NZE 18-(EQC 1995/195)

The 1934 Pahiatua Earthquake Sequence: Analysis of Observational and Instrumental Data

Gaye Downes, David Dowrick, Euan Smith, Kelvin Berryman

U22
018

The 1934 Pahiatua earthquake sequence: analysis of observational and instrumental data

Gaye Downes[1], David Dowrick[1], Euan Smith[2], Kelvin Berryman[1]
[1]Institute of Geological & Nuclear Sciences Ltd
[2]Victoria University of Wellington

Summary
Descriptive accounts and analysis of local seismograms establish that the epicentre of the 1934 March 5 Ms7.6 earthquake, known as the *Pahiatua earthquake*, was nearer to Pongaroa than to Pahiatua. Conspicuous and severe damage (MM8) in the business centre of Pahiatua in the northern Wairarapa lead early seismologists to name the earthquake after the town, but it has now been found that the highest intensities (MM9) occurred about 40km to the east-southeast of Pahiatua, between Pongaroa and Bideford. Uncertainties in the location of the epicentre that have existed for sixty years are now resolved with the epicentre determined in this study lying midway between those calculated in the 1930's by Hayes and Bullen.

Damage and intensity summaries and a new isoseismal map have been compiled from extensive newspaper reports and from 1934 Dominion Observatory "felt reports". They replace previous summaries and isoseismal maps of Hayes and Eiby.

The earthquake was felt over a large part of New Zealand from Auckland in the north to Dunedin in the south. The maximum intensity of MM9 occurred between Waione and Bideford, to the east of Pahiatua, in the northern Wairarapa. Modified Mercalli intensities of MM8 or more occurred over an area of approximately 5000 km^2. Pahiatua and Eketahuna were the most severely damaged townships (MM8), but many other small towns in the Wairarapa, southern Hawke's Bay, Manawatu and Rangitikei were also strongly shaken to intensity MM7.

The total population within the MM7-MM9 region was fortunately modest, and although the damage involved life threatening collapse of parts of buildings, the only casualties were two elderly people (one in Pahiatua, the other in Greytown) with heart illnesses who died of shock, and a woman in Feilding (MM7) who was bruised in bed by falling bricks. The very low casualty count is attributed to the fact that the earthquake occurred in the middle of the night, when most people were in their homes, most of which were timber-framed. If the earthquake had occurred in business hours a modest number (a dozen or so?) of casualties might have occurred, mainly due to the falling of brick gables and parapets of Pahiatua's commercial buildings.

Sand and water ejections and other evidence of liquefaction occurred at several locations in the Wairarapa and Manawatu areas. In the Manawatu these effects may have been intensified as a result of high rainfall in the preceding month. The high rainfall in the month before and immediately after the mainshock may also have contributed to other ground damage. Landslides, slumps and associated road cracks, and rockfalls occurred over a large area, particularly within the MM9, MM8 and MM7 isoseismals and with isolated instances in the MM6 and MM5 zones. Most were relatively minor and in weak soils.

Electricity services were disrupted in many places in the lower North Island. Other than in the epicentral area, where pole fixtures were broken also, triggered circuit breakers were the main cause for the power outage. Two water mains were broken, in Wanganui and Pahiatua, although minor leaks occurred in several other places

including one in the lower Hutt Valley. Disruption to other lifelines was limited to a half a day's hold-up of the railway service between Masterton and Woodville, due to fall of rock at the bluff between Pahiatua and Mangatainoka and slightly twisted rails there and between Newman and Mauriceville.

Shaking enhancement is indicated at several sites, with very localised damage occurring within areas of generally lesser or little damage. For example, Gladstone and Longbush, Moutua and Makerua have intensities MM8 assigned in an otherwise MM7 zone and parts of Wanganui and Petone experienced MM7 in an otherwise MM6 zone.

