Client Report
1996/33591D.10

CONFIDENTIAL

Earthquake Hazard Analysis - Stage 1 Recurrence of large earthquakes determined from geological and seismological studies in the Hawke's Bay area

J G Begg
A G Hull
R Robinson

November 1996

Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

AM 96/11
HBRC PLAN 4040

Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

Earthquake Hazard Analysis - Stage 1
Recurrence of large earthquakes determined from geological and seismological studies in the Hawke's Bay area

by

J G Begg, A G Hull, R Robinson

Prepared for

Hawke's Bay Regional Council

CONFIDENTIAL

Client Report 1996/33591D.10

November 1996

Earthquake and Ground Movement Hazards Group
Gracefield Road, PO Box 30-368, Lower Hutt, New Zealand, Telephone: +64-4-570 1444, Facsimile +64-4-566 6168

A Crown Research Institute

SUMMARY

Work undertaken for the Hawke's Bay Regional Council during the 1994-95 period has significantly refined the understanding of the region's geological setting for the assessment of earthquake hazard. Three earthquake sources have been defined and, where possible, comprehensively assessed as hazard sources.

New Zealand and Hawke's Bay lie at the boundary of the Australian and Pacific plates. As the plates are converging, the Australian Plate over-rides the Pacific Plate. The relative motion of the plates is resolvable into compressional (or convergence) and lateral (or horizontal shear) vectors. Plate convergence is occurring at a rate of 43 mm per year in the Napier area, resolvable into vectors of c. 35 mm/yr perpendicular to the plate boundary and c. 25 mm/yr of shear parallel to the plate boundary. These vectors of motion show at the surface as reverse and strike-slip faults. Accumulated stress at the plate boundary results in high rates of earthquake occurrence for the region, and earthquakes have been classified into three types for the purposes of this report.

Type A ("upper plate") earthquakes are generated at shallow to moderate depths (typically less than c. 25 km) within the over-riding Australian plate. **Type B** ("subduction interface") earthquakes are shallow to moderate depth (typically c. 15-35 km depth), and generated at the subduction interface between the Australian plate and the subducted Pacific plate. **Type C** ("deep focus") earthquakes are earthquakes generated within the Pacific plate (> 25 km beneath Napier). Earthquakes of **Types A** and **B** are evaluated as earthquake sources for the Hawke's Bay region. There is no available model for interpreting the potential of earthquakes of **Type C**, although they are thought to pose a lesser hazard because of their depth and lower relative hazard compared to the larger, shallower earthquakes which characterise the region.

Active fault traces in the Hawke's Bay region are the surface manifestation of major **Type A** earthquakes. This assessment of **Type A** earthquakes involved studying the locations and nature of preserved surface ruptures, evaluating their characteristic earthquake magnitudes and estimating their recurrence intervals.

Active fault trace distribution for the Hawke's Bay region is now well established at a scale of 1:50,000. These data are presented in the form of active fault trace location maps at that scale and as an attributed digital database. Fault styles are generally strike-slip at the western range front faults, contractional reverse faults in the central Waipukurau-Poukawa fault corridor and extensional normal faults in the east along the Haumoana-Ryan's Ridge fault zone.

Estimated characteristic magnitudes for the western strike-slip Ruahine and Mohaka faults remain unchanged from previous work. Earthquake magnitude for both these faults is

estimated at M 7.5 and recurrence intervals are estimated at 1000-5000 and c. 900 years respectively. Surface rupture for such events is expected. Trenching of the Waipukurau-Poukawa system proved a reverse fault style for the zone and a generalised recurrence interval of 2000-4000 years. Surface rupture is expected to accompany such events. The magnitude and recurrence interval for past earthquakes at the Haumoana fault zone are poorly constrained, but estimated at c. M 7.0 and c. 2000 years respectively. Surface rupture is expected to accompany future large earthquakes.

Type B earthquakes are generated at the subduction interface between the over-riding Australian plate and the underthrusting Pacific plate. **Type B** earthquakes are thought likely to be the region's largest with an estimated characteristic magnitude of c. M 7.8 - 8.0 and a recurrence interval of 350-650 years. Surface rupture on one or more than one of the region's fault systems in the over-riding plate may or may not be associated with such earthquakes.

CONTENTS

1.0 Introduction

The Institute of Geological & Nuclear Sciences undertook an initial assessment of earthquake hazards in the Hawke's Bay Region and defined work necessary for a comprehensive earthquake hazard assessment of the region. The resulting report (Begg, Hull & Downes 1994) identified likely elements of earthquake hazard in the region and designed and recommended a systematic work plan to quantify earthquake hazard. The first phase of the recommended plan was to locate and evaluate the active fault traces within the Hawke's Bay region, to characterise paleoseismic ruptures associated with these features and assess information and models for the evaluation of subduction zone rupture events. This report summarises the results of the Stage I earthquake hazard analysis undertaken during 1994/95.

1.1 Background & study objectives

As a result of agreement between the Hawke's Bay Regional Council and the Institute of Geological and Nuclear Sciences Ltd (GNS; Contract Services Agreement, 9 January 1995), this study was undertaken by GNS with the following objectives:

- To locate all known active faults at a scale of 1:50 000 for the Hawke's Bay region;
- To determine the magnitude and recurrence of all earthquake sources capable of producing earthquake shaking of intensity MM > VIII in the Heretaunga Plains and the Waipukurau/Waipawa areas; and,
- On completion of the above, to develop a work programme for Stage II of the Earthquake Hazards Assessment.

In accordance with the objectives stated above we have completed the following work:

- Conducted an aerial photograph study and limited field check of the Hawke's Bay region where existing information on the location of active faults was poor or absent;
- Compiled updated maps in both analogue and digital form of fault locations at a scale of 1:50 000;
- Evaluated earthquake recurrence and magnitude for geological structures judged capable of producing shaking intensities of MM ≥VIII in the Heretaunga Plains and Waipukurau/Waipawa areas. These sources were investigated using surface and subsurface mapping techniques. Trenches were excavated and exposures logged and photographed to analyse the deformation history of specific fault zones;

- Prepared an outline for Stage II (liquefaction hazard mapping) of the Earthquake Hazard Analysis.

In the following sections of this report we describe our methods of investigation, results and conclusions followed by a section listing additional work that could help refine the present conclusions, and a summary of remaining work in the Earthquake Hazards Analysis.

1.2 Research team

North American geologists Drs Harvey Kelsey and Sue Cashman (Humboldt University, Arcata, California), and Jim Trexler and Pat Cashman (University of Reno, Nevada) worked on this project without payment for a period of two months. Pilar Villamor (a Spanish doctoral student, Departmento de Geodinamica, Universidad Complutense, Madrid), and Dorothee Neun (a final year honours student at University of Clausthal, Lower Saxony, Germany) also assisted with field work. The programme was seen by their university departments as a valuable part of their professional training.

The involvement of these national and international collaborators, as well as a supplementary research grant from the Institute of Geological & Nuclear Sciences, greatly enhanced the scope of the programme. In all, a total of about 20 person months of scientific effort have been dedicated to this study.

Responsibility for the data collection and interpretation contained within the various sections of this report are as follows:

	JGB	PV	TDT	DN	HMK	SMC	PHC	JHT	AGH	KRB	SB
Aerial photos	•	•	•	•	•	•	•	•			
Fault checks	•	•			•	•	•	•	•		
Map plots	•	•	•	•	•	•	•	•			
Digitising			•								
Fault attributes	•				•	•	•	•			
Trench logging	•	•	•	•	•	•	•	•	•	•	•
Log interpretation	•	•	•	•	•	•	•	•	•	•	•

Where JGB = J.G. Begg, PV = P. Villamor, TDT = T.D. Townsend, DN = D. Neun, AGH = A.G. Hull, HMK = H.M. Kelsey, SMC = S.M. Cashman, PHC = P.H. Cashman, JHT = J.H. Trexler, KRB = K.R. Berryman and SB = S. Beanland.

Information on subduction zone seismicity was written by R. Robinson.

1.3 Acknowledgements

The compilers wish to thank the team members who helped in the many facets of field and office work throughout this project. In particular, the skills and dedication of Harvey Kelsey, Sue Cashman, Pat Cashman, Jim Trexler, Pilar Villamor, Dorothee Neun, Tracey Townsend, Kelvin Berryman and Sarah Beanland were vital to the success of the programme. The assistance and cooperation of Hawke's Bay Regional Council office staff and surveyors during the project was invaluable. Contractor Bruce McIntyre took an active interest, and his technical skills were a great asset to the trenching team. Massey University staff, Drs. Vince Neall and Alan Palmer and students Jude Hanson, Andrew Hammond and Shane Cronin were of great assistance in the trenching of Mohaka fault and establishing a chronological framework for trench sediments. The efforts of those who analysed samples to a tight timetable are also appreciated; Erica Crouch (GNS) examined samples for pollens and spores, John Carter (Victoria University of Wellington) worked on opal phytoliths, Shane Cronin (Massey University) worked on tephra geochemistry and Hugh Melhuish and Joe McKee (GNS) undertook radiocarbon dating. The programme would have been impossible without the willing cooperation of landowners in the area. Jim Hengesh and Bill Stevenson provided useful reviews of the draft report.

2.0 Study Methods

2.1 Earthquakes in Hawke's Bay

The earth's near surface layer (the "lithosphere", about 75 km thick) is divided into a number of large, rigid "plates" that move at varying rates and directions relative to one another. The rates are slow (up to about 10 centimetres per year) but act over very long periods of time. In areas where two plates are converging their collision often results in one plate sinking beneath or "subducting" beneath the other. The subduction process is a gradual but continuous process occurring over millions of years. Subduction occurs most often when one of the colliding plates is oceanic in character (thin, dense lithosphere) and the other is continental in character (thick, light lithosphere), resulting in the oceanic plate being the subducted one. Once subduction begins the subducted plate is colder, and hence heavier, than the surrounding rock so that the process is self-reinforced by the weight of the subducted slab pulling downward. The presence of subducted plates at depth can be traced by the occurrence of earthquakes within it, down to maximum depths of about 700 km. The surrounding, relatively warmer rocks can support earthquake generating stresses only to depths of 20 to 40 km.

Because the Hawke's Bay region sits close to the boundary between two such plates, it is the site of numerous earthquakes. These earthquakes result from the sudden release of stresses built up by relative movement between the Pacific and Australian plates over considerable periods of time. As a result of the normal subduction process, stresses build up within each of the two plates as well as along the subduction interface between them. This results in three general types of earthquakes which occur in distinct portions of the earth's crust as shown in Figure 1a and 1b, and discussed below:

Earthquakes in Hawke's Bay are of three principal types:

- **Type A** earthquakes occur within the over-riding Australian Plate from the transfer of stress because of coupling between the two plates at the subduction interface (= "upper plate" earthquakes);
- **Type B** earthquakes occur at the interface between the subducting Pacific Plate and the over-riding Australian Plate (= "subduction interface" earthquakes); and
- **Type C** earthquakes occur in the upper part of the subducting Pacific Plate as it bends downwards beneath the Australian Plate (= "deep focus" earthquakes; Figure 1).

A typical, or "generic", model of a subduction zone can be compiled from world-wide studies, as has been undertaken by Byrne et al. (1988) (Figure 1a): There is almost always a wide "active margin" in which deformation, earthquakes (**Type A** earthquakes), and possibly volcanism, occur in the overlying plate (Figure 2). The active margin extends from near the "trench", where subduction initiates, inland for some distance. Usually, but by no means always, the size of these **Type A** earthquakes is less than that of large subduction interface (**Type B**) events. However, **Type A** events may be closer to population centres and play a larger role in seismic hazard. Earthquakes that occur within the subducted plate (**Type C** earthquakes) can occasionally be quite large.

No method has yet been developed for assessing the earthquake hazard contributed by **Type C** earthquakes. However, such earthquakes are thought to pose a lesser hazard to the region because they tend to be smaller and occur at a greater depth (> 25 km beneath Napier, > 40 km beneath the northern Ruahine Range) than **Type A** earthquakes, within the descending Pacific plate, and because that plate may be relatively de-coupled from the Australian plate (the propagation of seismic energy may be retarded). For these reasons **Type C** earthquakes are not considered further in this report. The purpose of this section is to summarise the methods used in studying **Type A** and **Type B** historic and prehistoric earthquakes of the Hawke's Bay region.

2.1.1 Field studies

The focus of this year's work for Hawke's Bay Regional Council has been on gathering and assessing data related to **Type A** (shallow crustal) earthquakes and assessing the hazard presented by **Type B** (subduction interface) earthquakes.

The work programme undertaken during 1994-95 involved aerial photographic analysis to establish the location of active fault traces, their sense of displacement and identification and field reconnaiance of possible trench sites.

In early January 1995, the team set up a base in Hastings and the principal effort involving trenching and logging commenced. Trenches were dug, logged, interpreted and sampled during January, February and early March 1995. Ground checking of active fault traces continued throughout this period. Samples collected were then distributed to appropriate workers for analysis. The trenching work was particularly widely reported within the Hawke's Bay region.

2.1.2 Historical seismicity data versus paleoseismic data

Paleoseismic data consists of information on prehistorical earthquakes derived from the landscape and/or the geological record. Historical seismicity and paleoseismic databases are independent of each other and complementary sources of earthquake information. Earthquake hazard cannot adequately be assessed without information from both sets of information. Analysis of historic seismicity data is a useful technique providing reliable records for the last 150 years (at best). However, because the return period of large, damaging earthquakes is great in comparison, it cannot be regarded as representative of the region's actual seismic potential. Paleoseismic analysis portrays another facet of the seismic environment. Careful examination of active fault traces covers a much longer period, providing data on the most hazardous of prehistoric **Type A** (and sometimes **Type B**) earthquakes during thousands, or tens of thousands of years. Paleoseismic information, however, does not register earthquakes of magnitudes of less than about M 7, and rarely provides precise, absolute dates for major events.

One of the main objectives of this study for Hawke's Bay Regional Council was to generate a useful paleoseismic database so that realistic estimates for **Type A** earthquake recurrence intervals became available for modelling purposes. Field data collected during the course of the study are stored in technical files of the Institute.

In the report below, the component of seismic hazard contributed by **Type A** earthquakes will be discussed first followed by discussion of hazard posed by **Type B** earthquakes.

2.2 Past large, shallow earthquakes in Hawke's Bay

The historical record of large, shallow earthquakes provides a graphic illustration of the occurrence of large earthquakes in the region. The presence of abundant surface fault traces of pre-historic origin that displace young geological and geomorphological features indicates that such earthquakes have also occurred within the region during the immediate geological past. The purpose of this section is to outline the method of estimating the magnitude and recurrence intervals of large, shallow, pre-historic earthquakes.

2.2.1 Estimating earthquake magnitudes from surface fault trace characteristics

Seismic hazard related to **Type A** earthquakes is assessed by measurement of active fault trace lengths, single event displacements and large earthquake recurrence intervals and comparing the data with established seismic hazard models. Relationships between earthquake magnitude and rupture length (Bonilla et al. 1984, Wells and Coppersmith 1993) and calculation of earthquake moment magnitude (Hanks & Kanamori 1979) have been established empirically for a large number of world-wide historical earthquakes representing a wide range of tectonic environments.

Using this large database of historical earthquake information, Bonilla et al. (1984) calculated empirical relationships between earthquake magnitude, fault rupture length and surface displacement. Wells & Coppersmith (1993) refined their analysis using an extended database compiled from worldwide historical earthquakes, and determined relationships between moment magnitude, surface rupture length, subsurface rupture length, rupture area, and maximum and average displacement per event. They concluded that in general, for most earthquakes, slip on the fault plane is manifest at the surface in the following manner:

- the length of surface ruptures is equal to about 75% of the subsurface rupture lengths, but that the ratio of surface rupture length to subsurface rupture length increases with earthquake magnitude;

- the average surface displacement is about half the maximum surface displacement per event; and

- the average subsurface displacement on the fault plane is approximately equal to the average surface displacement.

Their statistical analysis identifies good correlations between earthquake magnitude, surface rupture length, subsurface rupture length and rupture area, and that these relationships are consistent regardless of faulting styles, slip types and tectonic environments. The relationships can be used to estimate maximum earthquake magnitudes both for surface faults and for subsurface seismic sources such as blind faults (faults that never reach the earth's surface), and to estimate the expected surface displacement along a fault for an earthquake of a given size.

Hanks & Kanamori (1979) deduced from historical seismic data that earthquakes in California have an upper magnitude limit, c. M 8.0, that is characteristic of its tectonic setting. Similarly, using the Hanks & Kanamori mathematical model a maximum magnitude can be established for each of the fault zones within Hawke's Bay.

The results of these studies provide a basis for assessing the size of most earthquakes occurring on faults of the Hawke's Bay region. The method involves three major steps:

- the location and mapping of active surface fault traces and fold axes;
- estimation of earthquake magnitudes on the basis of the relationship between fault rupture length, displacement and magnitude; and
- estimation of earthquake recurrence intervals on active fault traces through careful evaluation of the number and timing of events from trenching studies, especially those involving multiple rupture episodes.

Some detail of the method used during this study for each of these steps is outlined below.

2.2.2 Accurate location and characterisation of active fault traces and fold axes

Throughout this study, and in the study of active faulting in New Zealand, the term "active" means that displacement has occurred within the last 125,000 years. In a formal sense, the term is applied only to faults where displacement can be shown to have occurred during that time. The formal term can, therefore, only be used when historical rupture has occurred and/or when a geological or geomorphological feature known to be younger than 125,000 years old has been displaced. The record of historically ruptured faults in the region is obviously very limited.

In many parts of the Hawke's Bay region, geological units and geomorphological features of the appropriate age are absent and many fault traces that appear clearly on aerial photographs cannot be said to be "active" in the formal sense. During the course of aerial photographic analysis of the region for this study, it was noted that the geomorphology varied substantially across the region. In many areas there are no sediments or landscape features suitable for preserving evidence of fault rupture during the last 125,000 years and therefore no information is available to assess the "activity" of faults. In other areas it can be safely assumed that the ground surface was of substantial age (ie about 20,000 to 5,000 years old). In these areas, fault traces tend to be well preserved, many resulting from multiple ruptures. In still other parts of the region, the ground surface is very young (ie <5,000 years) and fault traces are preserved only in exceptional circumstances. In this case, most fault traces, even relatively young traces, have been buried or removed by erosional processes. For the purposes of this report the term "active fault" refers to:

- faults that have ruptured historically;
- faults that have demonstrable post 125,000 year rupture; and
- faults that do not have proven post-125,000 year displacement, but can reasonably be assumed to have post-125,000 year rupture on geomorphological grounds.

In some circumstances, reverse faults may not penetrate to the surface ("blind faults"), propagating instead at low angles into basinal sediments. In these cases, an actively growing fold of the ground surface may be the only visible expression of the fault.

Surface fault traces and fold axes were located by stereoscopic analysis of vertical aerial photographs for visible traces, and sketching their location on 1:50000 topographic maps (NZMS 260 Sheets U23-24, V21-24 and W21-22). Scale of vertical photos varied from c. 1:25000 to c. 1:6500. In all cases, care was taken to minimise error resulting from translation of fault locations and fold axes from aerial photographs to 1:50000 topographic sheets. Location error, however, is still judged to be greater than 100 m, although it is unlikely to exceed 200 m in most cases. In cases where fault traces were checked on the ground, location error is within 100 m.

Aerial photographic work was focused on the area south of Heretaunga Plains as this area is identified as having abundant active fault traces and is close to centres of population and urban development. Sense of displacement was noted for each fault trace where distinguishable on aerial photographs or where visited on the ground. The positions of axes of active folds are based largely on pre-existing geological literature, particularly Kelsey et al. (1993).

The information is presented in hard copy 1:50000 scale topographic maps (Infomap NZMS 260) and as a digitised, attributed database (held within ARC/INFO at GNS).

2.2.3 Estimation of earthquake magnitudes

In the absence of historical surface rupture information where instrumental measurements of earthquake magnitude have be made, the magnitude of past earthquakes can be estimated only from measurements of fault length and the amount of fault displacement.

Much of the work completed in the Hawke's Bay region this year focussed on establishing the rupture characteristics of active faults in the area. These characteristics are derived for surface fault traces and actively growing folds only and therefore relate only to **Type A** earthquakes.

