not so obvious close to the fault where they are highly fractured and jointed. It is possible that the northern end of the Wakarara monocline merges with the fault in this area (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. The lake has two paleo-overflow channels (the youngest of which was excavated in the McCool 2 trench) and one active channel which has cut through the Tertiary and Quaternary upthrown sediments on the east side of the fault trace. The distance between the two paleo channels is 32m and the distance from the younger of these two channels to the active channel is 34.0m. This makes a total of 66.9m of dextral offset. Evidence compiled by Raub et al., (1987) suggests that eastward uplift further south in the Wakarara area began somewhere between 80-60000 yrs B.P. and 11000 yrs B.P. This evidence comes from terraces with estimated ages of 60 to 80000 yrs B.P. which were upthrown to the northwest and those upthrown to the southeast dated at c 11000 yrs B.P. The rate of horizontal offset at McCool farm can be found by using this distance/time relationship established from this work. The earliest evidence here for the initiation of uplift toward the east appears to have been around 14082 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 4.75mm/yr is determined. 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, Raub et al., (1987) determined a horizontal offset rate of 3.36mm/yr. 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 in 14082 yrs B.P. (i.e. 0.28 mm/yr).

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 Ohakean in origin due to their lack of loess covering and the much higher Ratan terrace situated above and to the northwest (Figure 27). The fault trace bears 034° across the Ohakean 1 surface and is seen as a broad shallow u-shaped depression containing sags, ridges and rent features. The latest vertical uplift is up to the east (approximately 2m) and the latest horizontal offset on what appears to be an Ohakean 2 surface is approximately 40m. This makes a horizontal offset rate of 3.3 mm/yr for this portion of the Wellington Fault, based on the tread age for the Ohakean 2 terrace (Pillans 1994). These terraces are somewhat complicated by later Holocene events which eroded away most Ohakean 3 surfaces on the downthrown side of the fault.

Beyond the terraces the fault trace is found in a valley which has fault gouge on both sides of the valley bearing 020o. The trace can be followed up to the south east side of the Fort (Figure 26). North of the Fort on Awapai Station, the fault trace is indistinct there are no offsets either vertical or horizontal, only a swampy area fed by a spring on the fault trace. The regional dip of the Tertiary limestone is to the southwest and does not appear to be deformed by the fault. Further north the fault has offset a number of streamlets in the Glenross Road area. The largest of these horizontal offsets is approximately 200m.

At Willowford, Tertiary and Quaternary sediments are largely undeformed by faulting. Quaternary sediments close to the east side of the fault dip at 3o away from it. In the Willowford Road area there are a number of slump features, one of which has a semi-circular sag pond. The fault trace can be distinguished at the west end of the pond. On Willowford Station there is a linear feature which can be traced on aerial photographs to the north side of the Tutaekuri River to the head scarp of a large landslide.

North of the Tutaekuri River the Wellington Fault is upthrown mainly to the east. The trace is clear and distinct in the field. On aerial photographs, there are numerous offset streams and ridges. The geology either side of the fault consists of Tertiary silts, fossiliferous sands and the overlying Te Waka limestone.

TRENCHING ON SYME'S FARM (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 show dextral offset. The trench was excavated through the upper end of a blocked drainage site against the fault scarp. The trench was 16m long and up to 6m deep; it was logged on a scale of 1:20.

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 is composed of gleyed unconsolidated sandy loam. At the trench base is a tephra unit. This tephra is thought to be the Karapiti Tephra dated at c. 10100 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 (c. 10000 yrs B P., Donoghue et al., 1991) in the base. 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 yielded a date (NZA 4557) 8770 yrs B P. Above the paleosol to the west is a peaty loam. Within it at 60cm from the base is the Waimihia Tephra dated at 3280 +/- 20 yrs B.P., (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, on the eastern side of the trench wall, is unit of yellow-brown highly allophanic loamy material.

Structure

The main fault plane strikes 030o northeast and dips between 80o east and vertical. It extends 2.5m upward from the trench base. There is also a parallel fault 20cm west of the main fault plane. It has more of an eastward dip and extends only 80cm upward from the trench base (Figure 29). The westward-facing surface of the upthrown limestone block dips at 60o to the west. In the space betweem the limestone and the fault plane is an unconsolidated sandy unit containing a few limestone blocks and pebbles. Toward the western end of the trench the paleosol and the unit containing the Waimihia and Taupo Tephras appear to have been disrupted but there is no visible fault plane surface present.

PROPOSED SEQUENCE OF EVENTS FOR THE SYME FARM TRENCH AT HAWKSTONE STATION

The first movements recorded 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 offset in the nearby streams. This event or events ocurred pre-10100 yrs B P., which is the age of Karapiti Tephra (Wilson 1993) located at the base of the trench.

Then an interval followed when sediments accumulated on the downward side of the fault. These are the gleyed sandy unit containing Karapiti Tephra, on top of which is the Mangamate Tephra followed by the paleosol. Charcoal found 40 cm above this unit was dated (NZA 4557) at 8770 +/- 120 yrs B.P.

During the second earthquake event recorded within the trench, the paleosol was then faulted against the mottled sandy clay, close to 8770 yrs B.P. Colluvium consisting of sandy clay with limestone rubble then 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 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.

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. Close to the Syme trench is a blocked drainage site which was offset horizontally approximately 60m. From the minimum date for eastward uplift from the trench base, based on the presence of the Karapiti Tephra c. 10100 yrs B.P., and the distance offset horizontally, a maximum rate of 6 mm/yr is obtained. There is no date for uplift along this segment of the fault trace as the limestone on the downthrown side of the trench was not exposed.

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 which forms the cap of the Range dips gently to the southeast and contains small rounded to subangular greywacke pebbles up to 1cm across.

The fault then crosses the Puketitiri Road and runs parallel to Potter Road for some distance where it is seen as a break in slope along a west-facing slope of the Maniaroa Range. The fault trace then crosses Potter Road and can be followed across farmland, before being untraceable in the Awahohonu State Forest. The fault trace can be seen again on the other side of the Napier-Taupo highway at Waitara Road. Here the westward-facing scarp can be seen clearly. The paddock through which the trace passes has since been planted in pines. On the west side of the Te Waka summit there is a steep road cutting on the Napier-Taupo Highway. Here Tertiary sediments here 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 of where the 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). From the Wellington Fault looking north across Pukrtitiri Road a higher fault scarp can be seen diverging from the Wellington Fault. 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 valleys within the Te Waka Limestone.

TRENCHING ON WEDD'S FARM

This trench was excavated across the Te Waka Splinter Fault on the Wedd property which can be reached from Puketitiri Road.

The Wedd trench was excavated across the eastern flank of a broad u-shaped faulted valley, in the northwestward-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 overlain by tephra deposits from the Central North Island. All 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. It was logged on a scale of 1:20.