In addition to analysing observational data, surviving seismograms from the rather small and poorly equipped 1934 New Zealand network of twelve stations have been re-read and analysed. The addition of reliable teleseismic data to the local station data yields a solution for the epicentre (40.51S 176.29E; depth fixed at 12km) that lies within the highest intensity (MM9) isoseismal. Larger aftershocks and other moderate magnitude earthquakes that occurred within 10 days and 50km of the mainshock have also been located using local instrument data. The locations of larger aftershocks and the distance from Wellington of smaller aftershocks (magnitudes $M>3.5$) within 24 hours of the mainshock is used to delineate the probable mainshock rupture zone, which is at least 50km in length.

The total number of aftershocks was not as great as occurred in the 1931 Hawkes Bay and 1942 Wairarapa earthquake sequences.

Neither contemporary sources nor recent enquiries directed to old residents yield any evidence of a surface fault rupture within the MM9 isoseismal, although the strike-slip mechanism at 20km depth determined by preliminary teleseismic body wave modeling of Doser and Webb suggests that it is a possibility that needs to be considered. Berryman et al. have recently identified a fresh-looking, active fault that lies within the MM9 isoseismal which might be a candidate.

The tectonic significance of the 1934 earthquake sequence, that is, whether it occurred in the upper or lower plate and what mechanism was involved, awaits the completion of Doser and Webb's modeling (which is not part of this project). Their modeling will also determine whether the distribution of aftershocks is of interest for comparison with stress-triggering models. The relationship of the 1942 Wairarapa earthquakes to the 1934 Pahiatua earthquake also seems to warrant investigation, as the only reliably recognised surface rupture in the June 1942 earthquake lies within 30km of the largest aftershock in 1934 and within 10km of later smaller aftershocks. Source mechanisms of the three 1942 earthquakes (June Ms7.2, August Ms7.0 and December Ms6.0) from continuing studies of Doser and Webb and planned seismological and engineering studies of the same earthquakes will contribute greatly to our understanding of the tectonics of the sequence from 1934 to 1942.

To conclude, this project has achieved its objectives of

- identifying the epicentres of the mainshock, larger aftershocks and other moderate earthquakes in March 1934 from observational and instrumental records
- determining intensities and the distribution of intensity of the mainshock
- documenting building damage within the highest intensity areas of the mainshock.
- providing a reliable epicentre for teleseismic body wave modeling, thus enabling the tectonic significance of the earthquake to be interpreted.

THE 1934 PAHIATUA EARTHQUAKE SEQUENCE: ANALYSIS OF OBSERVATIONAL AND INSTRUMENTAL DATA

Gaye Downes[1], David Dowrick[1], Euan Smith[2], Kelvin Berryman[1]

[1]Institute of Geological & Nuclear Sciences Ltd, Wellington

[2]Victoria University of Wellington, Wellington

Abstract

Descriptive accounts and analysis of local seismograms establish that the epicentre of the 1934 March 5 Ms7.6 earthquake, known as the *Pahiatua earthquake*, was nearer to Pongaroa than to Pahiatua. Conspicuous and severe damage (MM8) in the business centre of Pahiatua in the northern Wairarapa lead early seismologists to name the earthquake after the town, but it has now been found that the highest intensities (MM9) occurred about 40km to the east-southeast of Pahiatua, between Pongaroa and Bideford. Uncertainties in the location of the epicentre that have existed for sixty years are now resolved with the epicentre determined in this study lying midway between those calculated in the 1930's by Hayes and Bullen.

Damage and intensity summaries and a new isoseismal map derived from extensive newspaper reports and from 1934 Dominion Observatory "felt reports", replace previous isoseismal maps. Surviving seismograms from the rather small and poorly equipped 1934 New Zealand network of twelve stations (two privately owned) have been read and analysed. The addition of some teleseismic P arrivals results in a stable solution for the epicentre of the mainshock within, and to one end of, the MM9 isoseismal. Larger aftershocks and other moderate magnitude earthquakes that occurred within 10 days and 50km of the mainshock have also been located using local instrumental data. Approximate locations of other moderate magnitude earthquakes until October 1934 have been identified by their maximum intensity and S-P intervals on the Wellington Wood-Anderson seismograph. The distribution of S-P intervals of aftershocks (magnitudes M>3.5) within 24 hours of the mainshock is used to delineate the probable mainshock rupture zone.