Two main methods are available for estimating magnitude from surface faulting:

- Estimates of earthquake magnitude from fault data using the formula of Bonilla et al. (1984). These empirical formulae were derived by using an ordinary least squares regression analysis on records of surface wave magnitudes (M_s) for 58 historic earthquakes from around the world with their reported surface rupture lengths and surface displacements. Wells & Coppersmith (1993), using data derived from 361 historic fault ruptures from around the world, derived equations describing the relationship between earthquake magnitude and the fault-defining parameters of surface trace length and average displacement. In this report, the Wells & Coppersmith equations are assumed to be applicable for the active surface fault traces of the Hawke's Bay region, and that their standard deviation of estimated earthquake magnitudes ($\pm$ 0.3 M_s) is also applicable.
- Calculation of moment magnitude (M_w) of earthquakes generated by a fault use estimates of fault surface area, crustal rock rigidity and mean slip values for individual fault displacements. When good quality fault slip data are available, then moment magnitude provides the better method of estimating past earthquake magnitude, because it is based on data derived from the specific fault under consideration.

Maximum earthquake magnitudes for the four major **Type A** seismic sources, Ruahine/Mohaka faults, Waipukurau-Poukawa fault zone, and the Haumoana fault zone were evaluated using the Wells & Coppersmith relationships.

Table 1: Summary of rupture length data and estimated earthquake magnitudes for the principal on-shore fault zones of the Hawke's Bay region (**Type A** faults). Note that all magnitude estimates have a standard deviation of ± 0.3 M_s.

Fault	**Rupture length** (km)	**Likely displacement** (m)	**Estimated magnitude** (Ms)
Ruahine/Mohaka faults	[1]160	3-5	7.5
Waipukurau-Poukawa faults	[2]150	3	[3]7.8
Haumoana fault zone	10-30	3	?7.0

1 Assuming segment boundaries at Woodville and the middle Mohaka River.
2 Assuming segment boundaries at the lateral limits of the aftershock sequence for the 1931 Hawke's Bay earthquake (see Figure 21).
3 Based on the magnitude of the 1931 Hawke's Bay earthquake.

2.2.4 Dating

The relative timing of rupture events is established using normal stratigraphic principles. Fault displacement of a sediment contact indicates fault rupture younger than the age of the depositional boundary. Progressive displacement of successive sediment contacts indicates a succession of earthquake rupture events.

Chronology can be established using a variety of methods, the best of which are through the use of either distinct markers horizons of known age or radiometric dating of material present in the sediments. Volcanic tephra (ash) horizons are frequently the most precise and reliable chronological marker horizons. Four prominent volcanic ash layers (tephras), dated elsewhere using radiocarbon techniques, provide a good time framework for the last 25 000 years in the Hawke's Bay area; these are:

- Taupo Pumice, 1800 years BP (before present);
- Waimihia Tephra, c. 3400 years BP
- Kawakawa Tephra, 22,600 years BP.

Volcanic glass is an essential component of each ash, and each ash has characteristic glass chemistry. Analysis of glass chemistry provides a method of correlation with ashes (often already precisely dated) outside the region. Tephra analysis and glass chemistry for this report was undertaken by Shane Cronin of Massey University (see Appendix 2).

Radiocarbon dating is the primary method of dating for the last 40 000 years, providing a basis for many other forms of dating. It relies on the presence of carbon within the sequence, usually in the form of wood or charcoal. Where obvious macroscopic wood is absent, the presence of disseminated carbon in some soils may provide a useful reference date in estimating timing of fault rupture events. Appendix 1 details radiocarbon dates derived from samples extracted from trench sites.

Less clearly defined marker horizons such as loess (wind-blown silt) or paleosol (fossil soil) horizons and fossil pollen stratigraphy (palynostratigraphy) may also provide useful time constraints. A comprehensive loess stratigraphy for the Hawke's Bay region is being developed but there is still difficulty in correlating the sequence with its better known equivalents to the west and the south of the region. A number of other less useful techniques such as palynology and opal phytolith studies were used in the course of this work in an effort to further constrain the event chronology (see Appendix 1).

2.2.4 Estimation of earthquake recurrence intervals

Paleoseismic data are generated by excavating trenches across active fault traces, preferably where there is some indication of multiple rupture episodes, and deposits of suitable age to determine chronology of events. Three-dimensional information on offset of dated landforms and subsurface layers (buried landforms) are required to define the rupture history of active faults. Fault-normal trenching (perpendicular to the line of the fault trace) was selected as the best method to provide the required information at minimum cost. Fault-normal trenches are valuable in determining vertical displacement on fault planes but they are of limited use in defining strike-slip displacement. For this project strike-slip displacement was assessed using lateral offset of surface landforms, measurement of striae on fault planes, and trends of fault rupture-related fold axes in the trench walls. Positions of trenches excavated during the course of this work are shown in Figure 3.

Careful logging of trench walls defines a sequence of rupture events for that fault during the period of time represented by sediments between the base of the trench and the surface. Ideally, each rupture episode can be accurately dated using one or several of a range of geological dating tools. From the dates of each rupture event, recurrence intervals can be calculated, and simple averaging provides an estimate of recurrence interval, with a calculated error, for rupture episodes on that fault.

In reality, most rupture events cannot be dated accurately. Instead, a chronological table of sedimentation and hiatus events, dates and rupture episodes is produced. From this table, recurrence intervals can be estimated from the maximum age of the sediments and the number of rupture events. Dates interspersed within the sequence provide control on the timing of fault ruptures. In some cases, the timing of individual rupture episodes may be well constrained.

Trenching of selected sites was undertaken using a local contractor and involved trenches across active fault traces up to 5 m deep and 25 m long. Detailed logging of each trench wall involves establishment of a one metre reference grid, followed by careful examination and documentation of the sediments, their stratigraphy and the relationships with fault displacements (Figure 4). Using the grid as a guide, trench walls were logged on graph paper, photographed and sampled.

3.0 Study results

The Heretaunga Plains area and southwest to the centres of Waipawa and Waipukurau contain a large part of the population and investment within the region. Coincidentally, it is also a corridor along which a major active fault system is located. The Waipukurau/Poukawa fault zone was identified as the primary focus of investigation because fault traces are relatively long and continuous, they occur close to the population centres of Waipawa, Waipukurau and the Heretaunga Plains, and have geomorphic features suggesting recent activity. The fault system is the closest source with the potential of producing ground shaking of MM IX to X in these areas. In addition, the only historical data on very large earthquakes in this region is the 1931 Hawke's Bay earthquake, which involved rupture of faults in the northernmost part of this system; therefore additional information was required to assess the magnitude potential and recurrence of earthquakes in the region. Twelve trenches were dug for this study across active traces in the Waipukurau/Poukawa fault zone between Waipawa and Pakipaki.

Paleoseismic data derived from trenching work undertaken during early 1995 are summarised below. Tables listing carbon dates, tephra geochemical analyses and palynological samples are provided as Appendices 1 and 2. Detailed trench logs and associated notes are kept at Gracefield.

3.1 Waipukurau-Poukawa faults

3.1.1 Waipawa

A 2.4 m deep trench was excavated across a 1.9 m high, west-side-up scarp, trending 014° across a late Quaternary fluvial terrace of the Waipawa River (GRV22/186340). As shown in Figure 5, a low to moderately west-dipping reverse fault was exposed in the excavation. The stratigraphy of the hanging wall is different from that of the foot wall. On the hanging wall, a planed surface on Cretaceous Whangai Shale, is overlain by a gravel sequence and an upper overbank silt sequence. The foot wall consists entirely of a sandy silt unit to the base of the trench. Trench wall instability limited collection of detailed information in this trench, although on the basis of limited data, a dip-slip sense of displacement can be inferred.

Fault displacement history

The late Quaternary sequences record at least two episodes of deformation. No material suitable for dating was obtained from the trench and the only information available on recurrence interval is that at least two rupture events have occurred since the latter part of the Last Glaciation (c. 12 000 years ago). The uppermost unit, the soil, is undeformed, draping over the underlying sequence. The most recent event is defined by penetration of faults into Unit E (Figure 5), offset or lack of continuity of units across the faults and by truncation apparent at the base of the uppermost sequence on the hanging wall. Dip-slip displacement associated with this rupture, measured on the base of Unit E, is c. 1.5 m. An additional but similar displacement on the base of Unit H seems likely. The older event is defined by offset of the eroded surface of the Whangai Shale and the greater displacement of the older gravels (sequence 3); the Whangai Shale surface is not exposed on the footwall side of the fault in the 2.5 m to the base of the trench below its position on the hanging wall. We conclude from minimal data that fault slip for the last two events has been principally dip-slip.

3.1.2 Argyll Road

As shown in Figure 6, three trenches were dug across one of two sub-parallel fault traces trending c. 035° to 050° across an outwash fan of Kaikora Stream (Figure 7), 400 m west of the junction between State Highway 2 and Argyll Road (GR V22/186390). Natural exposures in stream banks were also examined in three locations. The two fault traces, each represented by 3-4 m high west-side-up scarps, merge into a single scarp 500 m northeast of the northern trench site. Sketches of three natural outcrops in Kaikora Stream provide further important information (Figure 8a,b). The following discussion is based on integration of data from all these sites. The only radiocarbon date derived from the Argyll Road trenches, 9486±120 years BP (NZ 8306), is from wood in Argyll 3 (which failed to intersect a significant fault), but two further dates from the Kaikora Stream sections add constraints to the integrated event chronology, which is discussed below.

Low angle reverse faults were exposed in trench walls in the two northeastern trenches (Figure 9, the middle of the three trenches). Five depositional sequences in these two northern trenches were identified and three rupture events are required to explain progressive fault displacements (from the second oldest sequence to the second youngest); a further event is inferred from folding of the oldest sediments. The uppermost unit, the surface soil, is undeformed and therefore formed after the last rupture episode. A radiocarbon date of 2565±69 years BP (NZ 8307) was derived from wood at the base of unfaulted fan deposits in Kaikora Stream gully.

A sediment sequence older than any exposed in the trenches is exposed in the Kaikora Stream gully. That sequence contains a tephra with associated twig fragments that yielded a radiocarbon date of 23460±280 years BP, which correlates with the 22 600 year Kawakawa Tephra.

Fault-slip orientation data, striations on fault planes and fold axial trends, indicate a predominant dip-slip sense of displacement. Fault plane striations (slickensides) and fold slip directions for the trenches indicate that the maximum dextral strike-slip component is less than or equal to 5% of the total fault displacement. Thus the fault is regarded as purely dip-slip in sense.

Fault displacement history

Analysis of samples from the Argyll Road trenches and the gullied walls of Kaikora Stream provides constraints on the chronologies of the sequences and therefore the rupture episodes (Figure 8a,b). Radiocarbon dating of wood from the base of the unfaulted uppermost sequence provides a minimum age for the last rupture episode of 2565±69 years BP (NZ 8307; V22/f433; see Appendix 1). Wood from Sequence 5 yielded a radiocarbon date of 9486±120 years BP (NZ 8306; V22/f435) within Argyll 3. This unit predates four rupture events recorded in the other Argyll Road trenches. Glass geochemistry of a tephra within a sequence unconformably underlying Sequence 5 suggests a possible correlation with the 10 000 year-old Karapiti Tephra, but a date from twigs immediately below the tephra was 23460 ± 280 years BP, indicating a likely correlation with Kawakawa Tephra. The number of rupture events that occurred during the time period represented by the unconformity above the tephra cannot be determined. Assuming an age of 10 000 years for sediments above the unconformity (based on radiocarbon date NZ 8306), the average recurrence interval for the fault is 2 000 - 2 500 years.

Table 2: Summary of Argyll Road trench stratigraphy and Kaikora fan stratigraphy, with inferred fault rupture history and event chronology.

Sediment sequence	Key stratigraphic markers	Rupture episode	Kaikora fan correlative	Chronology
Sequence 1	Soil Carbon trace V22/f433		Soil Wood	 NZ 8307 2565±69 yrs BP
		Episode 4 faulting		
Sequence 2	Silt Gravel			
		Episode 3 faulting		
Sequence 3	Paleosol Silt Gravel			
		Episode 2 faulting		
Sequence 4	Paleosol Silt Sand, gravel		Sandy gravel	
		Episode 1 folding		
Sequence 5	Sand, gravel V22/f443, f444 Wood V22/f435		Silt Wood	Recycled pollen and spores NZ 8306 9486±120 yrs BP
Unconformity		**All episodes unrecorded**		
Sequence 6	Tephra V22/f437		Tephra Twigs V22/f437 Sandy gravel	?Kawakawa? Tephra NZA 5681 23460+/-280 yrs BP

3.1.3 Moturoa

At Moturoa (Figure 2; V22/219430) trenches were excavated in three places, but none intersected a fault plane. Here, the fold geometry of limestone rocks suggest that a fault exists, but that the trace has been buried by Holocene swamp sediments. In the northernmost trench a tephra, presumed to be the 22600 year old Kawakawa Tephra, dips at c. 30° to the east, but the dip is interpreted as of depositional origin.

3.1.3.1 Fault displacement history

The feature trenched was not conclusively demonstrated to be a fault. Trenching indicated that there has been no surface displacement within the last 6000 years and failed to confirm any Late Quaternary displacement. The dip on the 22600 year Kawakawa could be partly attributable to tectonic tilting. The results of this study do not preclude the possibility that an active fault lies nearby to the east of the trenches.

3.1.4 Opapa

Two trenches were excavated across a fault trace near the Opapa radio masts (Figure 3; GRV22/251505). The fault scarp at Opapa trends 060-065°, is west-side-up and has a height of up to 7 m. The height of the scarp suggests that it represents several earthquake-related displacement events. It is highest near the Opapa radio masts becoming increasingly less prominent as it trends into the Poukawa basin to the northeast. Trenches were excavated where the scarp is prominent and relatively high (Opapa #1, V22/251505) and further north (Opapa #2, V22/255508) where the scarp is low.

Although sediments exposed in the walls of the northern trench (Opapa #2) were gently warped and unfaulted, low angle reverse faults, with a set of steeply-dipping normal faults in the hanging wall, were exposed in the walls of the southern site (Opapa #1; Figure 10a,b). Six depositional sequences were identified in the sediments of the walls of the southern trench, the youngest of which is undeformed. Four rupture episodes are required to explain the pattern of fault displacement inferred from the exposed layers.

Slip direction of the shallow-dipping reverse faults was defined using fold axial trends and consists primarily of dip-slip movement with little or no lateral component. Such folding is regarded as being related to fault displacement. The high-angle normal faults occurring on the hanging wall define a small graben structure, also interpreted as a consequence of fault-related folding.

Dip-slip displacements associated with rupture events range from about 1.3 to >2 m and translate to likely earthquake magnitudes of c. M_s 7.8.

Table 3: Summary of Opapa #1 trench stratigraphy, lithologies, fault rupture history and event chronology.

Sediment sequence	Key stratigraphic units	Rupture episodes	Chronology
Sequence 1	Soil Disseminated carbon V22/f434 Taupo pumice Waimihia Tephra		NZ 8308 615±33 yrs BP 1 800 yrs BP 3 400 yrs BP
		Episode 4	
Sequence 2	Silt Disseminated carbon V22/f436 Matrix-supported shale clasts		NZA 5680 1 344±76 yrs BP
		Episode 3	
Sequence 3	Fine silt Matrix-supported shale clasts V22/f445		mostly spores; no interpretative data
		Episode 2	
Sequence 4	Sand and gravel		
Sequence 5	Sand and gravel		
		Episode 1	
Sequence 6	Sand and gravel		

Fault displacement history:

The age of the base of the section is unknown, although judging by the absence of Kawakawa Tephra, is unlikely to be less than 22 600 years BP. A paleosol within Sequence 3 may be correlative with a similar feature widely distributed in the North Island of 10-12 000 year age. A specific statement regarding the recurrence interval on the basis of all four events is impossible, and the best approximation is a 4-6000 year recurrence interval for past earthquakes. The last rupture event at this location probably preceded deposition of the Waimihia Tephra about 3 400 years BP.

3.1.5 Poukawa

A single trench was excavated across a fault trace located at Poukawa (GRV22/301548) shown on Figure 3. This fault ruptured during the 1931 M_s 7.8 Hawke's Bay earthquake (Figure 11a,b). At the trench site the fault scarp trends at about 040° and is unlike other sites in that it was excavated through a ridge (ground level dropping to the east and west) and the faults on the trench walls were largely parallel to bedding of the late Quaternary sand and silt layers. Sediments exposed in the walls of the trench consisted of 5 depositional sequences. Each sequence is ruptured by faults.

The oldest two sequences are folded and the younger three are draped over the fold (Figure 12). Faults seen in the hanging wall are parallel to bedding and then cut up through the section. A thin, discontinuous pink volcanic ash near the base of the trench is thought to be the Kawakawa Tephra at 22,600 years BP. Deformation in the trench is attributable to four episodes, two folding events followed by two faulting events. Several independent lines of evidence indicate that the predominant sense of slip on the fault is dip-slip. While strike-slip displacements were recorded locally in 1931 and the assumed best-fit dislocation solution for the earthquake (Haines & Darby 1988) involved a lateral slip component, there is little evidence of significant strike-slip at the trench site.

Table 4: Summary of the Poukawa trench stratigraphy, lithologies, fault rupture history and event chronology.

Sediment sequence	Key stratigraphic units	Rupture episodes	Chronology
Sequence 1	Scarp-derived colluvium		Post-1931
		Hawke's Bay earthquake - faulting episode 2 *Faulting episode 1*	1931 Ms 7.8 Hawke's Bay earthquake
Sequence 2	Silt to silty sand		
Sequence 3	Prominent paleosol V22/f440, f441, f442 Fine sand and silt		
		Folding episode 2	
Sequence 4	Alluvial sand and gravel, scoured base		
Unconformity		*Folding episode 1*	
Sequence 5	Tephra Alluvial sand and gravel V22/f439		Karapiti Tephra c. 10 000 yrs or Kawakawa Tephra, 22600 yrs

Fault displacement history:
The last displacement episode occurred during the 1931 Hawke's Bay earthquake. The deformational centre of the 1931 earthquake was in Hawke Bay north of Napier (Haines and Darby 1987) and rupture that occurred onshore during that earthquake was significantly less than that of the characteristic deformation associated with paleoseismic events documented during the course of this work (Hull 1990). Three other deformational episodes have occurred within the last 10 000 (or 22600) years. If the tephra is the 10000 year Karapiti, the averaged recurrence interval for the last 10 000 years is 2 500 years. If the 1931 Hawke's Bay earthquake is considered atypical of the characteristic rupture, so not included within the calculation, the recurrence interval rises to 3 500 years. If the tephra is Kawakawa (22600 years), the recurrence intervals for the fault are essentially doubled to 5000 to 7000 years. The amount of time and number of rupture episodes represented by the unconformity above the tephra is unknown. The first two events in the record involved folding followed by erosion. Low angle reverse-faulting occurred during the last two episodes, although folding may also have occurred. Dip-slip displacements associated with the fault ruptures are about 1 m and are likely to be associated with earthquakes of magnitude c. M 7.8.

3.1.6 Mutiny Road

The active trace of the Tukituki fault is visible as a west-side-up scarp that trends at c. 015-020° into the Heretaunga Plains on the eastern side of Mutiny Road (GRV22/359575). The height of this scarp gradually decreases from c 5 m in the south to nothing on the plains. The scarp height at the southern end suggests that several displacement events are represented. At the eastern end of the trench, Taupo Pumice alluvium laps against a pre-existing scarp wall, burying the last-formed trace and indicating that the fault has not moved in at least the last 1 800 years. While trenching failed to locate a fault displacement, gentle folding of bedding, axis parallel to the scarp, and near vertical jointing in the older sediments are consistent with the existence of a buried reverse fault east of the trench. The trench was excavated to a depth of c. 4 m and consisted largely of silt and sand lithologies. A 0.3 m thick pink tephra near the base is best correlated with the Kawakawa Tephra (22 600 years BP) and a thin white pumiceous horizon within a metre of the surface is correlated with the Waimihia Tephra (3 400 years BP). The 1800 year Taupo Pumice is not displaced and laps against a slope cut in the underlying sediments at the eastern end of the trench. Sub-vertical joints terminate at the base of a fine, sandy gravel unit consisting of pale limestone clasts, c. 2 m below the surface. It seems likely that these joints developed in response to at least one rupture episode between 22 600 years BP and 3 400 years BP. No attempt has been made to quantify the amount of deformation required to fold these sediments.

3.1.7 Middle Road

A fault scarp trending 018°, west-side-up 500 m west of Middle Road near Glenrae was trenched (Figure 2; V22/341528). The 9 m scarp height suggests that it represents several displacement events. The trench exposed a thrust fault at the eastern end, and the Late Quaternary stratigraphy is best defined in the hanging wall (Figure 13). The hanging wall consists of a large drag fold sitting on the shallow-dipping (16°W) thrust plane. The fold is overturned where it is truncated by the fault.