Stratigraphy

On the upthrown (eastward) side of the fault was the Te Waka Limestone (Figure 30). The downthrown side consisted of Te Waka Limestone covered by terrestial sediments that were either eroded into the valley locally or consisted of ignimbrites and tephras from the Taupo Volcanic Zone. The lowermost unit consisted of limestone bedrock overlain by limestone rubble. Above the limestone rubble is a red-brown allophanic unit with rounded pebbles 1-2cm across, which is overlain by a 30cm-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 horizontal marks was a brown allophanic unit with small 5mm angular pebbles. Overlying all of the preceeding units was a yellow-brown allophanic unit. This yellow-brown unit contained a pocket of Waiohou Tephra and number of distinct layers of tephra beginning with 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 Ash 1-2mm and then the Taupo Ignimbrite. On top of the Ignimbrite is a 20cm thick layer of topsoil.

Structure

The main fault plane seen within the trench is along the upthrown limestone surface striking 034o and dipping 85o west. There are possibly other vertical faults within the trench. These are between the red-brown allophanic unit with rounded pebbles and the brown allophanic unit with angular pebbles. It is possible that the surface scarp between the 15 and 16m horizontal marks in the trench is also fault derived. This scarp is seen on both sides of the valley running its full length. The scarp is always the same height and exposes the same two units, the Waimihia Tephra in the base and the Taupo Tephra at the top. There is no evidence of slumping along these scarps.

PROPOSED SEQUENCE OF EVENTS FOR THE TE WAKA SPLINTER FAULT

The first faulting event or events in this area are pre-Waiohau Tephra dated at 11,850 yrs B P., Froggatt and Lowe 1990). This resulted in the formation of the broad u-shaped valley in which the subsequent late Quaternary terrestial sediments accumulated.

This was followed by an interval where the above sediments accumulate in the fault trench. These sediments are firstly the red-brown allophanic unit and then the lower sandy layer. This was followed by the deposition of the yellow-brown allophanic unit and accumulation of carbonaceous material within it.

The first faulting event seen within the Wedd trench is recorded by the deformation of the lower sandy and yellow-brown allophanic units. 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 Waiohau Tephra. The asumption could be made that this earthquake event occurred post-deposition of the Waiohau Tephra dated at 11850 +/- 60 yrs B P., (Froggatt and Lowe 1990).

This is followed by another interval where 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.10100 yrs B.P., Mangamate c.10000yrs B.P. and Poronui 9810 +/- 50 yrs B.P. Tephras are deposited into the trench (Froggatt and Lowe 1990, Donoghue et al., 1991 and Wilson 1990).

The second faulting event is recorded (post-Mangamate Tephra c. 10000) by deformation in the centre of the trench between the 8-12m horizontal marks. Here there is a unit which is unrelated to those in the same stratigraphic positions on either 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. During this event the lower sandy unit is abruptly terminated and the Mangamate Tephra is deformed.

After the above event the Waimihia Tephra was deposited into the trench, at 3280 +/- 20 yrs B.P. Yellow-brown allophanic material is again deposited into the trench followed by the Taupo events. Firstly there are the Taupo precursors of Hatepe Tephra and Rotongaio Ash followed by the main Taupo ignimbrite.

A possible 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 that material from further down the valley, when moved sideways leaves a gap in the upper units. There are a number of these small scarps on the Wedd Farm. On the neighbouring Duno Farm they are 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.

The fault trace can be followed in the field and on aerial photographs northward. North of the trench site the fault trace narrows, then there is a right stepping extensional jog and the fault trace widens into another broad u-shaped valley. This valley is located west of the Maniaroa Trig; upthrow is to the east and there are possible horizontal offsets of 60 to 100m. The fault trace can then be followed as far as the upper reaches of the Mangaone River. The trace then becomes hard to follow and there may be a left step in the trace which has been eroded away in the softer sediments. Further north the trace is clear where it runs parallel to Camp Stream. From Camp Stream north the fault trace runs parallel along the ridge of the Te Waka range to the microwave station. This ridge appears to have been created by the fault and here the fault trace is easy to follow wherever it passes through the harder Te Waka limestone. The Te Waka limestone of the northern section of the Maniaroa Range dips opposite to the regional patten, but this change does not appear to have been induced by the splinter fault; the northwesterly dip is continuous across the fault trace.

At the microwave station the fault offsets terminate in a three fingered splay. This splay is typical of a fault termination where fault rupture ceases (Aki, 1988). 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 Te Mata limestone does not appear to have any offsets either vertical or horizontal north of the main fault trace (bearing 034o). There are some linear ponds and sink holes but it is possible that these features represent an eroded bedding plane on the ridge summit. Vertical offset at the microwave station appears to be in the region of 30m up to the east. 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 may have been fault generated. This landslide appears to have been generated post-Taupo Tephra c.1850 +/- 10 yrs B P. (C. Hannan pers.comm.). If an earthquake event did trigger this landslide then it would correlate to the post-Taupo Tephra event which formed the small scarp seen in the Wedd trench.

Unfortunately there are no Holocene formations preserved to give these offsets a yearly rate. Although offsets could be worked out from the limestone age it would give a false yearly rate because most faulting especially in the Wedd trench area of the Te Waka Spinter Fault has occurred within the last 20000 yrs. 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 maximum vertical offset rate of 2.5 mm/yr. Horizontal offset rates using the same date for upthrow to the east and the distance the upthrown block has moved (approximately 60m), give a minimum offset rate of 6 mm/yr for the southern segment of the fault in this area.

CHAPTER 6

THE RUAHINE FAULT FROM THE MANAWATU GORGE TO THE KAWEKA FOREST

The Wellington Fault trace bifurcates just south of Kahuki. 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 the Kahuki Stream. It is approximately 40m west of the Kahuki horst and graben system which is a part of the Wellington Fault. The outcrop is formed of fault gouge and is approximately 7m wide and 6m high. Between Kahuki and the Manawatu Gorge the fault separates Torlesse greywacke bedrock to the west and Plio-Pleistocene deposits to the east. This boundary can be traced through dense bush on Centre Road where it can be then be followed across a steep hillside just west of the Ballance Bridge (Figure 3). On the other side of the gorge the fault trace appears to have a sinistral sidestep. The trace at this point can be clearly seen on both aerial photographs and in the field, immediately to the south of Saddle Road. Unfortunately there are no outcrops in this area. The fault shows as a patch of swamp, where it crosses through Tertiary rocks. North of Saddle Road the fault trace disappears in Tertiary rocks. The Fault can be located again to the south of Wharite Road where it again becomes the contact between Torlesse basement and eastward-dipping Tertiary sediments.