Neither contemporary sources nor recent enquiries directed to old residents yield any evidence of a fault break. Nevertheless, the strike-slip mechanism at 20km depth determined by preliminary teleseismic body wave modelling of Doser and Webb suggests that it is a possibility that needs to be considered. Final body wave modelling results will determine whether further investigation of a recently identified fresh-looking, active fault that lies within the MM9 isoseismal is warranted.

Introduction

In March 1934, northern Wairarapa, southern Hawke's Bay and the Manawatu were strongly shaken by a large earthquake, which was felt over a large part of New Zealand. It was severely damaging in the town of Pahiatua. Its surface wave magnitude has been determined as Ms7.6±0.06[1], making it the fourth largest earthquake known to have occurred in 150 years of written history in New Zealand. In that time, New Zealand has experienced many large earthquakes (Figure 1). Most of them occurred before the mid 1940's -- that is, before the New Zealand seismograph network and knowledge of crustal structure and velocities were sufficient to allow calculation of reliable epicentres. To be most useful for seismic hazard studies, it is desirable to have as complete a set of information about an earthquake as possible, including the epicentre, depth, source mechanism, surface faulting (if any), intensity and damage data. Since 1943, not only have there been few large earthquakes but these have not occurred close to large centres of population. Consequently, there are few recent well-constrained isoseismal maps for attenuation studies, and data on the performance of structures and services in urbanized areas at moderate to high intensities are particularly limited.

Between March 1929 and September 1942, eight earthquakes, with magnitudes Ms6.9 or greater (Dowrick & Smith[1]), occurred, each having the potential to provide essential information on damage in high intensity, near-source areas. Two originated in sparsely populated areas of the South Island, but six were in more urbanized areas on the east coast of the North Island, one of the most seismically active regions of New Zealand. These earthquakes are some of the largest in our short recorded history.

Studies have been or are being initiated to quantify their effects and to refine our knowledge of their epicentres, depths, magnitudes and mechanisms, and to understand their tectonic significance. The studies include re-evaluation of the intensity and building damage for the June 1929 Ms7.8 Buller[2], the 1931 Ms7.8 Hawke's Bay[3] and the 1932 Ms6.9 Wairoa[4] earthquakes. By modelling teleseismic body waves Doser and Webb (pers. comm., 1997) have determined source mechanisms and moment magnitudes for seventeen South Island earthquakes, including the 1929 Buller, previously mentioned, and the March 1929 Ms7.1 Arthur's Pass earthquakes. Their modelling of North Island events is in progress. Collection and re-evaluation of data on damage and intensity and re-analysis of seismogram records for the 1942 Wairarapa earthquakes (Ms7.2 and Ms7.0) by Downes *et al.* will begin soon.

Active subduction of the Pacific Plate beneath the Australian Plate occurs along the Hikurangi Trough (Figure 1), with the result that most of the east coast of the North Island experiences moderate to high seismicity. The location of the Pahiatua earthquake in this important area has been uncertain for sixty years. In 1937, Hayes[5] located the epicentre offshore from Castlepoint (1934a, Figure 1) by using seismograms from New Zealand's network of twelve stations. Bullen[6] found a similar location in 1936 but by 1938[7] he had incorporated some teleseismic data into his analysis, obtaining what is called a "global" solution. This yielded more westerly epicentres close to Palmerston North and to Eketahuna (1934b and 1934c, Figure 1), depending on the weightings he gave to different stations. These epicentres are incompatible with Hayes's[5] isoseismal map. At this time, instrumental location was difficult because of the small number of seismographs. Most were quite simple instruments with no magnification and few of them had absolute, or even reliable, timing[9]. In addition, little was known about crustal structure and velocities of seismic waves in New Zealand. Hayes[8] and Bullen[6,7], using data from the large earthquakes of 1931-1934, attempted to identify crustal phases and to calculate their velocities at the same time as they determined epicentres, therefore having too many unknown parameters.