Sediments in the trench walls were divisible into five depositional sequences, the youngest of which is undeformed. At least three rupture episodes are required to account for progressive deformation of the sequences. The geometry of the fold axis and fault trend indicate that slip is predominantly dip-slip, and if any component of strike-slip has occurred, it is sinistral in sense.

Table 5: Summary of the Middle Road trench stratigraphy, lithologies, fault rupture history and event chronology.

Sediment sequence	Key stratigraphic units	Rupture episode	Chronology
Sequence 1	Well-developed soil		? 5 000 years
		Episode 3	
Sequence 2	Paleosol Silty fine sand		
		Episode 2	
Sequence 3	Paleosol Fine, sandy silt		
		Episode 1	
Sequence 4	Sandy silty paleosol Sandy, clayey silt Sand with gravel Sandy gravel		
Sequence 5	Sandy, silty clay Silty paleosol Sand, silt and mud Coarse grainstone with pink tephra clasts		?Karapiti or KawakawaTephra 10000 or 22600 years BP

Fault displacement history:
A minimum of three rupture episodes were recognised in this trench. Analysis of glass from the tephra clasts suggest correlation with either Karapiti or Kawakawa Tephra indicating that there have been at least three rupture events on the fault in the last 10 000 to 22600 years. The last rupture episode may have occurred at least 5 000 years ago, based on presence of an unbroken and well-developed soil overlying the fault. Minimum offset of sequence 2 associated with the last event is 1 to 1.5 m. Total displacement (associated with the the last and the second last rupture event) was measured at 1.5 to 2 m. Earthquakes associated with such ruptures are estimated to have a magnitude of c. M 7.8.

3.2 Haumoana fault zone

Fault traces of the Haumoana fault zone occur along a 70 km long belt in the southeastern Hawke's Bay region from Clifton and Cape Kidnappers south to Wanstead (Figure 3). The length of the fault zone, the number and youthful expression of fault traces and their proximity to the developed areas of Havelock North and the Heretaunga Plains indicate that faults of the zone could pose a significant seismic hazard.

All faults in the Haumoana fault zone are normal faults, most trending between 020° and 045° and with scarp heights between 0.5 and 10 m. Those with scarp heights of > 2-5 m are thought to represent multiple earthquake-related rupture episodes. Sharp and little eroded scarps are common, and a number of them displace young Holocene (<10000 year old) deposits. A set of traces cuts Holocene beach deposits at the coast between Haumoana and Clifton (V21/493679 to W21/510683), and others cut Holocene stream deposits throughout the zone (eg V22/455521). Rupture lengths of fault traces in this zone are shorter than those within the Waipukurau-Poukawa fault zone and the estimated maximum earthquake magnitude is c. M 7 if the faults represent primary surface rupture.

None of these faults were trenched during this study, our focus being the relationship between the active normal faults and the regional Elsthorpe Anticline. For seismic hazard assessment it is important to know whether the Elsthorpe Anticline is the surface expression of an active, sub-surface, west-dipping thrust fault or whether the traces merely represent the deep-seated collapse of a now-passive anticline. If the normal faults of the Haumoana fault zone are related to continued growth of the Elsthorpe Anticline, there is a considerable implied earthquake hazard to the Heretaunga Plains area, resulting from the underlying thrust fault.

Some effort was put into establishing the relationship between the normal faults and bedding on the limbs of the anticline. Figure 14 illustrates three alternative explanations for the existence of active normal faulting, including:

- bending moment faults due to active arching of bedding in the anticline;

- flexural slip faulting due to bedding-parallel slip associated with active fold growth; or
- normal faulting superimposed on an anticline that is no longer actively growing.

Bedding orientations of older Tertiary units involved in the Elsthorpe Anticline indicate that there was a period of active fold growth prior to the Pliocene, with re-activation in Pleistocene time. Few west-side-up faults were found in the course of this study and they had a higher concentration on the west limb of the anticline. These observations are inconsistent with a bending moment origin.

Fault scarps commonly trend parallel to bedding but their common east-side-up geometry on the western limb of the anticline is inconsistent with a flexural slip origin. In places where detailed ground observations have been made, some prominent normal faults are not parallel to bedding and trends are apparently unrelated to basement (Tertiary) structure. This feature is also inconsistent with flexural slip faulting.

The normal faults of the Haumoana fault zone fit best with the model of superposition on an inactive fold structure. While the possibility of an active low, angle reverse fault beneath the Haumoana fault zone cannot be ruled out, this work suggests that if it exists, it is not directly related to the development of the Elsthorpe Anticline. It is uncertain whether the Haumoana fault zone should be regarded as a single seismic source or whether each active fault trace is a separate seismic source.

The work that has been completed on the Haumoana fault zone suggests that the Elsthorpe Anticline is no longer actively growing, and that the normal faults of the zone are probably related to deep-seated gravitational failure within the uplifted core of soft sediments of the anticline. Such faults are unlikely to be the source of major earthquakes and scarps may develop in response to large earthquakes on other faults in the region.

3.3 Summary of Waipukurau-Poukawa fault displacement histories and recurrence intervals

During the course of this study, emphasis has been on understanding the paleoseismic histories of those active faults providing the greatest hazard to the more developed part of the Hawke's Bay region. Trenching of active fault traces of the Waipukurau-Poukawa fault zone has provided some new insights into the tectonic regime of the zone, and therefore the hazard to the Hawke's Bay region. In general:

- The faults are reverse faults with low to moderate dips to the west;
- Slip is primarily dip-slip; and

- Major **Type A** earthquake recurrence intervals in the representative sample of active fault traces trenched are somewhat longer than previously estimated.

The table below summarises paleoseismic data derived from the trenching programme.

Table 6: Summary of paleoseismic data derived from the Waipukurau-Poukawa fault zone trenching programme.

Site	**Rupture/ folding episodes**	**Estimated recurrence interval (yrs)**	**Last rupture**	**[1]Estimated earthquake magnitude**
Waipawa	> 2	<6 000	?	7.8
Argyll Rd	4	2000-2500	<2500	7.8
Opapa	4	4000-6000	>3400	7.8
Poukawa	2+2	2500-3500	1931 AD	*7.8
Middle Rd	3	2500-3500	?>5000	7.8

[1] - Estimated magnitudes should be regarded as having an error of ± 0.3 M_s.
* - Magnitude measured from historical data.

4.0 Hazard from Subduction Zone Earthquakes

The second main contribution to seismic hazard in the Hawke's Bay region is from rupture of the gently-dipping subduction interface that exists beneath the region. During a subduction interface rupture, seated on a gently-dipping fault at depth there is not necessarily associated primary surface rupture, although the paleoseismic history of some subduction zones can be evaluated by the pattern of coastal emergence or submergence. This pattern of deformation is also related to shallow crustal faults in New Zealand, making the history of earthquakes very complex to determine from the geological record in the Hawke's Bay area. For this reason, paleoseismic analysis of subduction interface events is not possible. Subduction interface earthquakes are among the largest known historically from active margins around the world. The hazard associated with these faults, although difficult to assess reliably, is an important component of a seismic hazard assessment for the Hawke's Bay region. The following section summarises work on subduction interface earthquake hazard for the region.

4.1 Subduction zones

At depths below about 40 km, the relative motion between the subducting plate and overlying plate occurs smoothly because the high temperatures on the interface (due to friction) make the rocks ductile. At lesser depths, however, the interface is sufficiently cool that smooth sliding is less likely, and the relative motion may occur in earthquakes instead. Indeed, the two largest earthquakes known occurred along shallow subduction interfaces; these were the Chile (1960, M_w 9.5) and Alaska (1964, M_w 9.2) earthquakes. Most subduction interface events are, of course, smaller than that, but world-wide (Figure 15) they are probably the most significant source of seismic hazard. The frequent occurrence of subduction interface earthquakes in regions such as Japan, Alaska, and Central and South America makes it impossible to ignore them in analyses of seismic risk for Hawke's Bay. However, in some regions their frequency is low enough that the risk they impose can go unrecognized. For example, it is only recently that the potential for large subduction zone earthquakes off the northwest coast of the USA (the Cascadia subduction zone) has become clear from geological studies: there have been no such events in historical times. Despite their relative infrequency (estimated at about once per 300-800 years for the Cascadia subduction zone), their potential size makes it prudent to include them in estimates of seismic hazard.

Subduction zones vary quite a lot in their potential for generating large earthquakes. Some zones, such as in the Mariana Islands, only generate rare large interface earthquakes such as the 1993 M8.1 Guam earthquake, the slip being taken up by aseismic stable sliding or numerous smaller ($M \approx 6$) earthquakes. Often such "quiet" subduction zones are also associated with rifting and volcanism in the crust above them (Scholz and Campos, 1995). Other factors involved are the age of the subducting plate, the amount of weak sediments carried down with the subducting plate, and the rate of plate convergence. However, it has proved difficult to make general rules about the seismic potential of any particular subduction zone and the best estimate of the potential for large subduction earthquakes are based on the historical record and/or geological studies of the resulting effects (paleoseismology). The degree to which a subduction zone is capable of generating large events is usually referred to as its "seismic efficiency", which is the ratio between the amount of slip accounted for by earthquakes and the amount of slip predicted by plate tectonics. Thus low efficiency means a long time between interface earthquakes (and perhaps smaller magnitudes) and high efficiency means shorter recurrence times (and probably larger magnitudes).

4.2 The North Island, New Zealand, subduction zone

In the North Island, New Zealand, the Pacific and Australian plates are converging (Figure 16), resulting in subduction of the former as indicated by the persistence of deep earthquakes extending to depths of about 300 km (Figure 17). The direction of convergence is about east-west and at a rate of 4.0 (Wellington) to 4.7 (East Cape) cm/year. This amount of motion must be taken up by slip during earthquakes or by other (aseismic) processes. The "active margin" (Figure 18) created by this collision extends from the Hikurangi Trough (off the east coast) inland at least as far as the western boundaries of the axial mountain ranges (from the Raukumara Range in the East Cape region through to the Tararua Range in the Wellington region). The volcanism and rifting in the Ruapehu-Taupo-Rotorua-Bay of Plenty region suggests that the seismic efficiency may be lower north of about 39-40° S than it is further south.

The subduction zone in the North Island is unusual in two ways. First, a much greater width of the convergent margin is above sea level than is the case in most other subduction zones. This means that large subduction events which are normally offshore (as in Japan, for example) may occur much closer to populated areas in New Zealand. Second, the direction of convergence is not perpendicular to the general strike (NE-SW) of the major geologic features and the subducted plate. This situation, known as oblique convergence (Figure 19a,b), results in the presence of the major, coast parallel, strike-slip faults in the overlying plate, such as the Wellington, Wairarapa, Ruahine, and Mohaka faults. Earthquakes on these faults account for a large part of the component of convergence parallel to the coast (Figure 19b). However, the component of motion perpendicular to the coast remains largely unaccounted for by these faults. It is usually assumed that this motion is taken up by some combination of slip on the subduction interface (seismic or aseismic), and slip during thrust type earthquakes on shallow faults between the Hikurangi Trough and the axial mountain ranges such as in the Waipukurau-Poukawa area. It is the relative partitioning of slip between these various tectonic components that determines the potential for large subduction earthquakes in the region.

In historic times, the three largest earthquakes in the North Island have been the 1855 Wellington earthquake ($M \sim 8$), the 1931 Napier earthquake (M_s 7.8), and the 1934 Pahiatua earthquake (M_s 7.6). The first was caused by slip on the Wairarapa fault over a length of about 120 km (from off the south coast to about Mauriceville). The typical slip on the fault was 12 m in the horizontal direction and up to 6 m in the vertical sense. Although detailed studies of the land deformation caused by this event (Darby and Beanland, 1992) suggest that the Wairarapa fault may join with the subduction thrust at depth, this was not a subduction interface event. Likewise, modelling of the surface deformation due to the Napier earthquake indicated that slip was on a fault above the plate interface (Haines, 1988). The Pahiatua earthquake is not known to have been associated with any surface rupture, and is thus a potential example of a subduction interface event: studies now in progress will hopefully shed more light on the mechanism of that event by using seismograms (worldwide) that still exist (T. Webb, pers. comm.).

Thus there have been no unambiguous great (M_s 7.5 or more) subduction events in historic times, although in recent years there have been a few examples of moderate magnitude (M

6 or so, one M 7.0) earthquakes on or near the plate interface below the eastern North Island or offshore (Webb and Anderson, 1995). Those authors have compiled a catalogue of North Island earthquake mechanisms and interpret the results as indicating that the subduction interface is indeed capable of generating large events, although the efficiency grades from "low" in the northeast to "moderate" in the southwest.

4.3 Possible subduction interface earthquakes in the Hawke's Bay region

In order to estimate the magnitude of the largest potential plate interface event in the Hawke's Bay region we need to estimate the size of the rupture surface (length along the NE-SW direction and width in the NW-SE direction). In the generic subduction zone model (Figure 1a) only a portion of the total width of the plate interface is thought to slip seismically, convergence being taken up by aseismic slip elsewhere. The seismic section "typically" extends from about 10 to 40 km depth, the resulting width depending on the dip of the interface.

As shown in Figure 20a, the position of the plate interface in the Hawke's Bay region can be defined fairly well by the distribution of the hypocentres of small earthquakes since 1987 (when the National Seismograph network was upgraded). For comparison, the situation in the Wellington region is shown in Figure 20b, where a local network of seismograph stations allows still lower magnitude events to be located. On Figure 20a we indicate the section of the interface interpreted as not slipping freely by Robinson and Benites (1995). They interpreted the "sticky", or partially locked, section as corresponding in extent to the zone of concentrated activity inside the subducted plate. The reason for that was that the mechanism of those intraplate events was predominantly tensional, reflecting the pull of the deeper subducted plate to the northwest. Thus such events could be expected to be more numerous close to the section of plate interface that was most resistant to that pull (the partially locked part). There is a similar concentration of activity in the Hawke's Bay region, although there are fewer events in total because of the higher detection magnitude threshold. Thus one possible estimate of the maximum width of a large rupture on the plate interface under Hawke's Bay would be about 50-65 km (compared to 75 km under Wellington). We emphasize that this estimate is highly uncertain.

The possible length of rupture of a large plate interface event is likewise uncertain. Reyners (1983) interpreted details of the seismicity and focal mechanism of recent earthquakes to indicate that the subduction plate was broken into distinct segments along its length. The relevant segment in the Hawke's Bay region corresponded roughly to the extent of aftershock activity following the 1931 Napier earthquake (Figure 21). This makes sense in that segmentation in the subducted plate is likely to be reflected by events in the overlying plate as well. The appropriate maximum length is then about 120 km. This is reasonable since it is almost always observed that the length/width ratio of large subduction events worldwide is greater than one (Sykes and Quittmeyer, 1981).

In order to calculate a magnitude for our postulated subduction interface earthquakes, we also need to estimate the amount of slip. Slip during many subduction interface events have been compiled by Sykes and Quittmeyer (1981): using their relations between slip and either length or area of rupture, a slip of from 2 to 4 metres (averaged over the entire fault) would be expected for a fault 120 km x 55 km in size: this would result in a magnitude of 7.8 to 8.0.

The total amount of slip perpendicular to the coast that needs to be accounted for is about 3.1 cm/year, based on the plate tectonic rate of convergence. However, it is very unlikely that this entire amount is taken up by seismic slip on the plate interface. Pacheco et al (1993), in a study of subduction zones world wide, found an average "efficiency" of about 25%, although the range is extreme (0 to 100%). If we accept the Webb and Anderson (1995) characterisation of the efficiency as grading from "low" (say 10%) in the East Cape region to "moderate" (say 50%) in the Wellington region, then a value of 30% would be appropriate for the Hawke's Bay region. That means that about 0.9 cm/year would be taken up by seismic slip on the plate interface. Given an average slip of 3 m per event, that gives a recurrence interval of 333 years. However, as Thatcher (1990) points out, the actual slip distribution in large subduction interface events, determined from details of the seismograms, is observed to be highly variable. He argues that it is the maximum slip that should be used in recurrence time estimates rather than the average (typically calculated from observations of the total event moment and rupture extent): the maximum is probably about twice the average slip. Using this value that would increase our estimated recurrence time to 666 years.

5.0 Conclusions

5.1 Hazards associated with Type A earthquakes

The focus of this work has been on active faults close to the population centres of the Hawke's Bay region that are capable of causing ground shaking > MM VIII. This work has refined the understanding of the seismic hazard presented by the Waipukurau-Poukawa fault zone by providing specific information on the style of faulting, slip per event, magnitude of earthquakes and recurrence intervals for large ground-rupturing events.

Estimated maximum earthquake magnitudes derived for **Type A** earthquakes within the Hawke's Bay region are summarised below.

Existing paleoseismic data (Beanland & Berryman 1987; Hull 1983; Berryman et al. 1988) are the most useful information to date on the Ruahine and Mohaka faults. Estimated maximum earthquake magnitudes are M 7.5 and recurrence intervals are 1000-5000 years and c. 900 years respectively.

Trenching proved the faults of the Waipukurau-Poukawa system to have almost exclusively reverse dip-slip displacement and a moderate westward dip. In most cases the faults can be linked with the actively growing folds identified throughout the region. In this region fold growth and fault rupture occur during the same seismic events. Reverse fault traces merge along trend into actively growing folds. Basins and ranges from the southern margin of the region to western and central Heretaunga Plains area are underlain by reverse faults.

Trenching across the zone indicates that each trace is the locus of several rupture events and that faults have a comparable rupture recurrence interval. Their mean recurrence interval, at 2000 to 4000 years, is somewhat longer than previously thought (eg 500-800 years in Begg et al. 1994). Historic ground rupture in 1931 indicates that not all faults in the Waipukurau-Poukawa fault zone rupture during each major earthquake. The estimated earthquake magnitude and calculated ground shaking intensities remain unchanged from previous estimates.

Paleoseismic data for the Haumoana fault zone does not yet exist. Several of the fault traces visited show clear evidence for multiple rupture events, several displace young surfaces and several have steep, little-modified scarps. These features point to a significant, though as yet unquantified, hazard.

Ruahine, Mohaka and most of the Haumoana faults traces are rarely located in highly developed areas (if at all), so fault rupture hazard is small. Deformation associated with fault rupture will impact on drainage and some elements of infrastructure. The greatest seismic hazard associated with rupture of these **Type A** faults is thought to be ground-shaking, liquefaction and slope stability. Faults of the Waipukurau/Poukawa zone present the additional hazard of rupture damage to southern Hawke's Bay towns from Waipukurau to Pakipaki.

5.2 Hazard associated with Type B earthquakes

Type B events are likely to be the largest that occur in the Hawke's Bay region. The best estimate of likely earthquake magnitude on the subduction interface is M 7.8-8.0. The calculated recurrence interval for **Type B** earthquakes is c. 350-650 years. Such earthquakes may not result in ground surface rupture (although some rupture may occur), but their impact on infrastructure as a result of surface deformation may be significant. High levels of ground shaking, liquefaction and slope stability problems are likely to throughout the region.

5.3 Hazard associated with Type C earthquakes

Some additional seismic hazard is inherent in the potential for **Type C** earthquakes, centred in the subducting Pacific plate. In the absence of models, magnitudes and recurrence intervals for such earthquakes are difficult to assess. A maximum expected magnitude for these earthquakes is M 7. Surface rupture is not an expected consequence of deep focus earthquakes, although ground shaking, liquefaction and slope stability may occur in parts of the region.

Table 7: Summary of seismic hazard information for the Hawke's Bay region. The assessment given for hazard is relative only; "high" means "high relative to the other earthquake sources".

	Fault	**Estimated magnitude** (Ms)	**Estimated recurrence interval (yrs)**	**Date of last rupture (yrs BP)**	**Hazard**
TYPE A					
	Ruahine fault	7.5	1000-5000	c. 500	? Mod.
	Mohaka fault	7.5	c. 900	c. 1100	High
	Waipukurau-Poukawa faults	7.8	2000-4000	*65 >2500	? High
	Haumoana fault zone	? 7.0	? 1000	< 6000	?
TYPE B	**Subduction thrust**	7.8 - 8.0	350-650	?	High
TYPE C	**Subducting plate**	? 7.0	?	?	?

* 1931 Hastings/Napier earthquake

6.0 Recommended work:

6.1 Additional return period studies

This work provides a first appraisal of the paleoseismic history of the central Hawke's Bay area. Some additional trenching may be useful in better defining second-order hazard associated with the Haumoana fault zone. There are some suitable trench sites along a series of normal faults in the Herehere/Mangaroa stream area behind Havelock North. These traces have scarp heights suggesting several rupture episodes and displacement has resulted in drainage ponding in places, favourable for preservation of fine-grained and carbon-rich deposits.