The Fault crosses Wharite Road and from here on to the Ohara Depression traverses through Torlesse greywacke basement rock only. It passes to the east of Wharite Trig where it is mapped by (Marden, 1984) as a series of fault breccia zones. The trace then becomes less defined and in the headwaters of Coppermine Creek, Mang-a-tua and Raparapawai catchments there are extensive zones of brecciated Torlesse rock occurring through each catchment. These could be collectively termed the Ruahine Fault Zone. North of the Raparapawai catchment the Ruahine Fault Zone crosses the crest of the Ruahine Range east of Maharahara Trig. North of this Trig a number of streams are dextrally offset and in the upper reaches of the Makawakawa catchment the drainage patten has been influenced by fault activity (Marden 1984). Fault exposures of brecciated bedrock can be seen in cuttings on Takapiri Road. The fault zone is seen on aerial photographs striking along the upper reaches of the Pohangina River. Here Torlesse basement has been sub-divided into 3 north-east trending belts (Sporli and Bell, 1976 and Marden 1984). The fault zone bounds 2 of these - the Pohangina Melange and the Western Axial Belt, and consists of up to three traces. 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 crosses the Pohangina Saddle and close by Daphne Hut it shows two traces (Figure

31). Further north the fault zone crosses the Hinerua Ridge where it becomes difficult to follow on aerial photographs. It is possible that the fault and the boundary of Pohangina Melange merge for some distance past Stumpy No 2 trig, northward into the Ohara Depression.

THE OHARA DEPRESSION

From the Ohara Depression northward the character of the Ruahine Fault changes. The fault again becomes a contact fault between Torlesse bedrock of the Ruahine Range and 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 tree line, are numerous shutter ridges, offset spurs and streams (Figure 21). The offsets are dextral but they do not appear recent; the bends in the streams and shoulders of the ridges are rounded and not sharp. This made dextral horizontal offsets difficult to measure, but approximate distances of these offsets were between 50 to 100m. The fault trace continues north, bearing 030° through the Gwavas Forest, where upthrow is to the west. South of the Sentry Box the fault trace becomes more complex where displaced greywacke is pushed out into the Ohara Depression along the Matapura Fault (Figure 2) and a smaller un-named fault. Both of these faults may be splays of the Ruahine Fault and their presence is inferred 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. North of the 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. Further 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. McIndoe Flat has a number of younger terraces 20m above the river level, which appear to be Holocene and Ohakean in age. The youngest of these terraces is offset vertically by 50 to 80 cm and approximately 3m horizontally. Unfortunately the age of this terrace is unknown. All of the younger terraces in this area lacked a loess covering and have a thin veneer of volcanic material, which may have been reworked. At McIndoe Flat the main fault trace is seen to bifurcate; the westerly splinter bears north of the Ngaruroro River directly toward the Lizard.

At Omhaki, greywacke basement is upthrown to the west. The fault again passes into Tertiary sediments and it becomes the western boundary of the Mt Miroroa thrust fault. Further north, the fault traverses across the Lizard to the Kaweka Forest. The easterly splinter crosses Glenross road at Kohau and appears as a break in slope across the Te Waka Limestone. The trace then passes east of the Blowhard northward through the Kaweka forest (Figure 26). There is a lack of Quaternary deposits in this area and the usual offset spurs and ridges are missing.

There are no significant markers on the Ruahine Fault between the Manawatu Gorge and the Kaweka forest to determine the total horizontal offset. However a correlation might be made between the Sentry Box Limestone in the Ohara Depression and the upthrown limestone on Seconds Ridge 2.5km (Figure 22) north of the Ruahine Hut in the Ruahine Range (Beu 1994). The horizontal offset between these two nearest limestone outcrops on either side of the Ruahine Fault of the same type and age is approximately 7km. Beu (1981) gives three lines of evidence for uplift of the Ruahine Range during the Castlecliffian period. This indicates a mean uplift rate for the Ruahine Range of 1.7mm/yr. A tentative horizontal offset rate, found using the 7 km offset of the above outcrops and the onset of westward uplift (Castlecliffian), gives an offset rate of 7 mm/yr.

Strain Transfer Faults: Discussion

In the southern end of the Ohara Depression is the Cullens Fault, mapped by Raub (1985) as 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. There are linear features seen on aerial photographs from Daphne Hut by the North Branch of the Tukituki River across Stumpy No 2 to offset ridges south of Cullens Trig. It may be that strain is being transferred from the Wellington Fault to the Ruahine Fault via Cullens Fault. Offsets on the Ruahine Fault south of this area are almost non-existent; the fault does not even appear on some workers maps. To the north of this area the Ruahine Fault has a strongly marked trace. On the other hand the Wellington Fault in the Dannevirke area has an average offset rate of 10mm/yr, but in the Ohara Depression this drops to 3 or 4.6 mm/yr. In the northern sector of the Ohara Depression is another fault branching from the Wellington Fault named the Big Hill Fault. This fault is 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. The Big Hill Fault is considered to be a important part of the regional dextral strike-slip system; at its southern end the fault strikes northwest and has reverse motion (Erdman and Kelsey 1992; Cashman et al.,). If this fault is a transfer structure in recent times then the trace of the Wellington Fault should weaken after transfer. Correspondingly the Ruahine Fault trace should be weaker before transfer; yet in fact the opposite is true. The Wellington Fault trace north of the Big Hill Fault is noticeable in the field and on aerial photographs with offset spurs, shutter ridges, ponded drainage and offset streams with uplift to the east. The Ruahine Fault trace south of the Big Hill Fault also has shutter ridges, ponded drainage and offset terraces with latest uplift being to the east. It would seem that if the Big Hill Fault is a transfer fault then this action occurred before the initiation of eastward uplift (pre-14082 yrs B.P) However 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 deeper down in the crust. However it works there is no doubt that strain is beingtransferred from one fault to the other. Further north the Ruahine Fault is seen from trenching studies to be much more active than the Wellington Fault.

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 an overgrown scarp just west of Lawrence Hut. Sections of the fault trace can be seen from Lotkow Road along Gorge Stream where offsets along the fault trace have been described by Beanland and Berryman (1987). From the Lawrence Hut through the Black Birch Range to the quarry on Whittle Road the fault passes through Torlesse greywacke basement. To the north of the quarry, greywacke is found to the west of the fault and Tertiary siltstone to the east for about 6km. 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 upthrown block of Tertiary limestone on the Napier-Taupo highway (Grindley 1960).

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 the quarry (U20/092077). The quarry exposes basement greywacke with vertical bedding and some tight folding. This area 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 the blocked drainage of the fault trace. Aerial photographs of this area show the fault trace as a perfectly straight line. The latest vertical movements in this region show that uplift movement has shifted from the west side of the fault to the east probably within the last 20000 yrs. Streamlets in the area have been displaced dextrally by 8-10m.

Davis 1 Trench

The site for this trench is located approximately 100m to the north of the quarry at the end of Whittle Road. This trench was excavated at right angles across the fault trace through a swampy ponded drainage site. It was 29m long and up to 5m deep. The trench walls were cleaned down, marked with a 1m string grid and logged on a scale of 1:20 (Figure 34).