Hayes[5] also located, and lists magnitudes for other moderate to large earthquakes (to October 25 1934), including the March 10 Porangahau earthquakes. The b-value and the rate of decay of aftershocks in the Pahiatua earthquake, the 1931 Ms7.8 Hawke's Bay and the 1942 (Ms7.2 and Ms7.0) Wairarapa earthquake sequences have been calculated by Gibowitz[9]. According to him, the Pahiatua earthquake had fewer than 100 aftershocks with magnitudes greater than 3.3 in the month following the mainshock and another 110 aftershocks in the following six months. From the distribution of S-P intervals recorded at Wellington Gibowitz concludes that the length of the zone containing 90% of the aftershocks was about 70km.

No comprehensive account of the earthquake's effects on buildings and the environment has been published since Hayes's[5] 1937 paper in which he gives only a brief description and isoseismal map (Rossi-Forel scale), which he based on newspaper reports, official felt reports from a network of observers and reports from one of the Geological Survey's staff. The urgent need for important historical earthquakes to have isoseismal maps based on the same scale (Modified Mercalli scale) lead Eiby to compile a map in 1990[10] as an interim measure until comprehensive studies could be completed. Bullen's[7] "c" epicentre was used and Rossi-Forel intensities from official felt reports in the Seismological Observatory's files were converted to the Modified Mercalli scale. With no reports from Pahiatua nor from sparsely populated areas to the east of Pahiatua, Eiby's higher intensity isoseismal lines bear little resemblance to those of Hayes. The problem arises as to which map is more representative of the earthquake.

Ground damage caused by the earthquake has been investigated in Dellow[11], the information being derived from a small number of newspaper accounts. Fairless & Berrill's[12] catalogue of known instances of liquefaction in many large New Zealand earthquakes lists no reports from the Pahiatua earthquake.

This paper describes the results of successfully combining re-reading and analysis of early seismograms with the analysis of descriptive accounts, thus furthering our understanding of this important earthquake sequence.

Damage and intensity distribution of the 1934 Pahiatua earthquake

An important aspect of the early work of the Seismological Observatory was to collect information on the felt effects of earthquakes to assist epicentre location as the instrumental data alone were rarely sufficient until the mid 1940's. The Observatory maintained a file of newspaper cuttings to supplement intensity questionnaires, which often comprised self-assessed Rossi-Forel intensity only, sent in by its network of reporters. Small town newspapers and the main provincial papers were included, but the cuttings rarely extended more than a day or two after the main earthquake and experience has shown that useful material often appears much later. Several sources have been searched to extend the material in the Observatory's archives on the March 1934 earthquakes.

Firstly, the newspaper collection was made as complete as possible—primarily through the resources of the Alexander Turnbull Library. Archives of the Palmerston North, Tararua, Masterton and Wellington City and District Councils, and the Department of Works files in the National Archives were searched for information on building damage. Disappointingly, Works Department Engineers' building-by-building reports for nearly all the smaller towns significantly damaged in the earthquake were not found, although frequent newspaper references show that they were written. Apparently, the reports were considered confidential to building owners and read "in Committee". Very few other accounts have been located, either in the Alexander Turnbull Library or as a result of a January 1997 newspaper article in the *Bush Telegraph*, Pahiatua's local newspaper, requesting information. However, the newspaper reports that have been found are both extensive and detailed.