In addition, some further analysis of historical seismicity data may refine understanding of the return period of **Type C** earthquakes, their maximum magnitude and seismic efficiency.

6.2 Future work for earthquake hazard studies

6.2.1 Liquefaction Potential

1.1 Stage II Study Objectives

The objectives of this study were:

- to estimate and map the distribution of strong ground shaking for a range of time periods (Part 1);
- to assess the extent and distribution of areas susceptible to seismic liquefaction in the Hawke's Bay region (Part 2); and

to prepare a work programme for Stage III of the Earthquake Hazard Analysis Programme.

1.2 Work to be Undertaken

In accordance with the objectives stated above we will undertake the following work activities:

- Compile available records of historical earthquakes within and around the Hawke's Bay Region and combining these with paleoseismic information and those of the Stage I studies to develop a seismic hazard model for the region. This model was used to estimate the distribution of strong ground shaking in the region at various return periods, or probabilities of excedance.

- Prepare maps depicting the level of ground shaking and intensity expected at various return periods. These maps are valuable for planning purposes and consistent with return periods commonly used by the engineering community.

- Prepare an overview report to accompany the studies above that specifies the purpose of the study and the assumptions and limitations of the model, data, and interpretations presented.

- Collect available information regarding historical accounts of liquefaction in the Hawke's Bay Region, particularly for the 1931 earthquake.

- Prepare a series of liquefaction susceptibility maps which incorporate data from existing Quaternary geologic mapping (i.e. age and depositional environment of sediments), historical accounts of liquefaction, and geotechnical properties from existing boring logs.

- Identify appropriate scenario earthquakes to evaluate the potential occurrence of liquefaction in the Hawke's Bay region.

- Prepare a regional scale map which depicts the liquefaction potential for the earthquake scenarios in the Hawke's Bay region.

- Prepare detailed liquefaction potential maps (1:50,000) of the Heretaunga Plains, Wairoa, and Waipukerau/Waipawa which depict the occurrence of liquefaction during the scenario earthquakes.

- Prepare a report summarising the results of the studies, implications for liquefaction hazards in the Hawke's Bay region, and recommendations for the programme of work to complete Stage III of the Earthquake Hazard Analysis Programme.

6.2.2 Recommendations for Consideration by Territorial Local Authorities

Several issues have arisen from this study that may require further study that is not within the scope of the current earthquake hazard study for the Hawke's Bay Regional Council, but could be of interest to Territorial Local Authorities. The completion of these studies in conjunction with the regional study offers the potential for cost saving.

Central Hawke's Bay District

- Model the effects of scenario earthquakes on bridges, gas and water infrastructure of the District
- Mapping of active faults in Waipawa and Otane at a scale suitable for determining a building restriction zone similar to that currently in force in Waipukurau
- Lifeline services within or crossing active faults be assessed as to their vulnerability to fault rupture.
- New lifeline services be designed to minimise the threat to human life in the advent of a surface fault rupture.
- Emergency response procedures be reviewed to take into account the fault rupture hazard which may disrupt transport routes, energy and water supplies, and in some cases critical facilities.
- A review of public amenities (schools, hospitals etc.) and other aspects of Council responsibilities be carried out to evaluate the number of structures and activities vulnerable to the fault rupture hazard.

Hastings District

- Model the effects of scenario earthquakes on bridges, gas and water infrastructure of the District
- Lifeline services within or crossing active faults be assessed as to their vulnerability to fault rupture.
- New lifeline services be designed to minimise the threat to human life in the advent of a surface fault rupture.
- Emergency response procedures be reviewed to take into account the fault rupture hazard which may disrupt transport routes, energy and water supplies, and in some cases critical facilities.
- A review of public amenities (schools, hospitals etc.) and other aspects of Council

responsibilities be carried out to evaluate the number of structures and activities vulnerable to the fault rupture hazard.

Napier City

At present no active faults are well located within the boundaries of Napier City. Studies undertaken in future will address ground shaking hazards that will be important for Napier City.

- Model the effects of scenario earthquakes on port, airport, bridges, gas and water infrastructure of the City

Wairoa District

A number of active faults are known in the northwestern part of the District. Limited development in most parts of the District probably does not warrant studies more detailed than those to be undertaken for the regional studies. The town of Wairoa lies on alluvial materials that can be expected to amplify earthquake ground shaking.

- Model the effects of scenario earthquakes on bridges, gas and water infrastructure of the District

7.0 References

Beanland, S., Berryman, K.R., 1987. Ruahine fault reconnaissance. *New Zealand Geological Survey Report EDS 109*, 15pp.

Begg, J.G., Hull, A.G., Downes, G.L., 1994. Earthquake hazards in Hawke's Bay: initial assessment. Institute of Geological and Nuclear Sciences Client Report 333901.10 61 pp.

Berryman, K.R., 1988. Late Quaternary marine terrace distribution, stratigraphy, and deformation at Mahia Peninsula, New Zealand. Unpublished Ph.D. thesis, Geology Department, Victoria University of Wellington.

Berryman, K.R., et al. 1988. Seismotectonic hazard evaluation for the Mohaka River power development. New Zealand Geological Survey Contract Report 090/03, 91 pp.

Bonilla, M.G., Mark, R.K., Lienkaemper, J.J., 1984. Statistical relations among earthquake magnitude, surface rupture length, and surface fault displacement. *Bulletin of the Seismological Society of America 74 (6)*:2379-2411.

Byrne, D.E., Davis, D.M., Sykes, L.R., 1988. Loci and maximum size of thrust earthquakes and the mechanics of the shallow region of subduction zones. *Tectonics 7:* 833-857.

Cashman, S.M., Kelsey, H.M., Erdman, C.F., Cutten, H.N.C., Berryman, K.R., 1992. Strain partitioning between structural domains in the forearc of the Hikurangi Subduction Zone, New Zealand. *Tectonics 11(2)*: 242-257.

Cashman, S.M., Kelsey, H.M., 1990. Forearc uplift and extension, southern Hawke's Bay, New Zealand: mid-Pleistocene to present. *Tectonics 9(1)*: 23-44.

Cutten, H.N., Beanland, S., Berryman, K.R., 1988. The Rangiora Fault, an active structure in Hawke's Bay. *New Zealand Geological Survey Record 35*: 65-72.

Darby, D.J., Beanland, S., 1992. Possible source models for the 1855 Wairarapa earthquake, New Zealand. Journal of geophysical research 97: 12,375-12,389.

Dowrick, D.J., 1991. A revision of attenuation relationships for Modified Mercalli Intensity in New Zealand earthquakes. *Bulletin of the New Zealand National Society for earthquake engineering 24*: 210-224.

Froggatt, P.C., Howorth, R., 1980. Uniformity of vertical faulting for the last 7000 years at Lake Poukawa, Hawke's Bay, New Zealand. *New Zealand journal of geology and geophysics 23*: 493-497.

Haines, A.J., 1988. Deducing source properties of the M=7.8 Hawke's Bay, New Zealand, earthquake from the pattern of uplift and subsidence. *Seismol. Research Letters 59:* 36.

Haines, A.J., Darby, D.J., 1987. Preliminary dislocation models for the 1931 Napier and 1932 Wairoa earthquakes. *New Zealand Geological Survey report EDS 114.*

Hanks, T.C., Kanamori, H., 1979. A moment-magnitude scale. *Journal of geophysical research 84:* 2348-2350.

Henderson, J., 1933. Geological aspects of the Hawke's Bay earthquakes. *New Zealand journal of science and technology 15*: 38-75.

Hull, A.G., 1983. Trenching of the Mohaka Fault near Hautapu River, Hawke's Bay, May 3-6 1983. Earth Deformation Section Immediate Report, New Zealand Geological Survey File V19/831.

Hull, A.G., 1986. Pre-A.D. 1931 tectonic subsidence of Ahuriri Lagoon, Napier, Hawke's Bay, New Zealand. *New Zealand journal of geology and geophysics 29:* 75-82.

Hull, A.G., 1987. A Holocene marine terrace on the Kidnappers coast, Hawke's Bay, New Zealand: some implications for shore platform development and tectonic uplift. *Quaternary research 28*: 183-195.

Hull, A.G., 1990. Tectonics of the 1931 Hawke's Bay earthquake. *New Zealand journal of geology and geophysics 33*: 309-320.

Kelsey, H.M., Erdman, C.F., Cashman, S.M., 1993. Geology of southern Hawke's Bay from the Maraetotara Plateau and Waipawa westward to the Wakarara Range and the Ohara Depression. *Institute of Geological & Nuclear Sciences science report 93/2.* 17p.

Pacheco, J.F., Sykes, L.N., Scholz, C.H., 1993. Nature of seismic coupling along simple plate boundaries of the subduction type. *Journal of geophysical research 98*: 14,133-14159.

Reyners, M., 1987. Mohaka Hydro investigation: evaluation of seismicity data. Geophysics Division Contract Report 8, Department of Scientific and Industrial Research, 31 pp

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

Robinson, R., Benites, R., (in press). Models of fault interaction for the Wellington region, New Zealand: effects on the temporal clustering of large events. Journal of geophysical research.

Scholz, C.H., Campos, J., 1995 (in press). On the mechanism of seismic decoupling and back-arc spreading at subduction zones. Journal of geophysical research.

Smith, W., Berryman, K.R., 1983. Revised estimates of earthquake hazard in New Zealand. *Bulletin of the New Zealand National Society for Earthquake Engineering 16*: 259-272.

Smith, W.D., Berryman, K.R., 1992. Earthquake hazard estimates for New Zealand; effects of changes in the seismicity model. Department of Scientific and Industrial Research Contract Report 1992.

Sykes, L.R., Quittmeyer, C., 1981. Repeat times of great earthquakes along simple plate boundaries. Pp 217-247 *in*: Earthquake Prediction, An International Review, D.W. Simpson and P.G. Richards, *editors,* American Geophysical Union, Washington, D.C.

Thatcher, W., 1990. Order and diversity in the modes of circum-Pacific earthquake recurrence. *Journal of geophysical research 95*: 2609-2623.

Tichelaar, B.W., Ruff, L.J., 1993. Depth of seismic coupling along subduction zones. *Journal of geophysical research 98*: 2017-2037.

Van Dissen, R.J., Francis, D.A., Berryman, K.R., 1989. Geology and seismotectonic hazard assessment for proposed landfill at Hatuma Quarry, Waipukurau District. New Zealand Geological Survey Client Report 89/29.

Webb, T.H., Anderson, H., 1995. Focal mechanisms of large earthquakes in the North Island of New Zealand: strain partitioning at an oblique active margin. Geophys. J. Internat. (submitted).

Wells, D.L., Coppersmith, K.J., 1994. Updated empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement. *Bulletin of the Seismological Society of America 84*:974-1002.

Appendix 1:

Radiocarbon dates:

Site Grid reference	**Horizon**	**Radio-carbon number**	**Fossil Record Number**	**Conventional radiocarbon date (yrs BP)**	**Error (yrs BP)**
Argyll Rd V22/189394	Kaikora Stm fan AS2	NZ 8307	V22/f433	2565	69
Argyll Rd V22/189394	Twigs in tephra AS3	NZA 5681	V22/f437	23460	280
Argyll Rd #3 V22/186390	Wood	NZ 8306	V22/f435	9486	120
Opapa #1 V22/251505	Soil	NZ 8308	V22/f434	615	33
Opapa #1 V22/251505	Soil, base of F	NZA 5680	V22/f436	1344	76

Palynology: E.M. Crouch

Site, Grid reference	**Fossil Record Number**	**Unit**	**Pollen**	**Age**
Poukawa trench V22/301548	V22/f439	Unit G	Yes	? end of Last Glacial
Argyll #2 V22/187392	V22/f443	Basal unit	Yes	Indeterminate; pollen reworked
Argyll #3 V22/186390	V22/f444	Basal unit	Yes	Indeterminate; pollen re-worked
Opapa #1 V22/251505	V22/f445	Base of P	Yes	Indeterminate; pollen re-worked

Appendix 2:

Volcanic geochemistry

Mutiny Rd - top

Major elements	**Percentage (average for 10 glass shards)**	**Ferromagnesian minerals**	**Percentage**
SiO_2	77.290	Clinopyroxene	1
TiO_2	0.141	Orthopyroxene	56
Al_2O_3	12.410	Hornblende	43
FeO	1.200	Cummingtonite	<1
MgO	0.189		
CaO	1.050		
Na_2O	3.594		
K_2O	3.941		
Cl	0.185		
Total	**99.980**		

Mutiny Rd - base

Major elements	**Percentage (average for 10 glass shards)**	**Ferromagnesian minerals**	**Percentage**
SiO_2	77.449	Clinopyroxene	1
TiO_2	0.202	Orthopyroxene	63
Al_2O_3	12.417	Hornblende	36
FeO	1.060	Cummingtonite	<1
MgO	0.210		
CaO	1.006		
Na_2O	3.494		
K_2O	4.020		
Cl	0.143		
Total	**100.001**		

Poukawa

Major elements	**Percentage (average for 10 glass shards)**	**Ferromagnesian minerals**	**Percentage**
SiO_2	78.015	Clinopyroxene	3
TiO_2	0.199	Orthopyroxene	37
Al_2O_3	12.443	Hornblende	58
FeO	1.272	Cummingtonite	2
MgO	0.191		
CaO	1.247		
Na_2O	3.326		
K_2O	3.097		
Cl	0.209		
Total	**99.999**		

APPENDIX 3

Updated comprehensive seismic hazard table

Earthquake source	Faulting type	Estimated magnitude (M_s)	Estimated mean return time (years)	Date of last movement (years BP)	Comments and/or references
Ruahine fault	Strike-slip	7.5	1000-5000	c.500	Beanland & Berryman 1987
Waipunga fault	Strike-slip	7.5	2000	2 post-3500	Berryman 1988 Berryman et al 1989
Big Hill fault	Reverse-strike-slip	?	?	?	
Thorn Flat fault	Reverse-thrust	?	?	?	
Mohaka fault	Strike-slip	7.5	900	c. 1100	Hull 1983 Berryman et al 1988
Patoka fault	Strike-slip	7.5?	?	?	Henderson 1933
Hinuera thrust	Reverse-thrust	?	?	?	
Wakarara fault	Reverse-strike-slip	?	?	?30000	
Rangiora fault	Strike-slip	7.5	1350	2 post-1800	Cutten et al 1988
Taniwha fault	Reverse-thrust	?	?	?	
Waikopiro fault	Reverse	?	?	?	
Oruawharo fault	Reverse	?	?	?	

Glendevon fault	Reverse	5.7	9000-15000	2 post-20000	Van Dissen et al 1989
Napier-Hawke Bay fault	Reverse-thrust	7.8	2000-2500	AD1931	Henderson 1933 Hull 1986, 1990
Waipukurau-Poukawa faults	Reverse-thrust	7.8	2000-4000	AD1931 (north) south ? to >2500	Froggatt & Howorth 1980 Cashman et al 199?
Ryans Ridge fault zone	Normal	?	?	?	
Haumoana fault zone	Normal	7.0?	1000	?	Cashman & Kelsey 1990
Buried faults, active folds	Reverse-thrust	7.8?	?2300	?	
Kidnappers anticline	Reverse-thrust	7.5	c. 1000	2 post-2200	Hull 1987
Lachlan anticline	Reverse-thrust	7.8	1000	c. 300	Berryman 1988 Berryman et al 1989
Subduction zone	Reverse-thrust	7.8-8.0	350-650	?	Reyners 1987 Robinson (this report)
Deep focus	Normal	7.0	?	AD1953	Reyners 1987

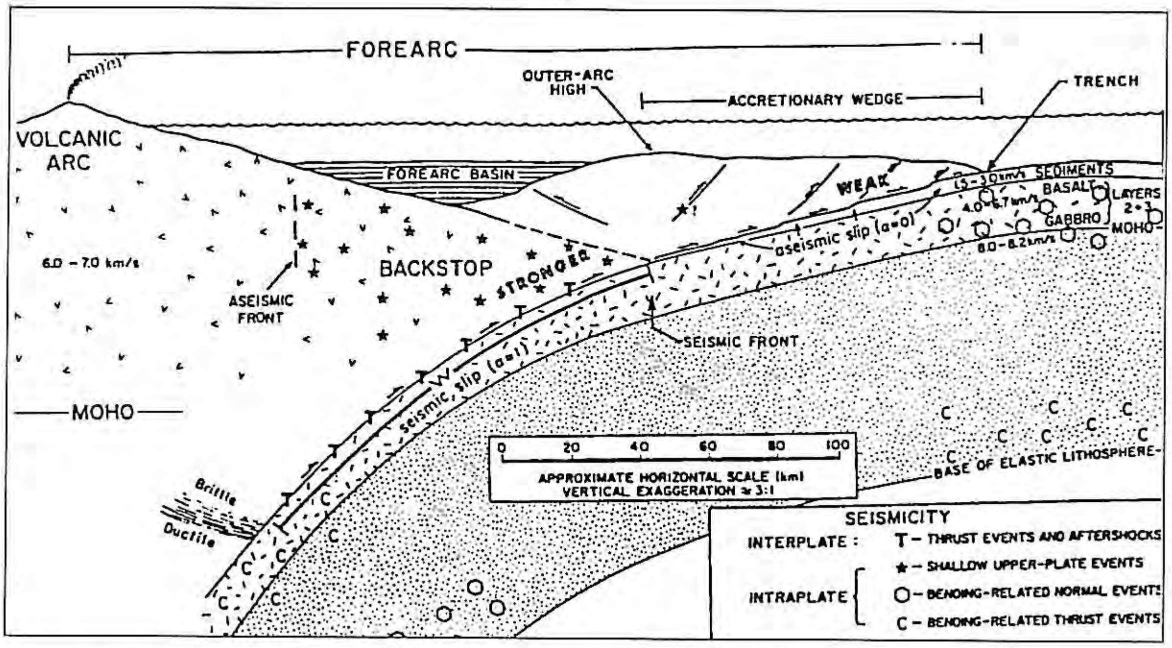


Figure 1a: Idealised schematic cross section of the shallow part of a subduction zone (after Byrne et al. 1988).

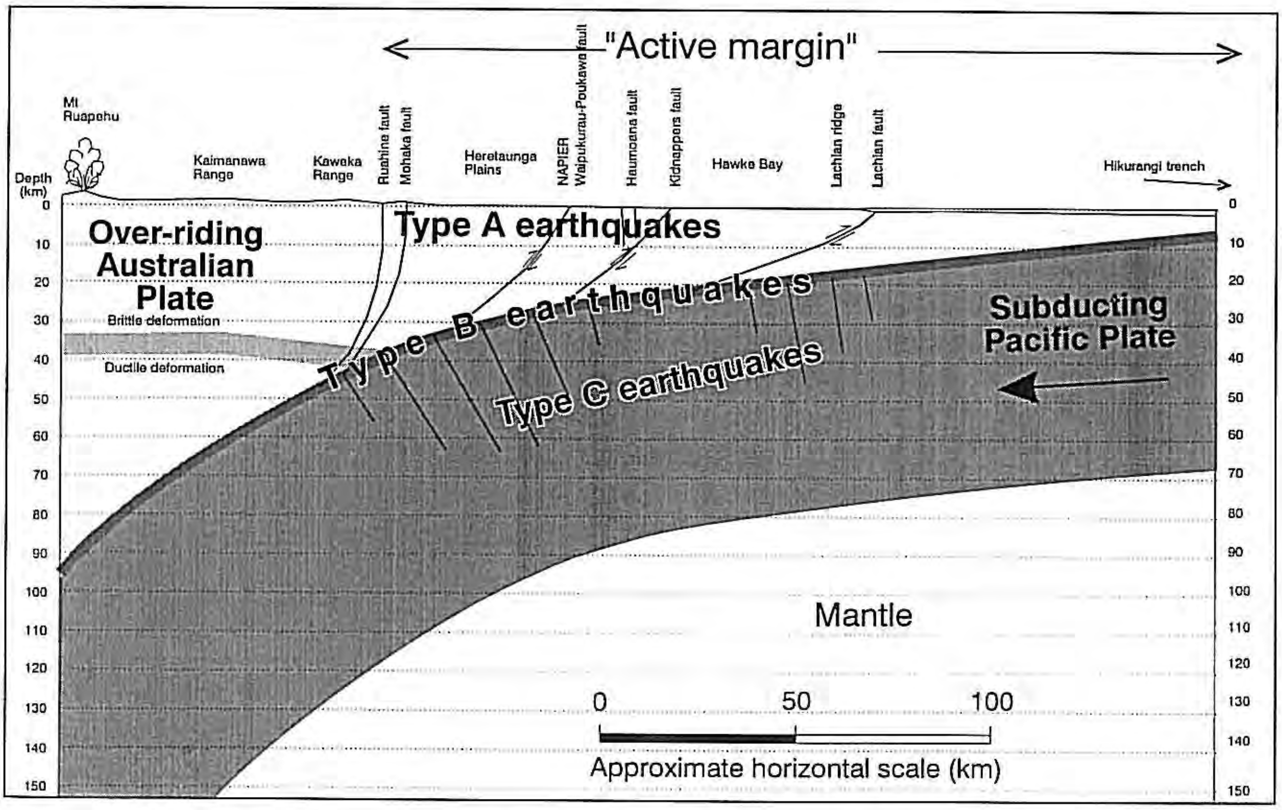


Figure 1b: Schematic cross section illustrating the tectonic setting of the Hawke's Bay region. The section line trends NW-SE and extends from the Hikurangi trench to Mt Ruapehu. Faults, fault zones and earthquake sources are shown.