Stratigraphy

The western wall of the fault was composed of greywake while the eastern side is composed of upthrown Tertiary siltstone of Kapitean age (Grindley, 1960). At the trench base a silty grey unit containing tephra and wood was exposed. Above this unit was a layer of peat containing some angular greywake pebbles. Overlying the gravelly peat is a lens of fine rounded gravel no more than 10cm thick. Above this gravelly lens is more peat with some siltstone chips. On top of this peat is 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 horizontal marks). Overlying the peat and blue-grey rubble was a 19cm thick layer of Waimihia Tephra. On top of this tephra was a 20cm thick layer of peat above which is the Taupo Tephra. This tephra is 16cm 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 1cm layer of peat, above which is a blue-grey rubble unit composed of angular to rounded greywake pebbles and cobbles which make up 85% of the total unit. The 20% matrix in this unit consists mainly of Taupo Tephra. The blue-grey rubble becomes more sandy in texture toward the top of the unit. It is not found across the full length of the trench but extending only to the 19m horizontal mark. Above the rubble another peat unit has accumulated which is up to 1.5m thick. Within this peat and 50cm from the surface is a layer of angular greywake pebbles. 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.

Structure

The main fault plane appears to be situated between the peaty units in the trench and the eastward upthrown Tertiary siltstone block. The fault plane strikes at 015o. At the contact the siltstone is crushed and broken. The dip angle of the fault is variable between vertical and 68o west; this variation may be caused by a down-dropped block of siltstone. However there are other fault surfaces within the trench sediments but many have disappeared due to the pliable nature of the sediment. For example there is a fold in the Waimihia Tephra. The fold axis can be aligned with a down-dropped segment of the blue-grey rubble (Figure 32 horizontal marks 13 and 14) but no faulting surface is seen. Vertical offset for one event comes from the height of the fold in the Waimihia Tephra and the corresponding height of the down-dropped blue-grey rubble which is about 60cm. Most of the trench sediments also have boudinage structures. There are depositional features where some blocks of tephras may have been reworked by faulting or redeposited by storm events. Between the 27 and 28m horizontal marks, Waimihia Tephra is found on top of Taupo Tephra. Between the 11 and 12m horizontal marks Taupo and Waimihia Tephras are found 1m above the other Waimihia and Taupo units in the trench. A scarp uphill and just to the south of the trench site is the probable source of this rubble and the blocks of redeposited Taupo and Waimihia Tephras.

Davis 2 Trench

This trench is located some 500m south of the quarry at the end of Whittle Road. Access to this site is from the forestry road to Lotkow Hut. The trench was excavated through basement greywacke and across the fault scarp. It was 12m long and up to 5m deep and was logged on a scale of 1:20.

Stratigraphy

This trench was excavated through shattered greywacke, the floor and both 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 parallel to the fault trace. 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 between the 4-6m horizontal marks is a unit of greywacke rubble consisting of angular cobbles and pebbles. Between the 1-3m horizontal marks in the south 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 dispersed layer of rhyolitic tephra. Above this is a dispersed 20cm thick layer of Mangamate Tephra. Overlying the Mangamate Tephra is another dispersed layer of rhyolitic tephra. Above the tephras is a unit of 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 carbonaceous material. On top of the above 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 20-30cm thick topsoil. The above units are the same for both the north and south trench walls; (Figures 36 and 37) only the structure of the greywacke contained within is different.

Structure

The main fault plane is vertical and has been uplifted by at least 2m to the east from the floor of the trench. This upthrown greywacke still contains some remnant bedding. The Mangamate, Waimihia and Taupo Tephras have all been disrupted along with an adjacent paleosol seen on the south trench wall between the 1-2m horizontal marks.

PROPOSED SEQUENCE OF EVENTS FOR DAVIS 1 AND 2 TRENCHES

Davis 1 Trench (Figure 34)

The first faulting event in recent times would be the initiation of the upward movement to the east along this segment of the Ruahine Fault. This movement began the creation of a trench in which materials could accumulate.

This would be followed by an interval where Tertiary siltstone is eroded into the trench. Wood from within the eroded siltstone gave a radiocarbon age (NZA 8233) of 7778+/- 81 yrs B.P. Drainage within the trench became blocked by the previous faulting event, causing peat to accumulate.

The second earthquake event seen within the trench downdrops a large silt block on top of the peat. Wood from beneath this block has a radiocarbon age of (NZA 8231) 5971 +/- 78 yrs B.P. There are gravels within the peat which also indicate an earthquake event at this time. A thin lens of fine rounded gravel was then deposited into the trench.

Another time interval occurs where up to 40cm 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 by 17cm. Wood from the top of this unit is radiocarbon dated (NZA 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 pre-3280 +/- yrs B.P. (Froggatt and Lowe 1990) when deposition of the Waimihia Tephra occurred.

During the following time interval 19cm of Waimihia Tephra is deposited into the trench after 3280 +/- 20 yrs B.P. Then up to 20 cm of peat accumulated on top of the tephra, followed by the deposition of up to 16cm of Taupo Tephra at 1850 +/- 10 yrs

B.P (Froggatt and Lowe 1990). Overlying the Taupo deposits is a further 1cm thick deposit of peat.

A fifth earthquake or storm event then deposits blue-grey rubble with 85% angular greywake pebbles and cobbles 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 60cm offset thrust fold is developed within the Waimihia Tephra. This corresponds with a 60cm offset in the overlying blue-grey rubble. The overlying peat is either offset or accumulated in the offset at a later date.

After the above peat accumulates a seventh earthquake or storm event deposits a layer of angular pebbles on top of the peat. A further 50cm of peat then accumulates on top of these angular greywake pebbles.

An eighth earthquake event causes fissures to open in which rubble is deposited at the 10m and 22-24m horizontal marks in the trench. Some of these fissures extend all the way to the present day surface.

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 11850yrs B.P.

During the interval between further faulting, more greywacke rubble fell into the trench. This was followed by the deposition of a yellow-brown allophanic unit on top of the rubble and some 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). The age of this tephra is 11850 +/- 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 by its stratigraphic position is most probably the Karapiti Tephra from Lake Taupo dated at 10100 +/- 80 yrs B.P. (Wilson 1993). Immediately above this tephra is the Mangamate Tephra dated at 9700-9780 +/- 170 yrs B.P. (Donoghue et al 1991). On top of this is another dispersed rhyolitic tephra which may be the Poronui Tephra dated at 9810 +/- 50 yrs B.P. (Froggatt and Lowe, 1990).

A third earthquake event post-9810 +/- 50 yrs B.P. disrupts the above tephras and there is 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 1850 +/- 10 yrs B.P., (Froggatt and Lowe 1990).

A fourth faulting event occurs post-1850 yrs B.P. and the Waimihia Tephra is offset vertically 13cm (south trench wall) 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, it can be seen that there are several earthquake events, common to both trenches.