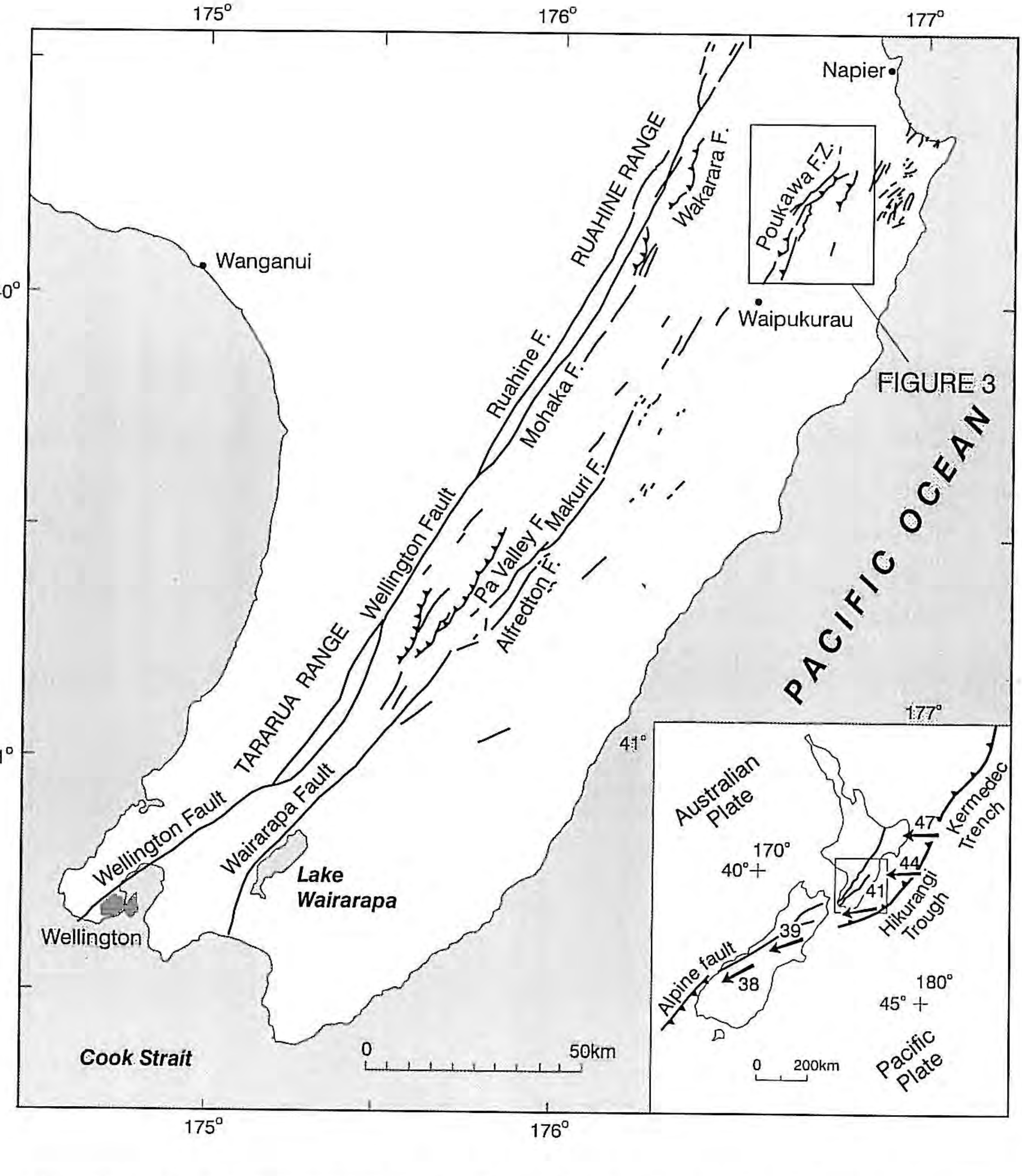


Figure 2: Map of the central and southern North Island showing the location and continuity of the principal active faults.

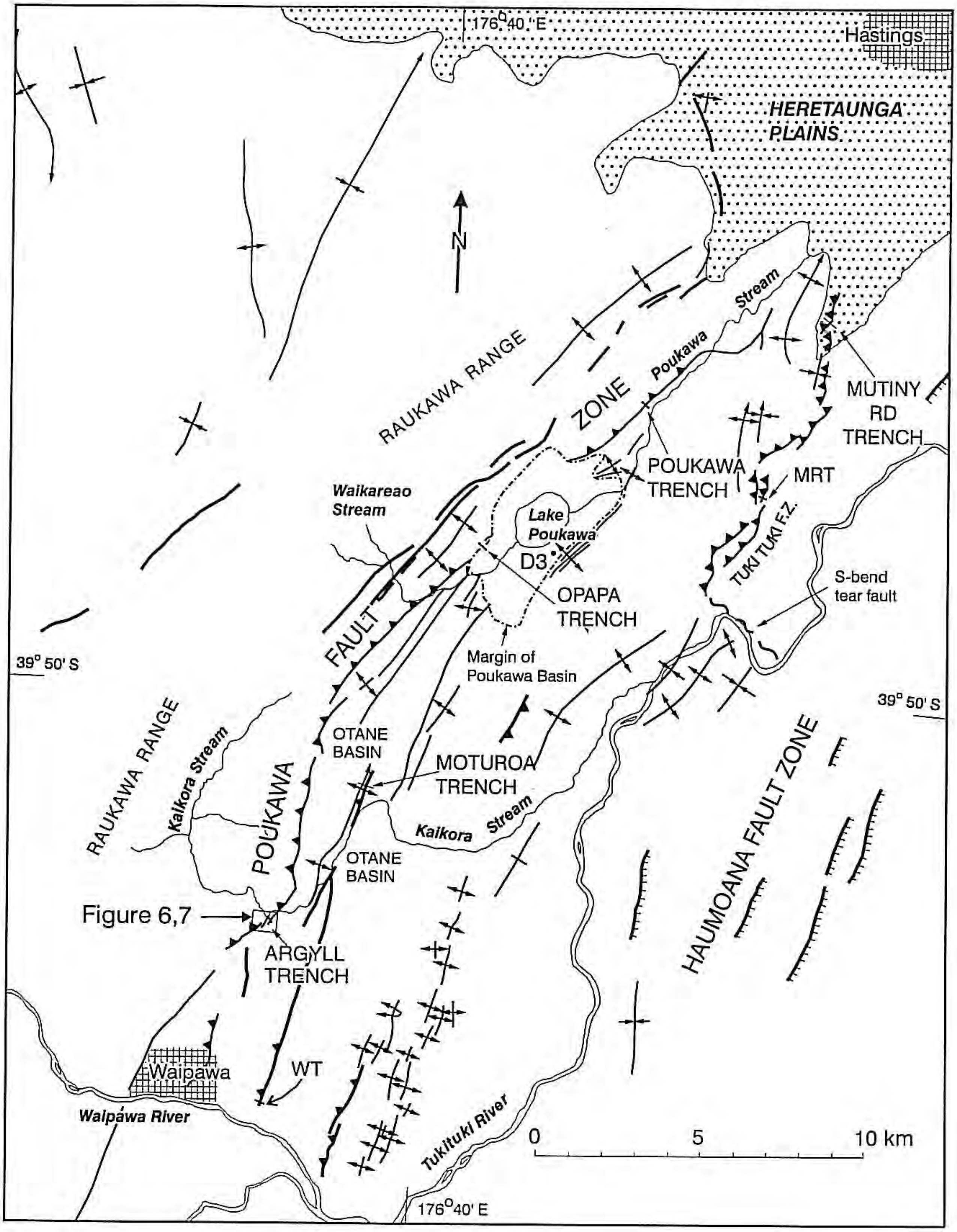


Figure 3: Location of the principal active faults, fold axes and population centres of the Waipukurau-Poukawa fault zone, showing also the location of sites trenched in the course of this study. MRT marks the position of the Middle Road trench site.

Figure 4: Examining, interpreting, logging and sampling trench walls is a skilled and time-consuming job. Photo: D. L. Homer.

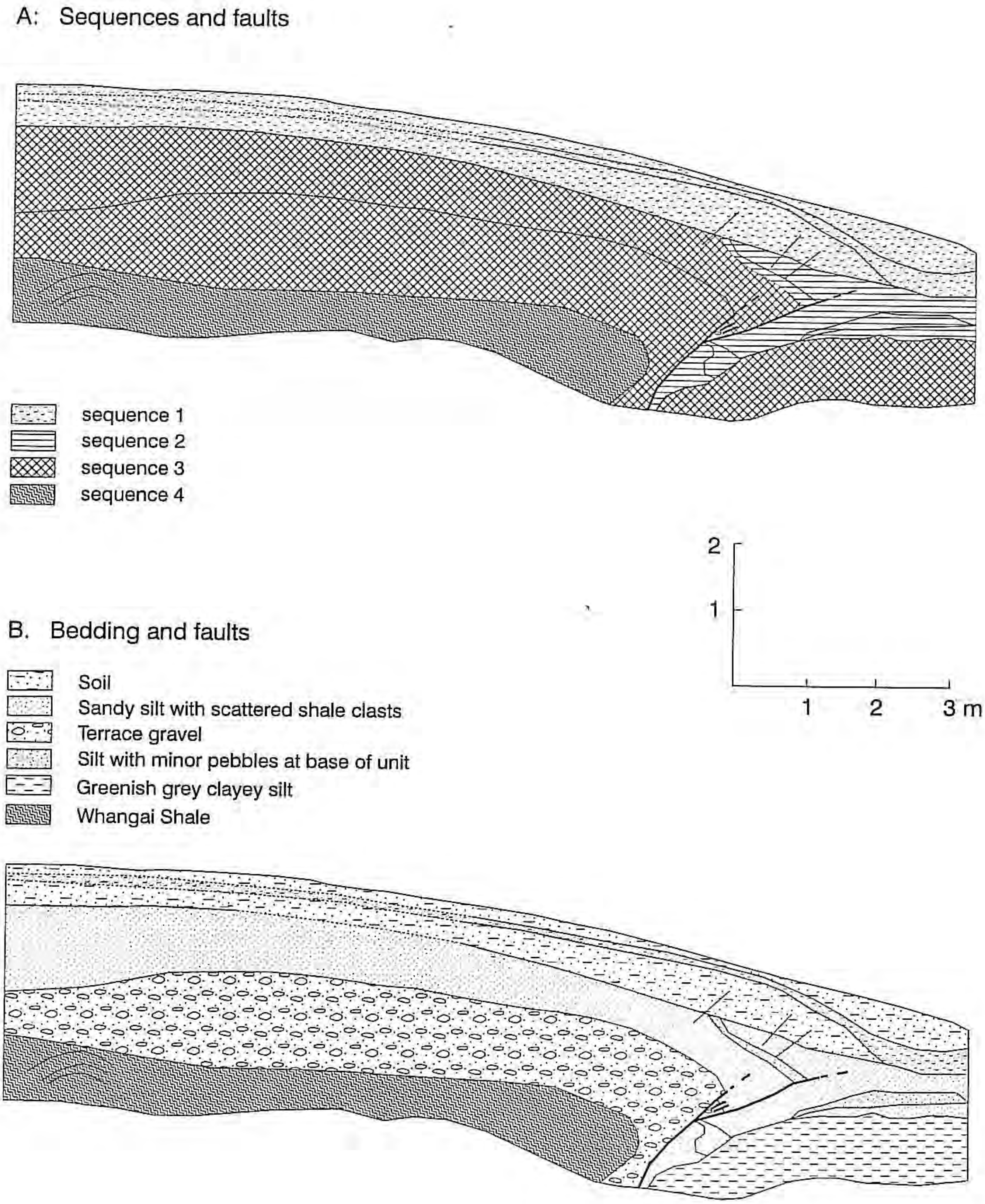


Figure 5: Generalised log of the Waipawa trench.

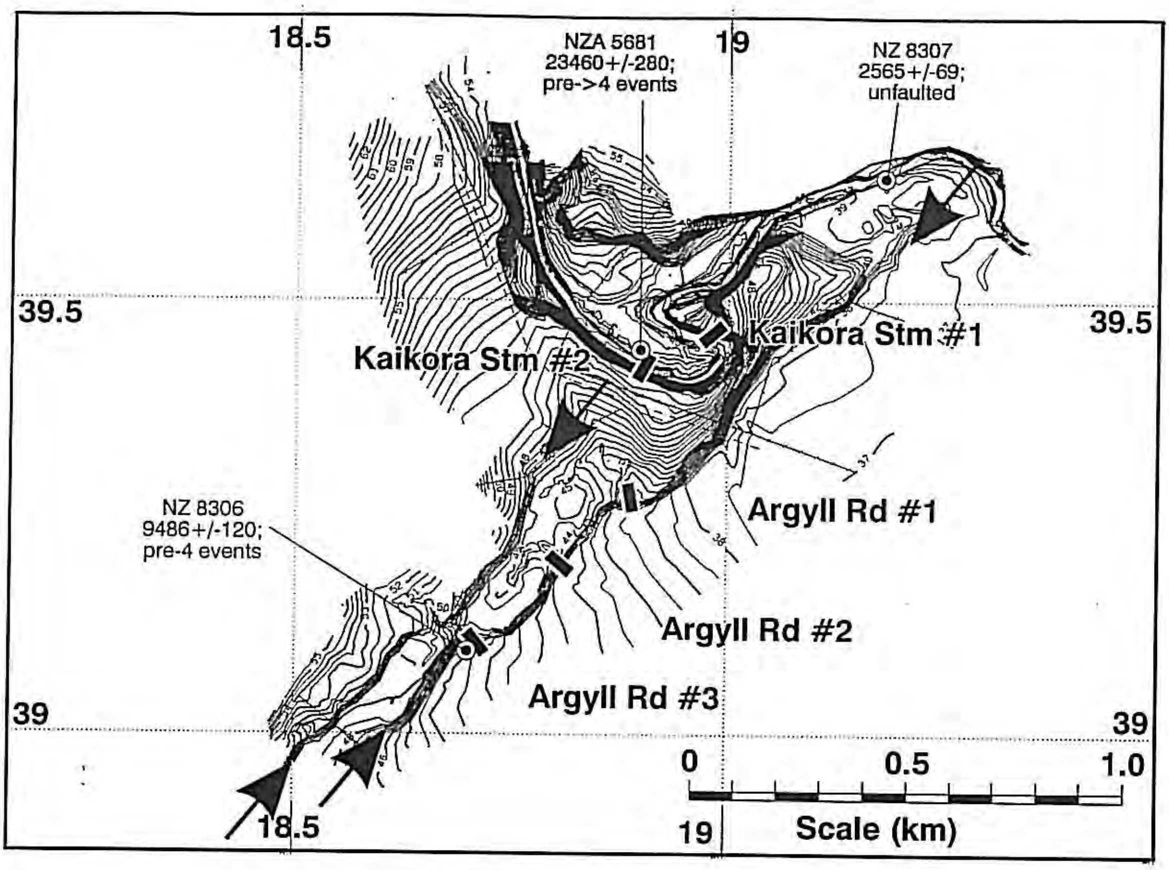


Figure 6: Detailed topographic map of the Kaikora fan area; contour interval is 0.5 m. Aroows show the position of the Argyll Road fault traces. The positions of the trench and section sites are shown.

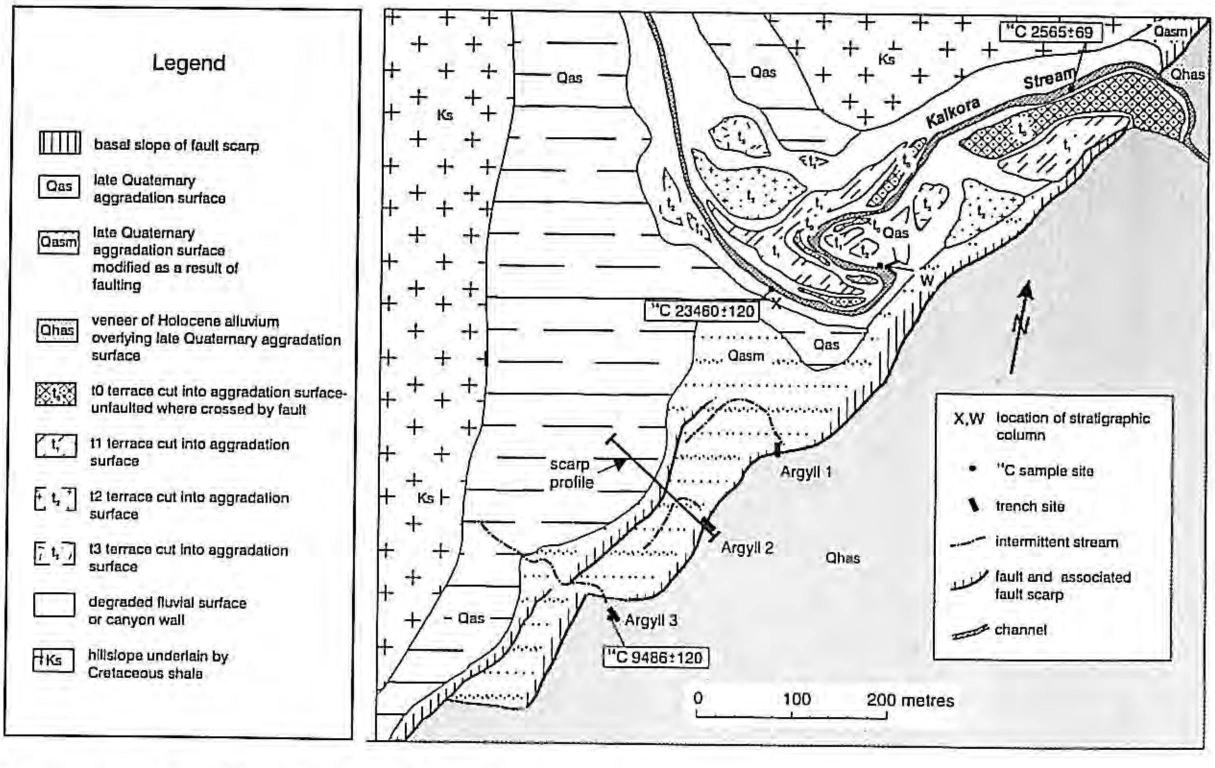


Figure 7: A geological map of the Kaikora fan area.

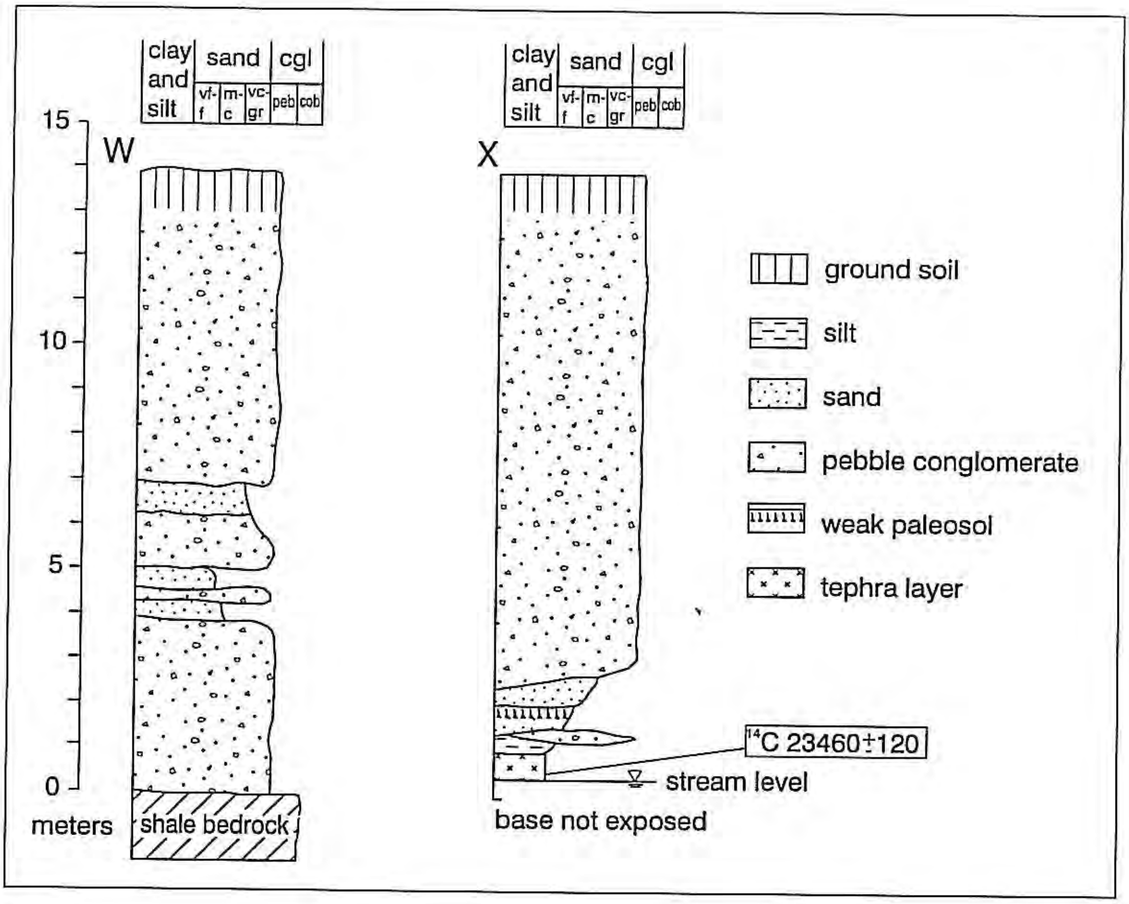


Figure 8: a) Measured section #1 of sediments exposed in the banks of Kaikora Stream.

b) Measured section #2 of sediments exposed in the banks of Kaikora Stream showing the relationship between fan gravels and underlying fine grained sediments. Note the radiocarbon date on twigs from a volcanic ash near the base of the section.

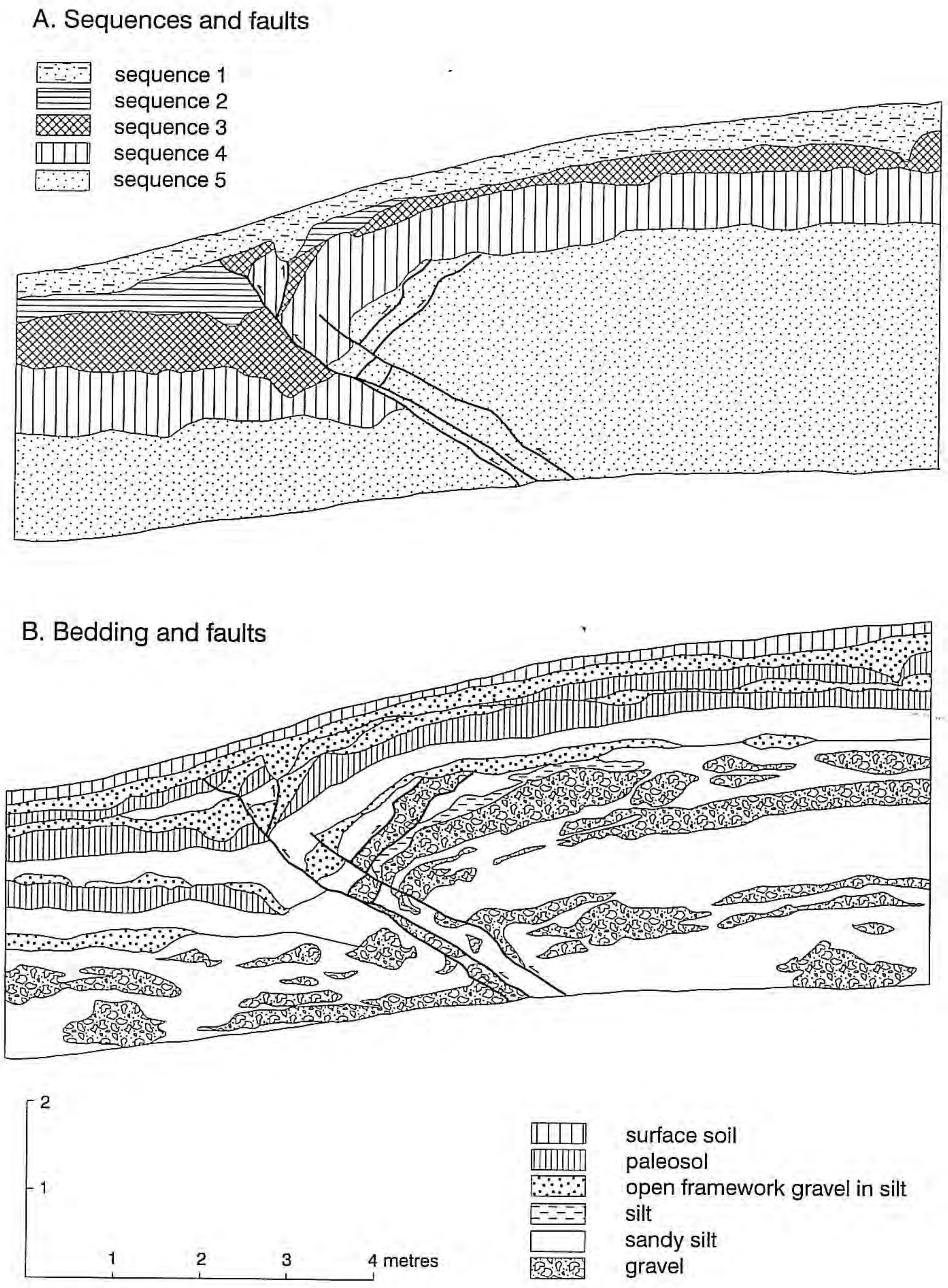


Figure 9: Generalised log of Argyll #2 trench.

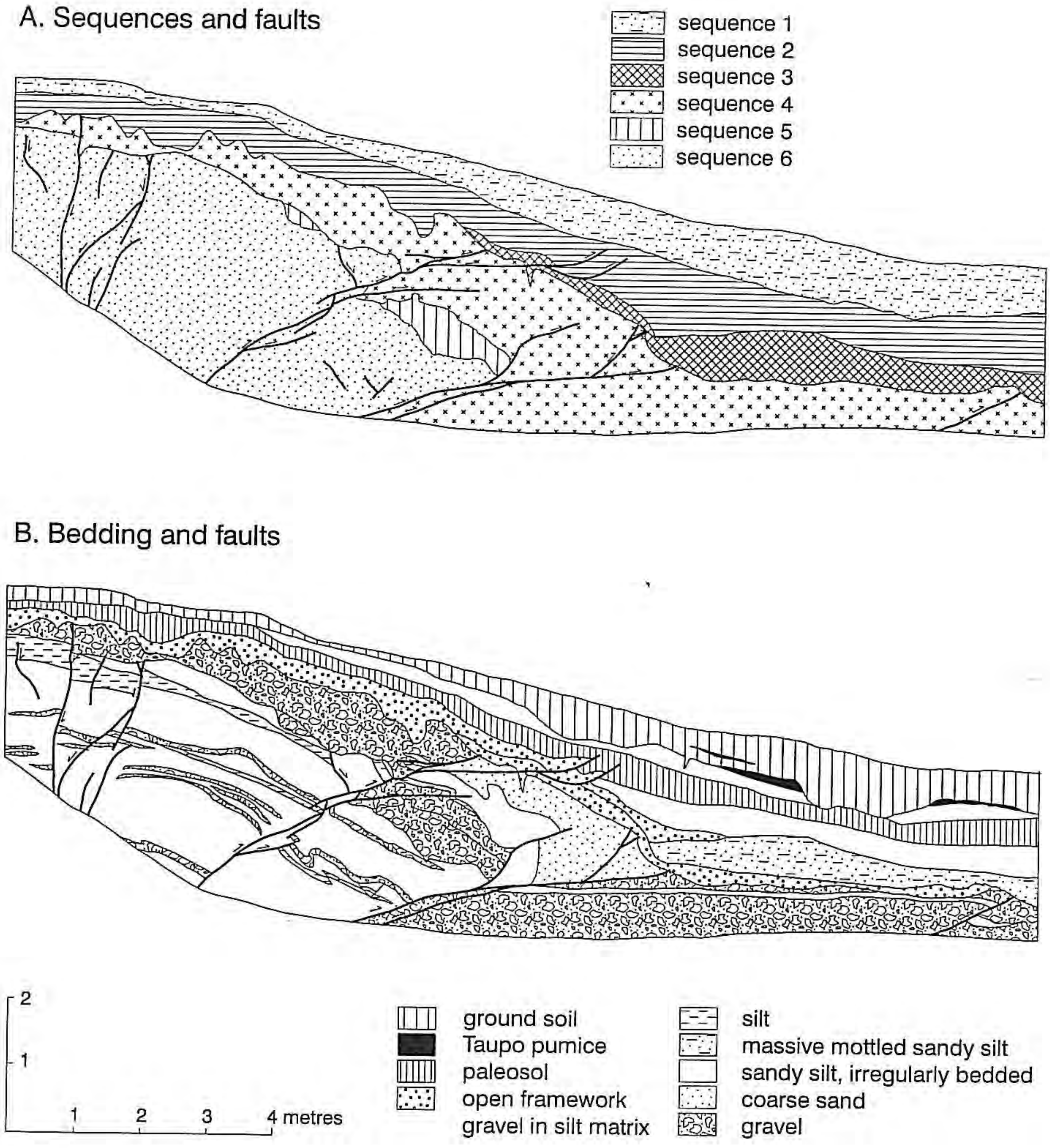


Figure 10a: Generalised log of the Opapa #1 trench.

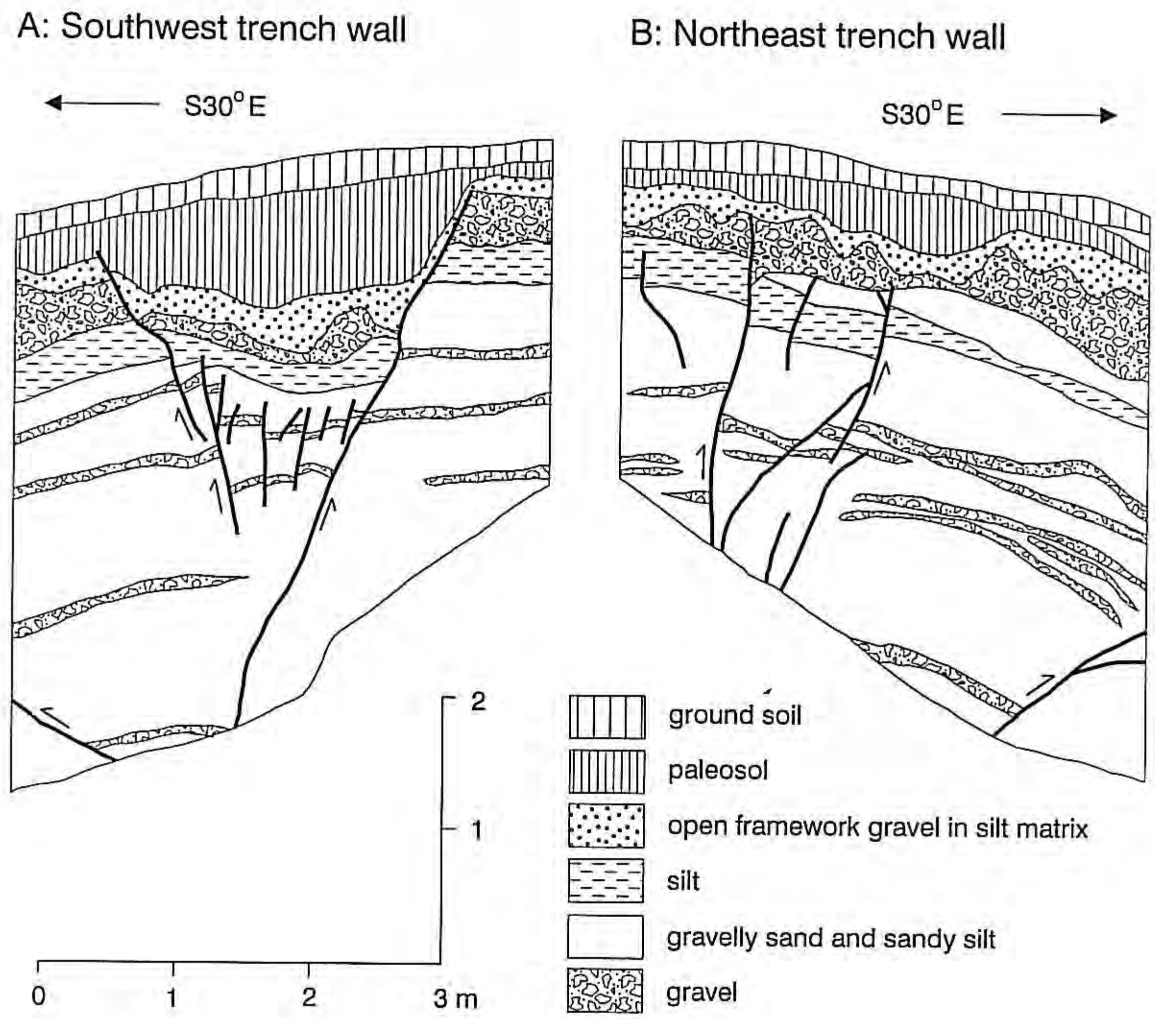
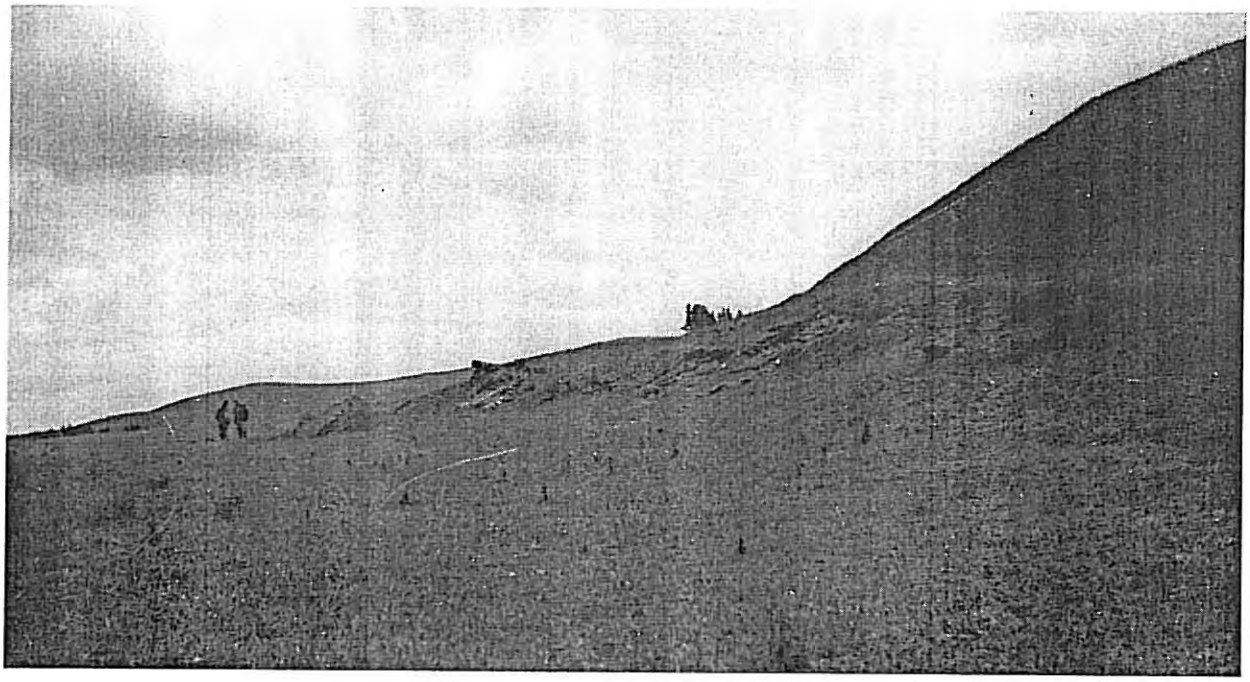


Figure 10b: Detail of the extensional faults in the Opapa #1 trench walls



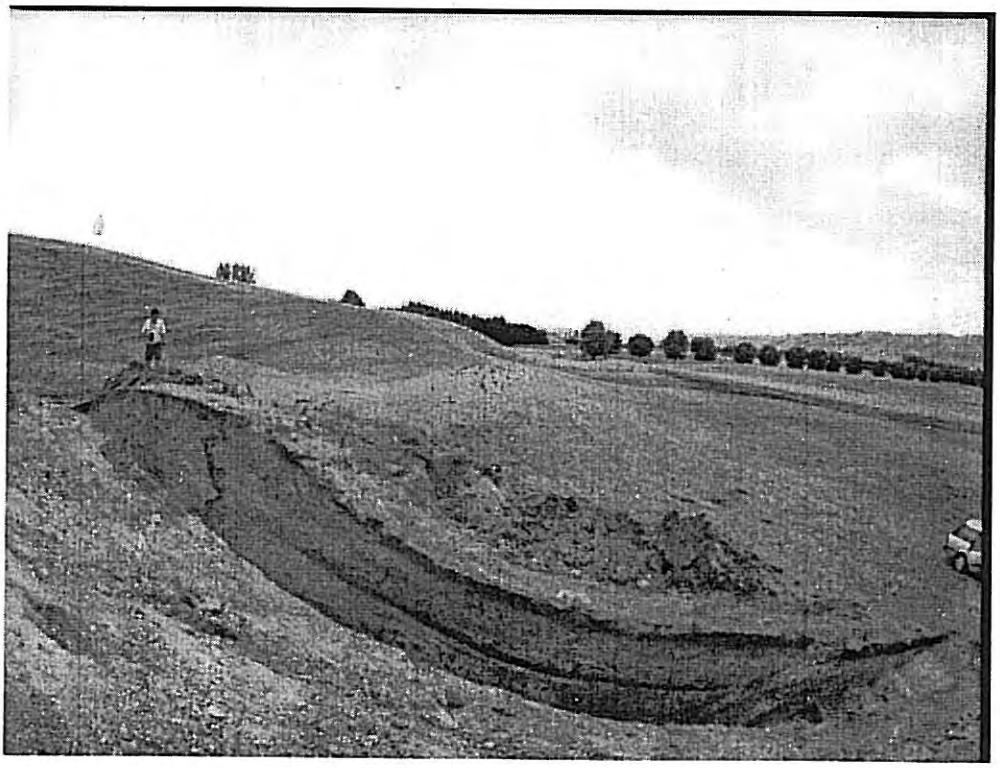
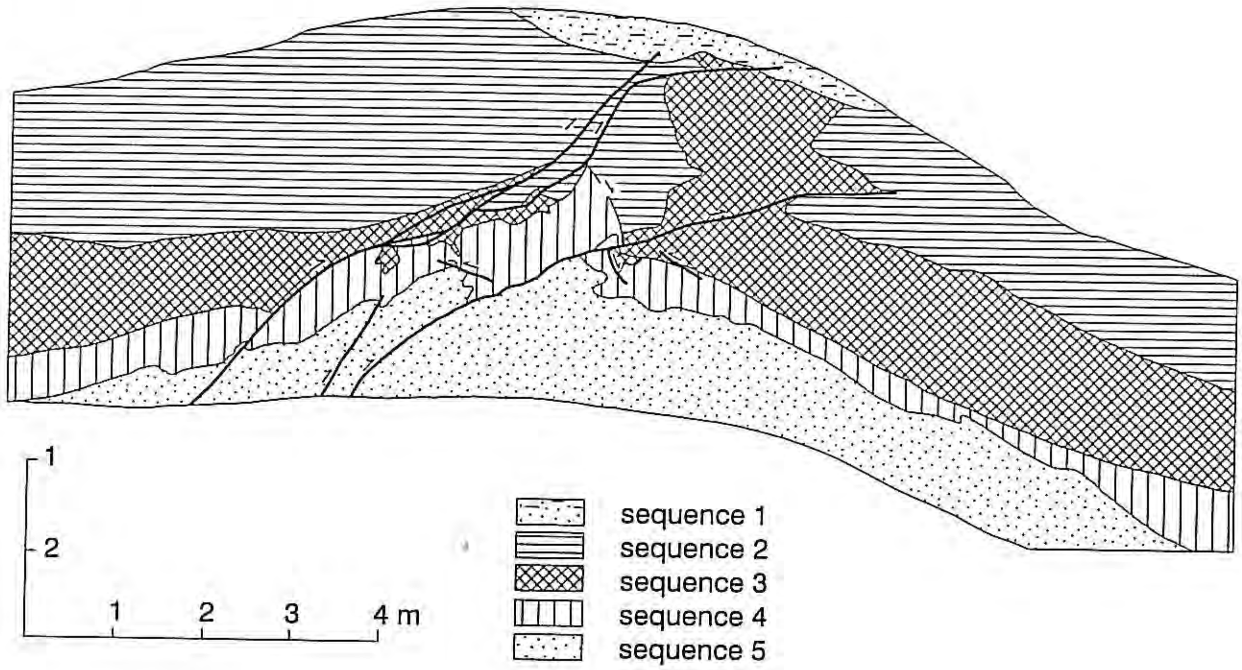


Figure 11: Photographs illustrating the 1931 fault rupture at the Poukawa fault trench site and a recent view from the same site.