The Ruahine Fault trace north of Whittle Road

North of Davis 1 trench site the fault continues to be upthrown up to 12 m to the east and offset horizontally by up to 10m in streams and 55m on shutter ridges. A greywacke rock found in the fault trench (unfortunately not in situ) had 2 sets of 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 10o away from and appearing to overly the first, consisted of a highly polished surface. These surfaces serve to illistrate 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 zig zag in Hot Springs Road (Figure 33). Off Makahu Road (just off the tarseal) 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 zig-zag). However the offset stream and accompaning terrace surface may have evolved their present shapes as a result of what appears to be a right (extensional) step in the fault trace. On the north side of the offset stream, where Taupo ignimbrite (1850 yrs B.P.) onlaps the terrace surface, is a 90cm vertical offset which is upthrown to the east. Dropping down off the ignimbrite surface onto recent terrace surfaces the vertical offset is seen to be 2m. This latest 2m offset appears to be an exhumed surface exposed by the river and the 2m vertical offset is only part of a recent faulting event and part of an older event. 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 then Taupo Tephra 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 90cm to the east. The fault trace is then lost in the Awahohonu State Forest. The fault trace appears again on the Napier-Taupo Highway, where it is seen as a difference between rock types, most of the trace having been eroded away. This may be due to with farming, roading and forestry activity 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 11850 +/- 60 yrs B.P. and records an overall upthrow to the east of about 10m. This gives a maximum vertical offset rate of 0.84 mm/yr. A minimum offset rate of 0.48 mm/yr is determined using the upthrow which occurred since the Taupo Tephra was deposited.

Horizontal offsets are more difficult to determine as streams are offset up to 10m and spurs offset up to 55m. It is possible that this discrepancy is related to the Taupo eruption. New streams had to cut through the newly formed ignimbrite which mantled the area giving an offset of 10 m post-Taupo Tephra, i.e., a rate of 5.4mm/yr. If the 55m offset scarp is used in conjunction with the age when eastward upthrow was first initiated (Davis 2 trench), then a rate of 4.64 mm/yr is determined.

Table 5: 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.

Davis 1 Trench	Davis 2 Trench
EQ	
EQ or storm event	EQ ?
post 1281	
post 1850	post 1850
pre 3280	
post 3623	
post 5971	
pre 7778	post 9810
	pre 10100
	pre 11850

This 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.

CHAPTER 8

PALEOSEISMIC HAZARDS FOR THE WELLINGTON AND RUAHINE FAULTS

FAULT 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 refers to those parts of a fault or faults that rupture as a unit during an earthquake (Machette et al. 1988). Schwartz and Coppersmith (1984) first proposed that rupture on a given segment of a fault may repeat many times with the same slip pattern characteristic to the segment. Since that time other earthquake researchers have agreed with that earlier study (Aki 1988, Bilham and King, 1988, Machette et al., 1988, Rockwell 1988 and Sanders, 1988). These workers have observed from paleoseismic and modern studies that for many faults the amount of slip at a point on many 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 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° or more), stepped or branched. Aki found that type 1 geometry was an earthquake starting point for 60% of real earthquake events studied and type 2 a stoppng point for 70% of real earthquake events studied.

Proposed rupture segments for the Wellington Fault

The proposed southernmost segment for the Wellington Fault is the Wellington-Dannevirke Segment. This is based on the characteristic behaviour and timing of similar earthquake events which occurred over the last 3000 yrs B P., between Wellington and Dannevirke. Data for this proposal comes from trenching and offset studies within the field area. Outside the field area additional data is supplied by published reports from Lensen (1957) Beanland and Berryman (1990) and Van Dissen et al., (1992). Between Wellington and Dannevirke the fault trace is continuous except in the southern Tararua Range where it is composed of two or more splays (Lensen 1957 and Van Dissen et al., 1992). The timing of earthquake events between

Wellington and Dannevirke is similar over the last 3000 yrs allowing for the +/- that accompanies paleoseismic dates (Table 5). Earthquake events from trenching studies outside the field area, listed in 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. Not all the trenches at Pahiatua yielded c. 300 yr dates but according to Wyss (1979) and Wells and Coppersmith (1994), earthquakes commonly rupture only partially through to the surface in some areas over their subsurface length. Unfortunately there is no earthquake event data published 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 1 single fault segment then it is a complex structure for approximately 165 km. It has slip rates ranging from 15mm/yr (max) in the north, to 5 to 7 mm/yr (Van Dissen et al., 1992) in the south. It should be noted that a slip rate of 15 mm/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. The southern segment from Pahiatua to Wellington has an average horizontal offset of 3 to 4.7 m (Berryman 1990). None of these figures are unusual. The San Francisco earthquake of 1906 ruptured an area 450km long and 10m wide; north of San Francisco offsets were in the range of 4.9 m to 5.5m whereas south of the city they were in the order of 1m (Niemi and Hall 1992). There is also the problem of the large horizontal offsets seen at Inglis', Beagley and Trotter farms. Here there is the 50m offset at Beagley Farm, only 5 faulting events over 5000 yrs seen at Inglis' Farm trenches and 5 seen in the Trotter Farm trenches, making an average horizontal offset of 10m per earthquake. If there were more earthquakes then why are they missing from all four trenches? Supposing there are no events missing from these trenches then a fault with such large horizontal offsets must have a large rupture zone. Of significance to the seismic hazard in the region is the relationship between offsets, rupture length and earthquake magnitude (Wells and Coppersmith 1994). Alternatively, there are periods of creep following an earthquake, before the fault becomes locked, leading to smaller horizontal offsets in each individual earthquake.

It is possible that the Wellington-Dannevirke segment of the Wellington Fault extends as far north as the southernmost Ohara Depression. This area was not trenched, but horizontally offset features were of a similar size to those in the Dannevirke area. It was not possible to determine the age of the offset Torlesse greywacke basement scarps and spurs. However these offset features were sharp and clear even in areas where the rock was shattered.

The next proposed faulting segment for the Wellington Fault is the Ohara Depression-Mohaka River Segment. This segment begins near the Tukituki River and ends north of the Mohaka River. Observations of faulting behaviour in the south of the Depression by Raub (1985) are consistent with those found in the Big Hill, Puketitiri, and Mohaka River areas. The latest earthquake rupture events occurred post-1165 +/- 50 yrs B P., in the Wakarara area (Raub, Cutten and Hull 1987). In the Big Hill area at least two events have occurred post-Taupo Tephra deposition at 1850 yrs B P. The Syme trench at Hawkstone Station in the Puketitiri area records at least one event post-Taupo Tephra deposition. Trenching studies in the Mohaka River area (Hull 1983) also show at least two rupture events have occurred within the last 1900 yrs B P.

Holocene horizontal offset rates increase northward similar to the Wellington-Dannevirke segment of the fault. The Wakarara area has 2.7 to 3.5 mm/yr (Raub 1985) and the rates for Big Hill are 4.9 mm/yr. There is a tentative offset rate for the terraces north of the Ngaruroro River of 4.9 mm/yr. At Hawkstone Station the minimum offset rates are 6 mm/yr and up to 7.9 mm/yr is recorded by Hull (1983) in the Mohaka River area.

Proposed rupture segments for the Ruahine Fault

The proposed southernmost segment for the Ruahine Fault is the Kahuki-Ruahine Range segment. This segment covers the area between the fault beginning 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 offsets. There is only one locality where the fault shows evidence of Quaternary movement, close to Maharahara Trig (Marden 1984, see chapter 6).

The next proposed segment for the Ruahine Fault is the Ohara Depression-Waipunga River Segment where the latest uplift has been mainly to the east, in contrast to the Kahuki-Ruahine Range segment with little recent offset. There is evidence of recent offsets on this segment at McIndoe Flat on the south bank of the Ngaruroro River. In the Puketitiri area, the Davis 2 trench has evidence of at least one rupture event post-1850 yrs B P., and up to four rupture events are seen in the Davis 1 trench post-1850 yrs B P. North of the Napier-Taupo Highway close to the Waipunga River Beanland and Berryman (1987) think that two fault rupture events may have occurred in the last 5000 yrs.

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. A worldwide data base of earthquake source parameters have been used for these studies. Some of these formula have been used by Berryman (1990) to provide an estimate of the likely magnitude of an earthquake in the Lower Hutt-Wellington area. The single event displacement formula 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 meters. The results predict a 7.4 to 7.5 magnitude earthquake for a single event 3.4 to 4.7m offset. Using the same formulae an earthquake with an average single rupture of 10m (Wellington-Dannevirke segment) would produce a M_s earthquake of 7.8. The second formula for an M_s earthquake uses rupture length $M_s = 6.24 + 0.69 \log 10L$ where L=length in kilometres. This would also produce an M_s earthquake of 7.8 over the 165 km length of the Wellington-Dannevirke Fault segment. However some workers (Wyss 1979 and Kanamori 1983) do not to use M_s as it measures seismic-wave amplitude at a specific period (approximately 18 to 22 sec). M_s values are stable between nearby stations but there is a significant difference between distant stations. Furthermore for very large earthquakes M_s becomes saturated and does not record faulting characteristics. Some workers think that M_s becomes saturated at $M > 7.5$ (Kanamori 1983) while others (Wells and Coppersmith 1994) report M_s becomes saturated above $M > 8$. Most workers now use M (moment magnitude) which does not saturate with magnitude and is uniformly valid with respect to Richter and surface wave magnitudes. There are difficulties with calculating M for paleoseismic events because in most cases M is calculated using microseismic surveys to obtain the sub surface width and length of the fault. However Wyss (1979) proposed that M max could be obtained using a magnitude area relationship $M = \log A + 4.15$ (valid for $M > 5.6$) where A is area of maximum expected rupture W x L. The minimum expected rupture length for the proposed Wellington-Dannevirke segment of the Wellington Fault is 165 km. The width of the rupture zone is found using $W < 2/3\ L$ (Wyss 1979) making a distance of 110km and an area of 18,150 km^2. Using the above area and formula, the expected M max for this segment of the Wellington Fault is calculated at 8.4. The above width estimate is used based on Wyss' formula and the areas of deformation seen in historic earthquakes within New Zealand. The mapped surface rupture width of the Wellington Fault in the Dannevirke area is just 2 km. The San Andreas Fault has a sub-surface rupture width of 10 km (measured from microseismic surveys) and long narrow faults radiate less energy than wide faults of the same length (Wyss 1979). It is possible that the Wellington Fault is similar to the San Andreas Fault in this respect, the 2 km surface rupture width being all that is left after 300 yrs of erosion. However in light of other historic earthquakes seen in New Zealand the deformation zone will be much larger especially for the long Wellington-Dannevirke segment. In 1984 only 3 km of the 1931 Hawkes Bay earthquake rupture could be positively identified (Hull 1990). However to the average New Zealander there will not be a great difference between the estimated magnitudes of 7.8 and 8.4.

The estimated magnitude for the Ohara Depression-Mohaka River segment of the Wellington Fault is a little more difficult to determine accurately as there were fewer trenches excavated. In over 14000 yrs of eastward uplift (McCool 1 trench) there has been over 66.9 m of horizontal movement with up to 6 faulting events recorded within the trench. Again 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 between M 7.8 and M 8 according to the formulae given above. Further north at Hawkstone Station there is again a minimum horizontal offset of 60m. However the Syme trench appears to contain only 3 earthquake events over a similar period of time. It is possible that strike-slip action has smeared out some faulting events or perhaps the rupture did not always propagate to the surface along this segment of the fault. It seems likely that a rupture event at Hawkstone station would be as severe as that further south on McCool Farm. Although this segment of the fault has a lower mm/yr rate than the Wellington-Dannevirke segment it would seem that earthquakes when they occur would be equally destructive.

The proposed southernmost segment for the Ruahine Fault (Kahuki-Ruahine Range segment) does not appear to have been active during Holocene times. There is not enough data to make a magnitude prediction for this fault segment. On the other hand the Ohara Depression-Waipunga River segment of the Ruahine Fault has been very active. From the Davis trenches there are 10 possible fault rupture events recorded over 12000 yrs and 55m of horizontal offset. An average horizontal earthquake movement for this section of the fault would be 5.5m and the predicted magnitude is between M 7.5 and M 8.

The Modified Mercalli Scale as used in New Zealand lists 7.8 magnitude earthquakes 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". Earthquakes over 8.1 are listed as catastrophic with total destruction. This has already occurred in New Zealand once since European settlement, during the 1855 earthquake on the Wairarapa Fault. This was estimated as being an 8+ magnitude earthquake where 7,403 km^2 of land was raised permanently between 13 cm and 6.4 m (McSaveney and Hull 1985). The surface rupture length was at least 145 km and the maximun horizontal offset was 12 m. Fortunately few people lived in New Zealand at the time and the area where the earthquake occurred was almost uninhabited.

SUMMARY OF EARTHQUAKE EVENTS FOR THE WELLINGTON FAULT

A summary of faulting events for the proposed Wellington-Dannevirke segment of the Wellington Fault is presented in Table 5. EQ is an undated earthquake event where deformation is seen but there is no datable material at hand. Other earthquake events have been dated either post or pre the event in yrs B P. Van Dissen refers to the earthquake events from the Wellington-Lower Hutt area determined from trenching studies (Van Dissen et al. 1992). Beanland and Berryman refer to earthquake events seen in trenches at Pahiatua (Beanland and Berryman 1990).

Table 5: Summary of faulting events for the Wellington-Dannevirke segment of the Wellington Fault, likely to have been triggered by M>6.5 earthquakes.

Van Dissen	Beanland Berryman	Inglis Farm trench 3 +4		Beagley Farm	Trotter Farm trench 1+2	
c.300-450	c.300	pre 211	EQ	c. 290	c.257	c.257
c. 800	post 860	EQ	EQ			pre 257
	1010-1160	EQ	post1105			960
	c.3840				pre 2090	post3110
		post 4335				EQ
				post5324	pre 5000	EQ
					pre 6750	pre 6080
		pre 9434	post 10286			
					post 22020	
			pre 29200			
			EQ			
			EQ			

Table 6: Paleoseismic events (likely M>6.5 earthquakes) from the Ohara Depression-Mohaka River segment of the Wellington Fault. Dates are from trenching studies either post or pre the earthquake event in yrs B. P.