A. Sequences and faults



B. Bedding and faults

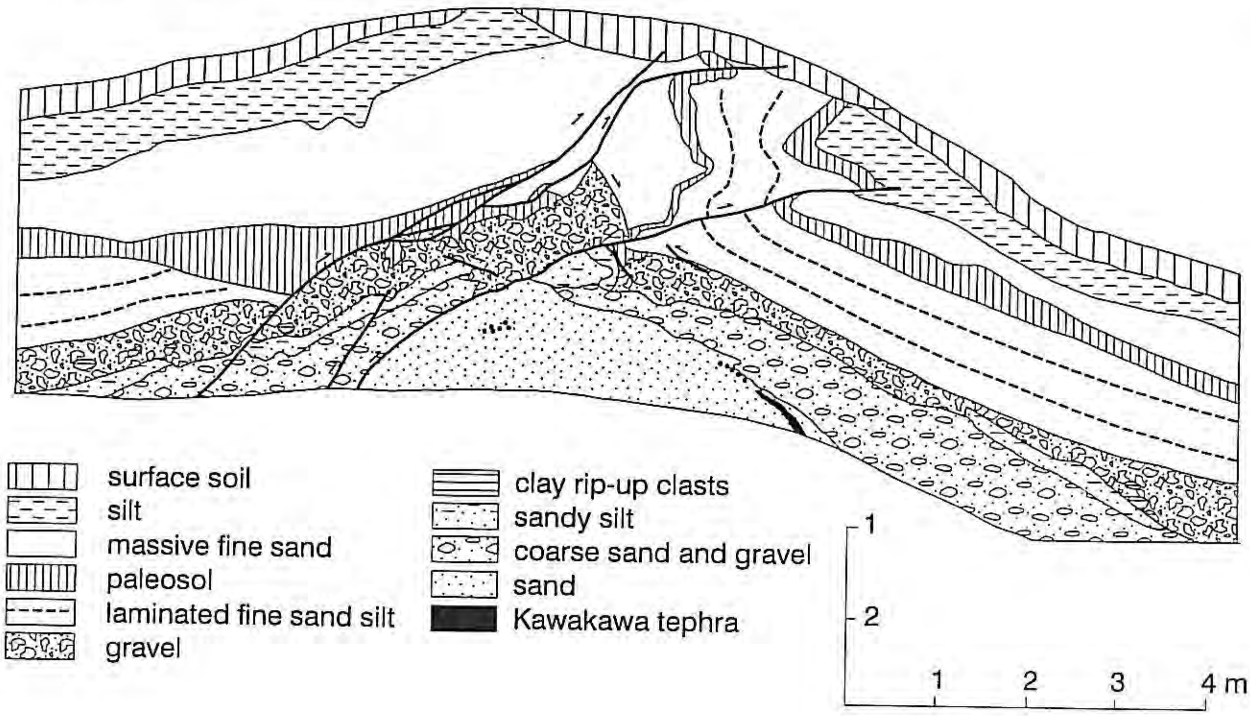


Figure 12: Generalised log of the Poukawa trench.

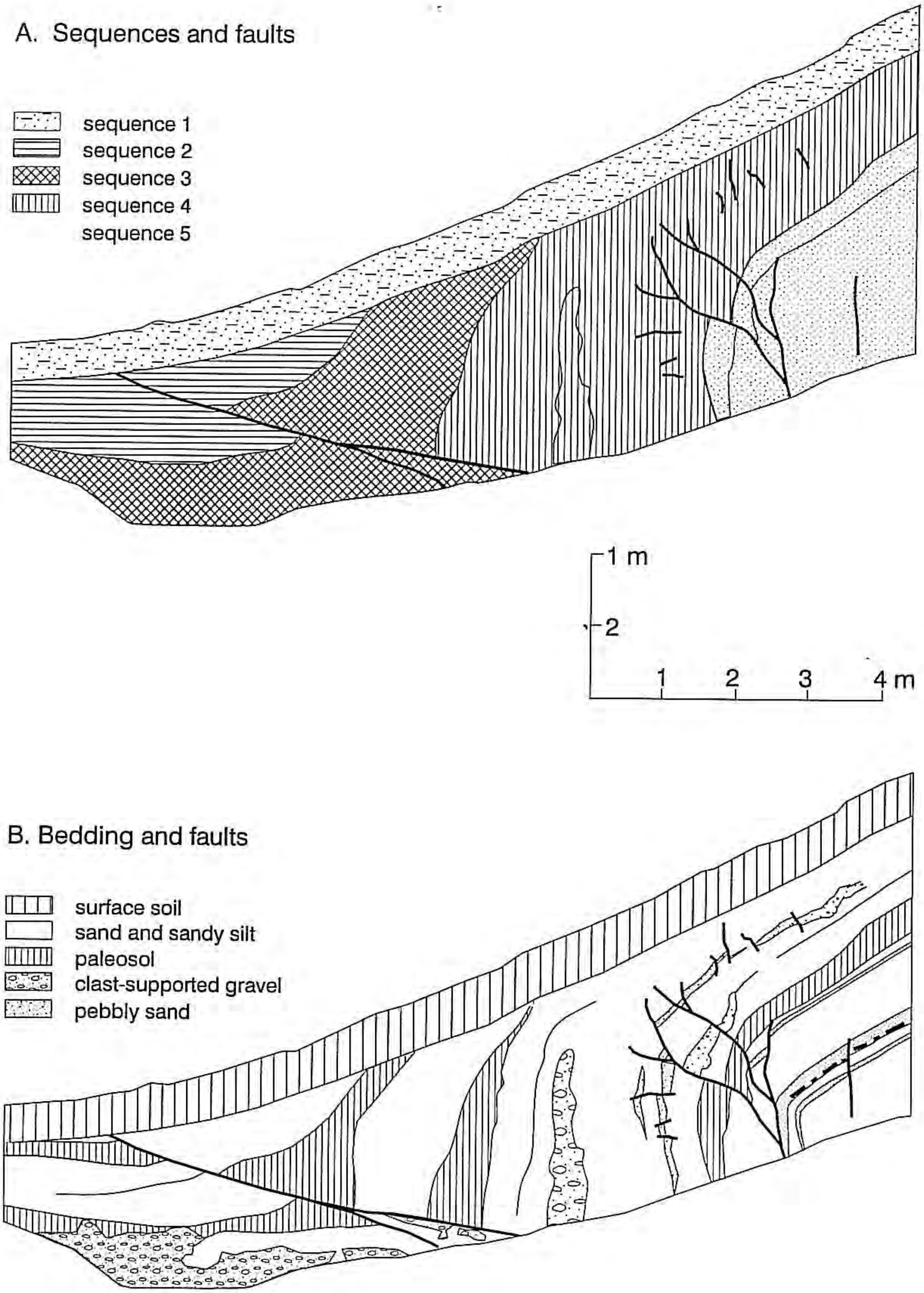


Figure 13: Generalised log of the Middle Road trench. The discontinuous dark line at the base of the sandy bed on the right hand side of the lower diagram indicates the position of the tephra horizon.

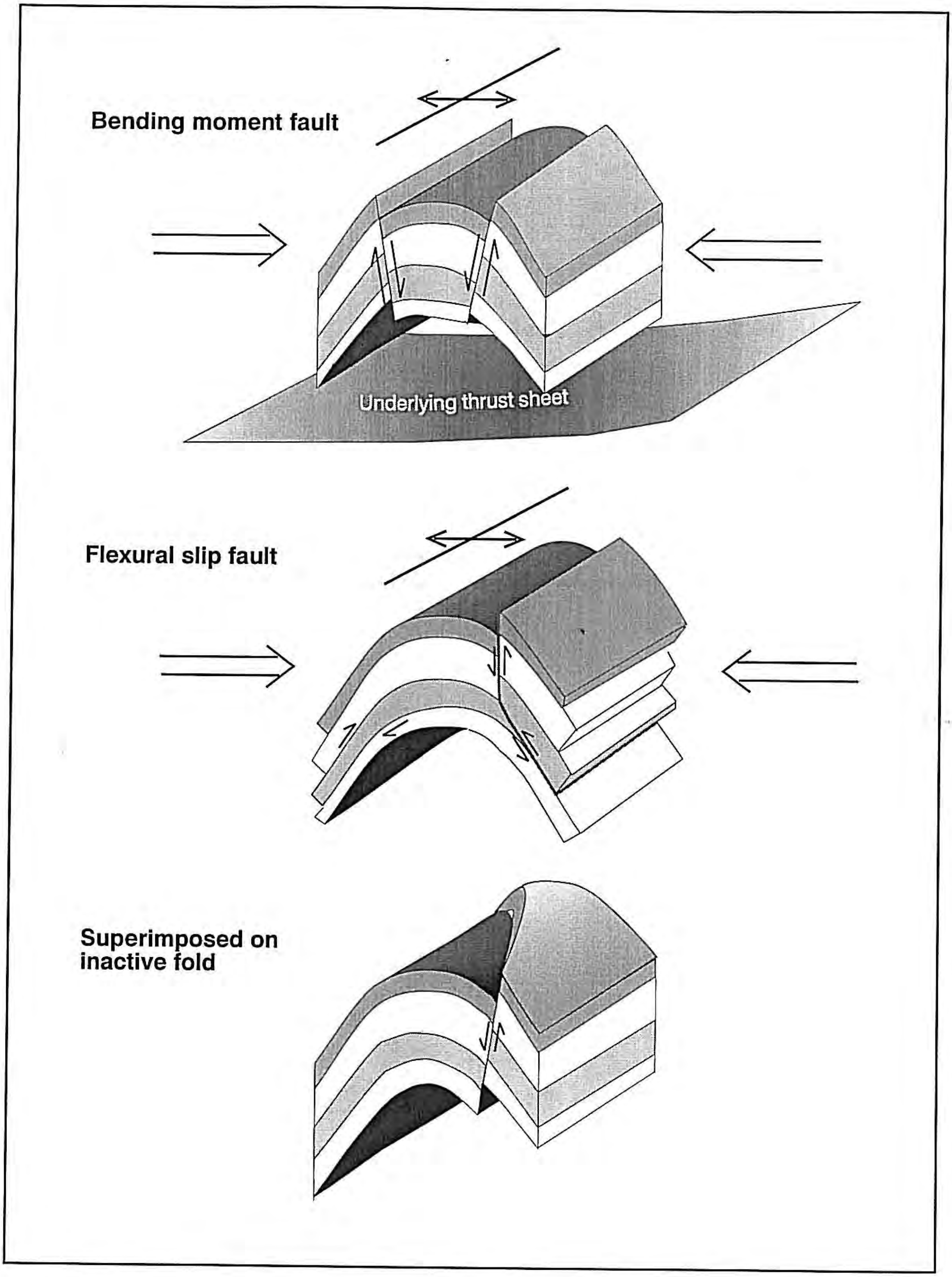


Figure 14: Diagram illustrating possible structural relationships between Haumoana fault zone normal faults and the Elsthorpe Anticline.

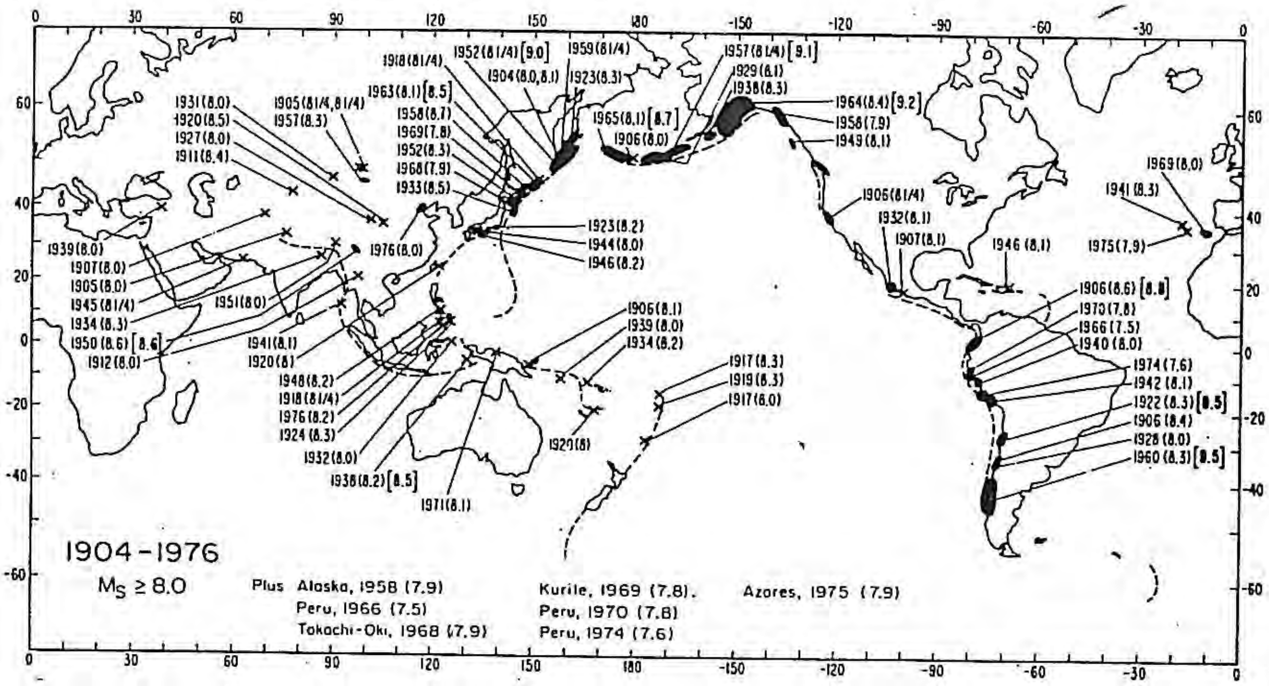


Figure 15: Map illustrating the world distribution of great earthquakes (>Ms 8.0) between 1904 and 1976. Black areas are rupture zones (from Uyeda 1982).

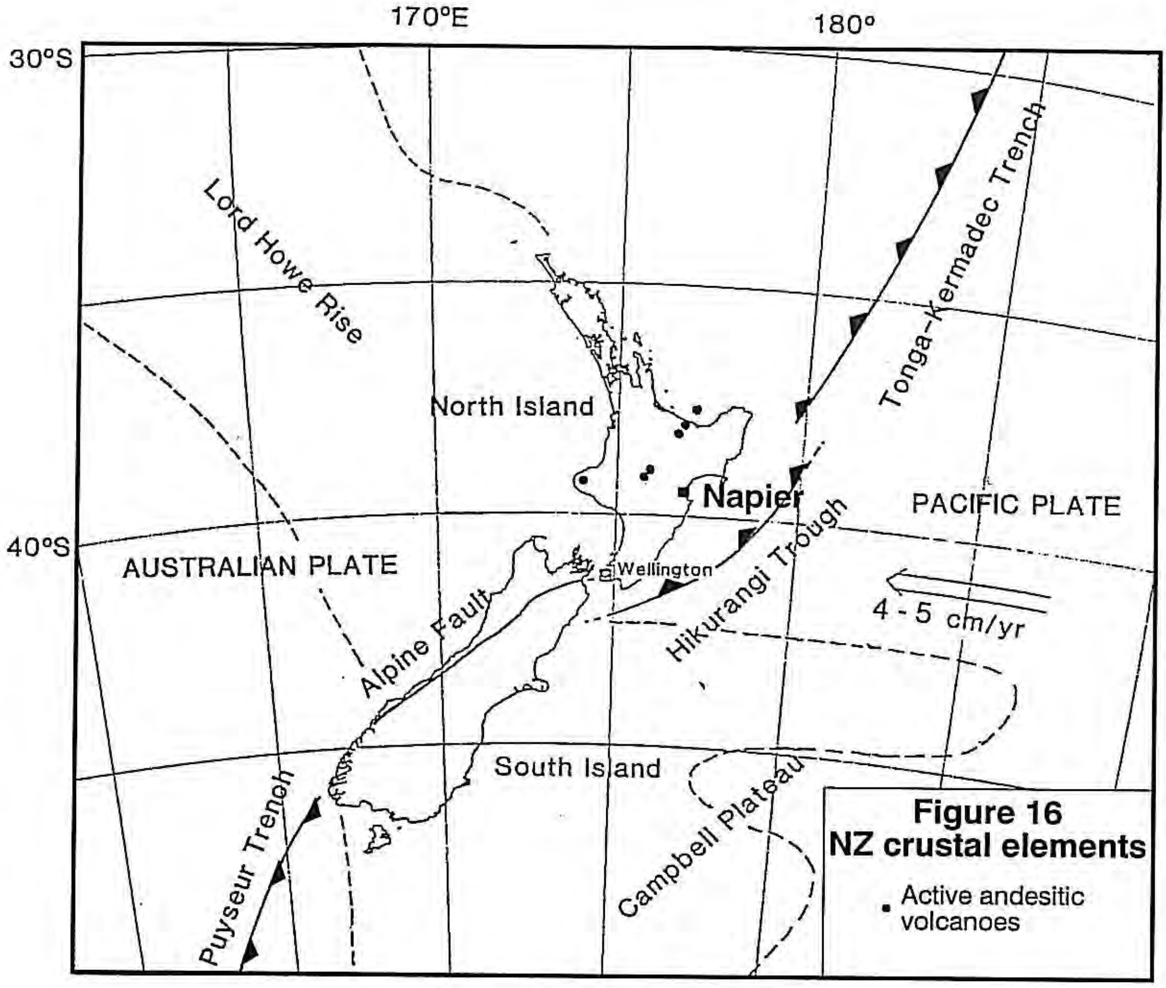


Figure 16: Map illustrating elements of crustal plates in the region surrounding New Zealand, and thier mutual boundary. The black dots are active andesitic volcanoes. Note the direction and trend of the relative motion between the plates.