Mc Cool 1 Trench	Syme Trench	Wedd trench-Te Waka Splinter Fault
EQ or storm		
pre 605 or storm		
c. 805		
post 1850	post 1850	post 1850
pre 3280		
5206 - 4295		
	10,000-8,770	post 10,000
pre 14,082	pre 10,100	pre 11,850

Table 7: Paleoseismic events (likely M>6.5 earthquakes) from trenching studies on the northern segment (Ohara Depression to Waipunga River) 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 post 1850	EQ ?
post 1281	
post 1850	post 1850
pre 3280	
post 3623	
post 5971	
pre 7778	post 9810
	pre 10100
	pre 11850

GROUND SHAKING AND LANDSLIDES

Ground Shaking

A large region can be shaken during an earthquake event, the Napier earthquake being felt over most of New Zealand (Hull 1990). The severity of shaking at any site within the region will depend on the magnetitude and the depth of the earthquake focus. Other factors include the distance of the site fron the epicentre, and the nature of the local site geology and topography. 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. There are a few houses built on the Wellington Fault, most are situated on the upthrown side where there is a better view of the surrounding countryside. However most farm dwellings have a single storey and are well constructed. Those farm houses that are located at some distance from the fault may survive with only cracked concrete slabs, older building will lose their chimneys and may come off their foundations, but there should be little loss of life involved 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 or less can temporarily lose their inherent strength and behave as viscous fluids (liquifaction). Structures situated on these materials can settle or be torn apart as the ground spreads laterally and flows. Another hazard is from 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, settlement, and slope mobility. The principal hazards associated with sensitive clays are excessive settlement and subsidence of the ground surface, formation of underground cavities and tunnels, and slope instability.

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 faults 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 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 also 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; the area displays unstable bedrock overlain by loose screes. A large magnitude earthquake in the area could activate landslides. 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 block of rock. Aerial photographs 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 of 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 quarry face. There is a railway tunnel within this limestone through which passenger trains pass several times a day.

Further north there is a large earth slump north of the Ngaruroro River where a linear feature 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.), so it is possible that this may date the post-1850 B P., earthquake event seen in the Syme trench at Hawkstone Station. There is further evidence for this being the faulting event recorded in the McCool 1 trench dated at c. 805 yrs B P. South of the Tutaekuri River in the Willowford area the Wellington Fault trace is largely covered by slumps. 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. The slunp at Te Pohue that blocked drainage to create the lake is sourced directly from the hillside which is the northern limit of the Te Waka Splinter Fault. Recent coring of the lake shows the landslide occurred shortly after the Taupo Tephra eruption 1850 yrs B P., (C. Hannan, pers. comm.). The Wedd trench located on the southern section of the Te Waka Splinter Fault shows evidence of earthquake activity around this time. Other evidence for an earthquake at this time comes from trenching studies near the Hautapu River where Hull (1983) reports that two fault movements had occurred in the last 1900 yrs B P. One of these earthquakes occurred 1200 yrs B P., and caused large landslides in the Mohaka River at Maungataniwha.

Landslide debris also causes blocked drainage and the formation of lakes. A major triggering mechanism for many of these landslide dammed lakes are earthquakes (Lowe and Green). Lake Ngatapa was formed during the 1931 Hawkes Bay Earthquake when a landslide dammed a tributary of the Mohaka River. The lake was 2 km long and up to 25 m deep. 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. On the northeast side of Lake Waikaremoana is another large landslide covering 53 km^2. Lake Waikareiti is a landslide pond filling a hollow in the debris. This landslide is radiocarbon dated at 11500 yrs B P., (Ward 1995). There are no dates from trenching studies on the Wellington Fault south of the Napier-Taupo highway close to 2200 yrs BP. However there is a pre-11850 yr B.P. date for the Te Waka Splinter Fault and a pre-10100 date for the Wellington Fault. 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 more landslide-dammed lakes to occur on oversteepened slopes close to the Ruahine and Wellington Faults, especially on the Ngaruroro River.

CHAPTER 9

DISCUSSIONS AND CONCLUSIONS

SUBDUCTION ZONE TECTONICS

The North Island Shear 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 Indo-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 micro plate 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 micro plate is quite thin in places where the gently dipping subduction zone is only at a depth of 10 to 30 km below the plates surface (Kamp 1988). The history of faulting along the North Island Shear Zone 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 Hikurangi Margin (plate deformation zone) 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 22-ma old accretionary margin lying adjacent to a 2 ma 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 2 to 4 ma and that the Shear 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 rotation.

The shear zone is inclined to the direction of relative plate motion at close to 50° so the 50 mm/yr plate movement at Hawkes Bay is translated into 40 mm/yr compressional and 30 mm/yr strike-slip component (Walcott 1978). In the Wellington area rates across the shear belt sum to approximately 21 mm/yr which is about 75% of the margin-parallel relative plate motion (Beanland 1995). Quaternary horizontal offset rates for the Wairarapa Fault average 11.5 mm/yr

(Grapes 1991) and for the Wellington Fault 5 to 7 mm/yr (Van Dissen et al., 1992). However the horizontal slip rate on the Wellington Fault is variable, being 5 mm/yr at Long Gulley and 6 to 7.6 mm/yr at Emerald Hill. This difference in slip rate along fault was thought to be the result of "off fault" deformation on low-slip, more northerly-trending faults that extend through Wellington City (Van Dissen et al., 1992). Further north at Pahiatua, offset rates for the Wellington Fault are in the region of 5 mm/yr (K. Berryman pers comm.). In this region the Ruahine Fault bifurcates from the Wellington Fault which may have a bearing on the above offset rate, although the Ruahine Fault north of the Manawatu Gorge does not appear to have been recently active. In the Dannevirke area the Wellington Fault shows signs of large single offset events (up to 10 m) and an horizontal offset rate between 10 to 15 mm/yr are among the highest in the world (Allen et al., 1988). This rate accounts for 50% of the activity expected by Walcott (1978) for the whole shear zone. In this area the Ruahine Fault appears to be largely inactive during the Holocene. Horizontal offset for the Wairarapa Fault and its associated splay faults in this area is unknown. However trenching studies by Francis et al., (1993) on the Waewaepa Fault (a segment of the Wairarapa Fault zone) show that horizontal offset rates are fairly low with only 3 movements recorded in the last 6000 yrs.

In the Ohara Depression offset rates and Holocene faulting activity for the Wellington Fault slows and for the Ruahine Fault increases consistent with a transfer of strain from one fault to the other. This either occurs at depth where the faults are close together or along cross faults within the Ohara Depression. Within the field area between the Ohara Depression and the Napier-Taupo Highway,both the Ruahine and Wellington Faults account for at least 1/3 of the 30 mm/yr strike- slip component for the shear zone. At Lake Poukawa southwest of Napier the Wairarapa Fault is assumed to have an horizontal offset rate of at least 1.2 mm/yr (Froggatt and Howorth 1980).

The recent trace of the Wellington Fault is upthrown mainly to the southeast. This 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 Raub et al., (1987) to be between 60,000 and 11,000 yrs B P.. From Mc Cool 1 trench the timing for this event is c. 14,082 yrs B P., and from the Syme trench at Hawkstone Station pre- 10,100 yrs B P.

The Ruahine Fault between Paihiatua 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. From the Davis 2 trench the timing for this phase of uplift is pre-11,850 yrs B P., the same as the Wellington Fault. 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 was dated at just 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 if this change in upthrow is the result of long term changes within the subduction zone or whether it is merely a short term aberration.

PREDICTION FOR FUTURE EARTHQUAKE EVENTS

Microseismic studies throughout the East Coast area reveal that earthquake activity is mainly confined to the subduction zone. The deformation along the plate boundary is thought to act in response to episodic compressional and extensional movement along with regional dextral shear. Episodes of compression are suggested by Walcott (1978) and Reyners (1989) to be the result of the subducted plate and the overlying microplate becoming temporarily locked together. It has been suggested by Walcott (1978) that the 1931 Hawkes Bay earthquake ended the compressive phase resulting in the decoupling of the overlying and underlying lithospheres. Earthquake activity up until 1987 was interpreted as relaxation in the subducted plate following the unloading of the plate interface by the 1931 and 1932 earthquakes. This interlocking of plates can be similarly interpreted in terms of faulting on the Wellington and Ruahine Faults (Reyners 1989). Prior to 1963, shallow earthquakes with a magnitude >6 in the vicinity of these faults occurred in 1940, 1951 and 1963. This suggested a relaxation phase (extensional) of the overlying plate. Now the plate interface is considered to be relatively uncoupled resulting in fewer large earthquakes at this time (Reyners 1989).

This study has established a framework within which the frequency of large magnitude earthquakes in the region can be estimated. Further trenching is required on dextral strike-slip faults of the North Island Shear Belt before a complete record for the last 30,000 years can be obtained. Using the available information from the 1931 Hawkes Bay and 1855 Wairarapa earthquakes plus the contents of this thesis and additional papers a few conclusions can be made. It is not a question **if** a large earthquake event will occur on the Wellington and Ruahine Faults, but **when** one will recur. If the frequency of earthquakes is examined for both the Wellington and Ruahine Faults, it can be seen that a large surface rupture earthquake occurs approximately every 1000 yrs. However within the last 2000 years earthquakes have been occurring more frequently. This is partly because the more recent events are better preserved within the trenches and partly because there seems to be a change in faulting style e.g. the current phase of uplift toward the southeast. 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 150 m (Marden 1984) making an offset rate of 2.1 mm/yr. Horizontal offset rates for Ohakean surfaces in the Dannevirke area are in the range of 10mm/yr. In general horizontal offset rates appear to increase toward the present, the older the offset marker the smaller the horizontal offset rate.

Current work from overseas suggests that rupture on one fault increases 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 can be seen where the Ruahine Fault shows little activity and the Wellingtin Fault has large offset events in the Dannevirke area. There are also indications that the interaction between the Indo-Australian and Pacific plates may be different to that first thought. New work by Webb and Anderson (1995) finds that slip vectors derived from the 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 Shear Belt. Also there is the work using the new GPS network investigating crustal deformation in the Wellington and Wairarapa region. Investigations by Darby and Beavan (1995) surveying the network suggests that the relative velocity across the region is one third to one half of the realtive velocity between the plates. Modelling by these authors shows possible distribution for 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

Wellington Fault

Table 8: Summary of paleoseismic activity for the Wellington Fault within the field area.

Rupture segment	Wellington-Dannevirke	Ohara Depression-Mohaka River
earthquake magnitude	7.8 to 8.4	7.8 to 8.4
rate of offset	10 to15mm/yr	3 to 6mm/yr
single average horizontal offset	10m	10m
timing of event	every 200 to 300yrs within the last1000	every 200? to 500yrs within the last 1000

Table 9: Summary of paleoseismic activity for the Ruahine Fault within the field area.

rupture segment	Kahuki-Ruahine Range	Ohara Depression-Waipunga River
earthquake magnitude	?	7.5 to 8
rate of offset	?	4.6 to 5.5mm/yr
single average horizontal offset	?	5.5m
timing of events	?	every 400 to500 over the last 1000

FUTURE WORK

Wellington Fault

Further work will need to be directed at delineating fault segments more firmly to enable more accurate rupture predictions. To accomplish this further 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 Dannevirke rupture segment. Trenching studies also need to be carried out in Torlesse greywacke basement in the Moorcock Stream and Alder Road areas to establish the northern limit of the proposed Wellington-Dannevirke segment. Likewise further trenching needs to be carried out on the Ohara Depression-Mohaka River segment to confirm the rupture length. Additional information on earthquake dates seen within trenches will make timing, magnitude and offset rates much more accurate.

To accurately predict the timing and recurrence interval of major earthquake events, all the strike-slip faults of the North Island Shear Belt will need to be trenched. There are gaps in the paleoseismic record in the Dannevirke area, for example between c. 6000 and c. 10000 yrs B P. Is this because there were no earthquakes or were there rupture events on other strike-slip faults within the North Island Shear Belt at this time? The general activity pattern of the Shear Belt faults needs to be established. For example is the latest uplift on the faults to the east and is strike-slip action increasing, or is this confined to the Wellington and Ruahine Faults only?

If the limestone block at the east end of the Manawatu Gorge did move eastward during a future earthquake rupture, it represents a significant hazard to road and rail transport in the area. Drilling through the toe of the limestone would establish if movement has taken place and date the event.

Ruahine Fault

There are trenching studies that could be carried out across the Ruahine Fault south of the Manawatu Gorge and north of the gorge at Ballantrae to establish the inactive or active nature of the fault in the Dannevirke area. Further trenching needs to be carried out on the Ohara Depression-Waipunga River segment to confirm rates of offset, timing of events and earthquake magnitude. There are suitable sites for trenching studies on Big Bill Station in the Ohara Depression.

There are a large number of slumps close to the Wellington and Ruahine Fault traces. If some of these events could be dated it might serve to confirm questionable earthquake data found within the trenches examined in this study. It was difficult to explain the small scarps found on Wedd farm and the accompanying the trench post-1850 yrs B P. The recent discovery that the earthquake-induced landslide at Te Pohue occurred post-1850 yrs B P., makes the possibility of these scarps being created by earthquake activity more likely.

ACKNOWLEDGEMENTS

We would like to thank the following people and organisations for their assistance in various aspects of this project.

Our thanks are especially extended to the Earthquake and War Damage Commission for without their financial support this research would not have been possible. We also thank Alan Hull and Kelvin Berryman of the Institute of Geological and Nuclear Sciences, who provided funds for extra radiocarbon dates and trenches.

Special thanks are due to Drs Alan Palmer and Bob Stewart of the Soil Science Department, Massey University who supported this project and patiently answered a non-ending string of questions.

We are grateful to Malcolm Boag of the Soil Science Department who assisted with the surveying of fault displacements.

Permission to reproduce the topographical maps was provided by the Department of Survey and Land Information.

We thank all the farmers in the Hawkes Bay area who freely allowed us to wander at will over their land. Special thanks are extended to Messrs Inglis, Trotter, Beagley, McCool, Wedd, and Davis who allowed us to dig large trenches on their land.

JAH especially thanks her parents, the late J.W. and N.E.I. Hanson, who taught her to think independently, ask questions and look for answers.

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