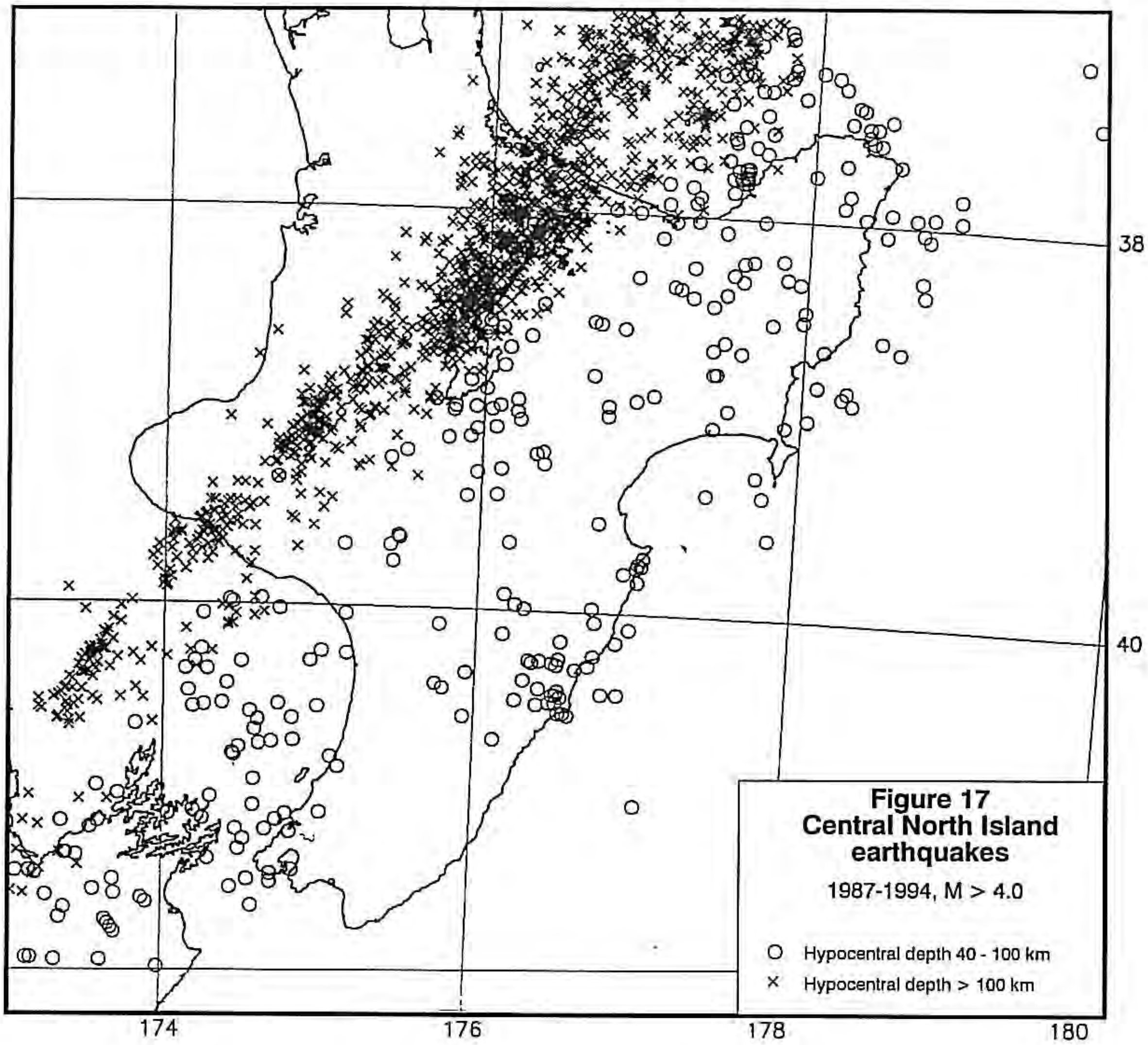


Figure 17: Epicentres of earthquakes with M > 4.0 between 1987 and 1994 are plotted on a map of the central and southern North Island. Crosses indicate earthquakes with hypocentral depths of > 100 km, hollow circles have depths of 40-100 km.

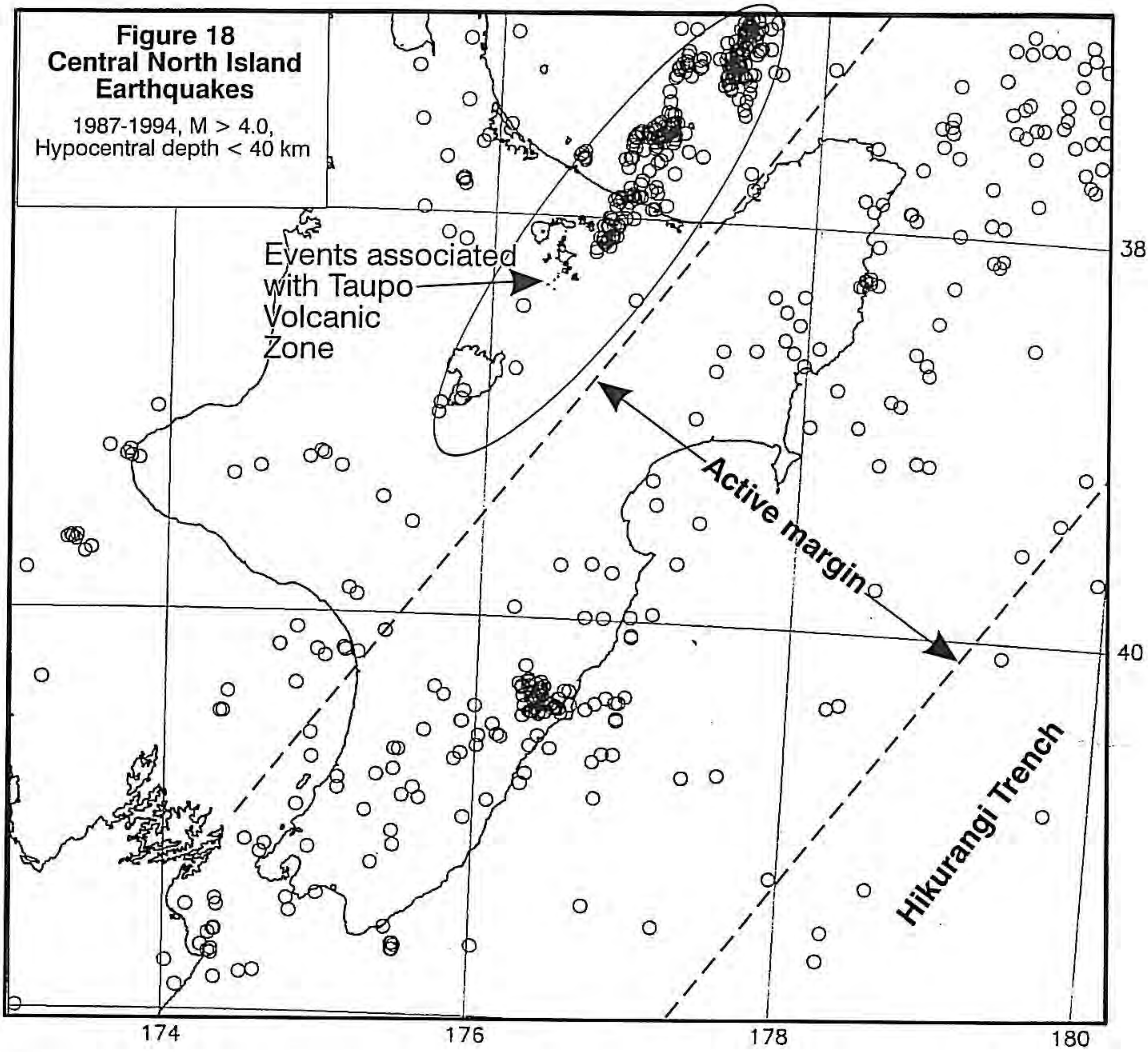


Figure 18: Epicentres of shallow crustal earthquakes with M > 4.0 between 1987 and 1994 with hypocentral depths of < 40 km. Note the cluster of earthquakes associated with the NE end of the Taupo Volcanic Zone.

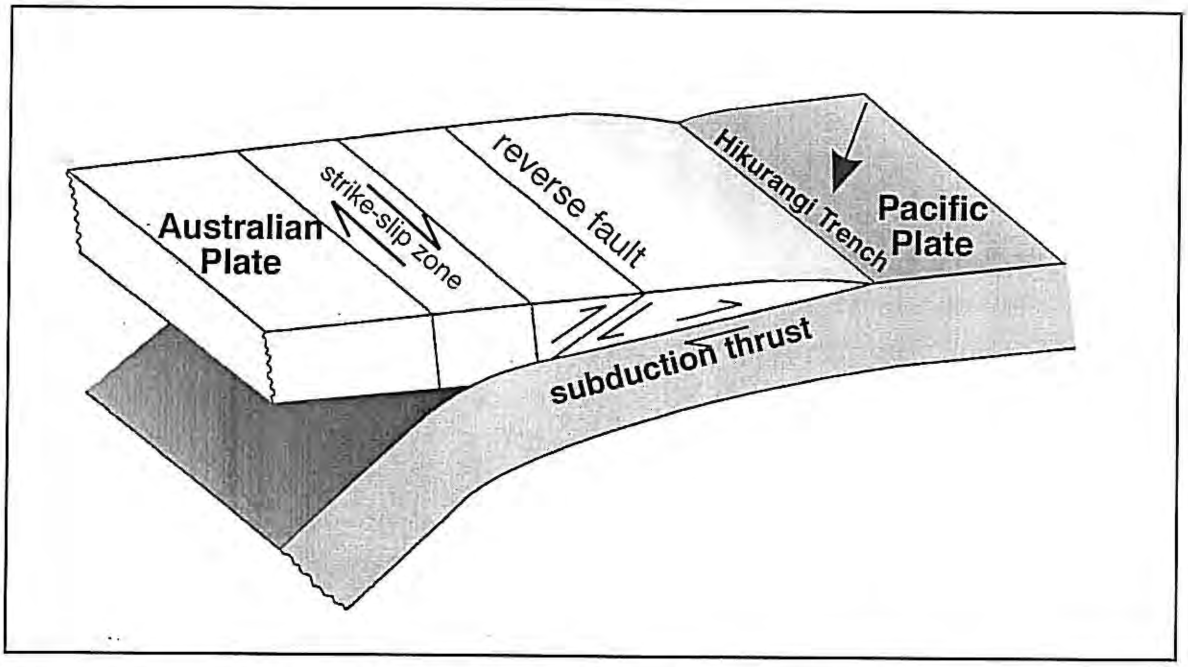


Figure 19a: Cartoon model showing the idealised partitioning of deformation at an obliquely convergent plate boundary.

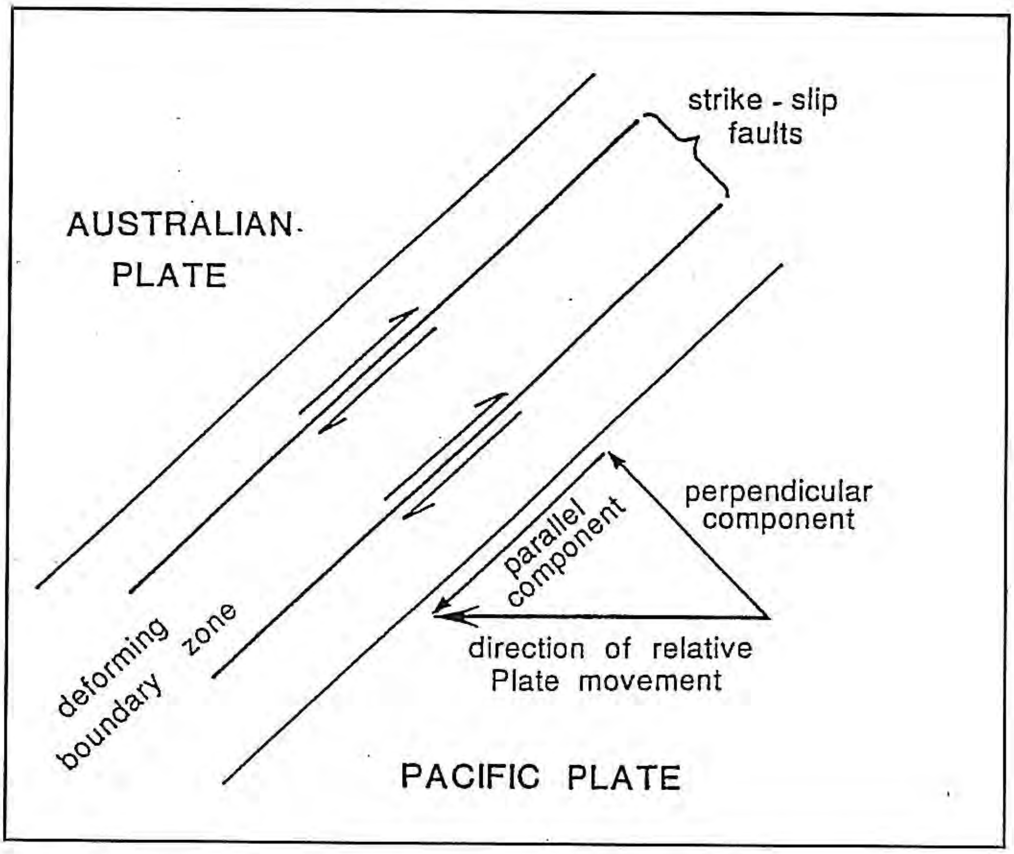


Figure 19b: Plan view illustrating partitioning of strike-slip and compressional components of the relative plate motion at the Hikurangi margin.

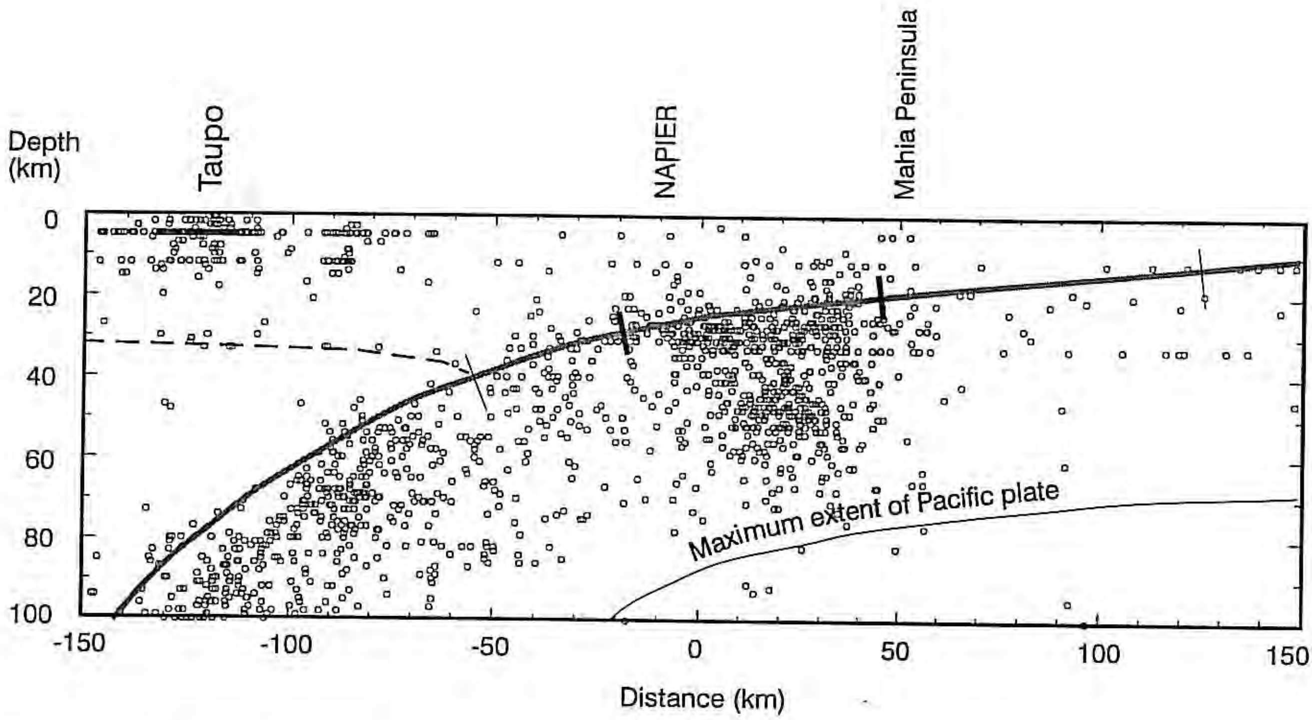


Figure 20a: Earthquake hypocentres plotted against a NW-SE orientated plane between offshore Hawke Bay and the Taupo area. Earthquakes define the top of the Pacific Plate and the lower brittle/ductile transition zone within the over-riding plate. The subduction interface between the small, solid ticks is thought to be locked; its maximum possible extent is indicated by the thin lines.

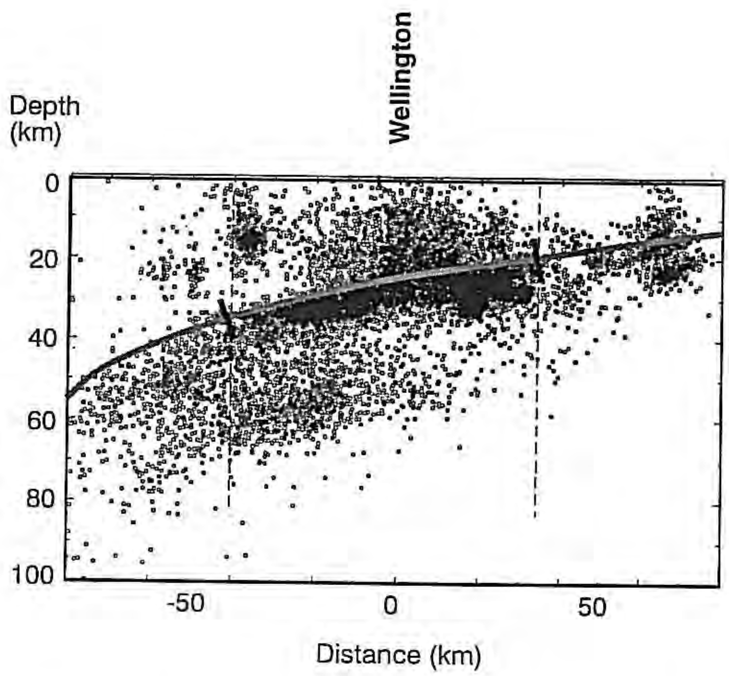


Figure 20b: A comparable plot for the Wellington region.

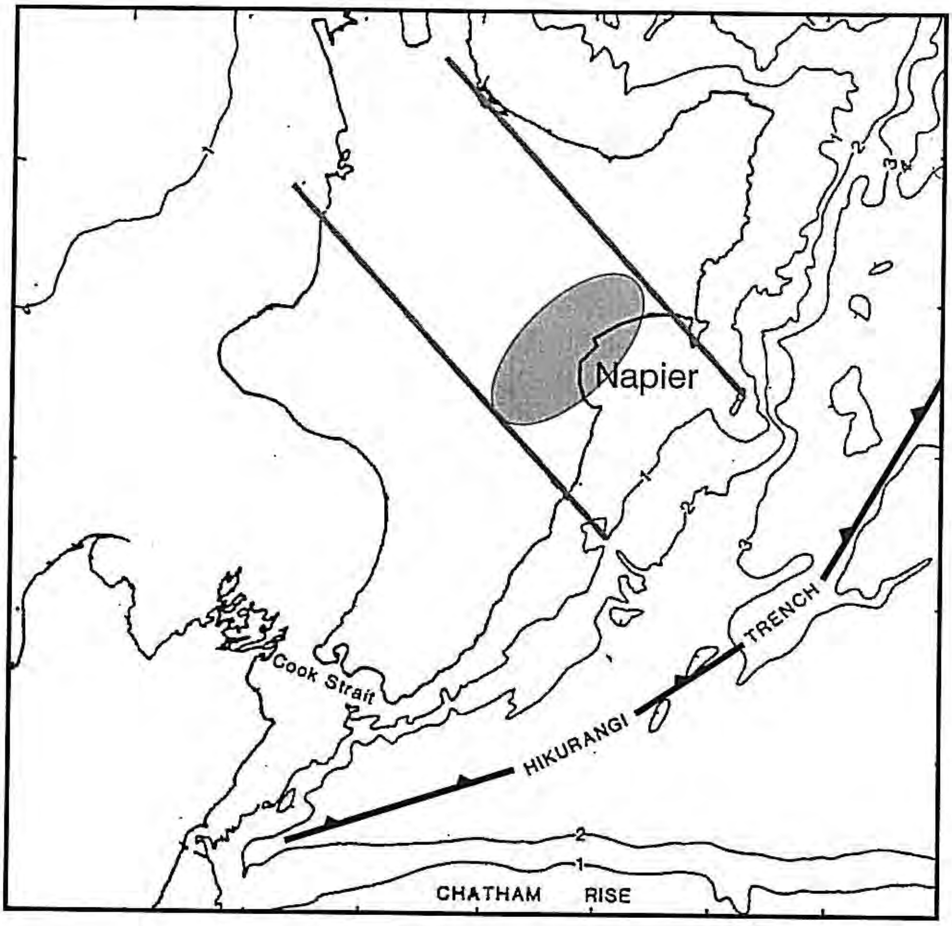


Figure 21: A map illustrating the possible segmentation of the subducted Pacific Plate at the Hikurangi margin. The NE and SW margins of the aftershocks from the 1931 Hawke's Bay earthquake may mark the limits of the tears within the subducted plate (indicated by heavy dotted lines). Bathymetric contour interval is 1 km.