Several people who lived as children in the area of highest intensity have been contacted, one person supplying useful new information on ridge cracking, extensive landslides on the eastern side of the Puketoi Ranges and to the east of Tiraumea, and most importantly, the frequency of small aftershocks on the morning after the mainshock. His memory of the weather, time, etc. was excellent, probably because the event was marked by having to abandon the family home.

M. Ongley, one of the Geological Survey's geologists on a field survey of the east coast from Cape Turnagain to Castlepoint, also provides some descriptive material and a sketch showing the distribution of landslides[13]. According to Ongley, the damage was greatest to the east of Pahiatua, but everywhere it was less than that caused by the 1931 Hawke's Bay earthquake. Several newspaper articles written by special correspondents sent out to survey the damaged area concur with Ongley's judgement.

Using the above sources, a new isoseismal map of the Ms7.6 1934 March 05 Pahiatua earthquake has been compiled (Figure 2a, Figure 2b). Intensities have been assigned using the 1992 version of the Modified Mercalli scale adapted for New Zealand conditions[14], although use was also made of 1996 modifications suggested by Dowrick[15].

The earthquake was felt over a large part of New Zealand from Auckland in the north to Dunedin in the south. The maximum intensity of MM9 occurred between Waione and Bideford, to the east of Pahiatua, in the northern Wairarapa. Pahiatua and Eketahuna were the most severely damaged townships (MM8), but many other small towns in the Wairarapa, southern Hawke's Bay, Manawatu and Rangitikei were also strongly shaken to intensity MM7.

Damage in the highest intensity zones

Modified Mercalli intensities of MM8 or more occurred over an area of approximately 5000 km^2, the MM8 and MM9 isoseismals having lengths along their major axes of 95 km and 70 km respectively (Figure 2b). Although the total population within this high intensity region was fortunately modest (c. 23,000), serious damage was done to many houses and non-domestic buildings.

While the damage involved life-threatening collapse of parts of buildings, the only casualties were two elderly people (one in Pahiatua, the other in Greytown) with heart illnesses who died of shock, and a woman in Feilding (MM7) who was bruised in bed by falling bricks. The very low casualty count is attributed to the fact that the earthquake occurred in the middle of the night, when most people were in their homes, most of which were timber-framed. If the earthquake had occurred in business hours a modest number of casualties (a dozen or so?) might have occurred, mainly due to the falling of brick gables and parapets of Pahiatua's commercial buildings.

Within the intensity MM9 isoseismal the population was entirely rural, with most buildings being farm buildings of timber construction, and the houses having brick chimneys. In addition to damage associated with the collapse of chimneys, some timber houses suffered heavy damage due to racking, and a few were so damaged as to be uninhabitable, e.g. J. Duncan's house near Tiraumea in the centre of the isoseismal pattern.

Most damage to non-domestic buildings occurred in two of the larger towns in the region of higher intensities, namely Masterton, and Pahiatua, with populations of about 9000 and 1600 respectively. Pahiatua experienced an intensity of MM8, Masterton only MM7. Thus Pahiatua was the town most severely damaged in the earthquake, and damage to buildings there is described below.

According to the remarkably detailed press reports of the time, most chimneys in Pahiatua fell. Two weeks after the earthquake (19 March) the "Pahiatua Herald" reported that there were 412 houses in the borough and 603 chimneys needed repair or rebuilding. As discussed by Dowrick[15] this level of damage to chimneys is consistent with intensity MM8.

Non-domestic buildings in Pahiatua were either one or two-storeyed. Considerable damage occurred to many of the brick ones, with walls wholly or partly falling in a number of buildings. As shown in Figure 3, the upper storey front facade of the Wairarapa Farmer's Cooperative Association's general store fell into the main street.

Other business premises which suffered damage from falling brick walls, parapets or gables were the Tararua Electric Power Board's offices (1 storey), Oxley's buildings (2); Hall-Watson/Timms (2); Taylor tobacconist (2); Woodward's Chemist, et al. (2). Many other buildings had their brick walls cracked to some degree. The roofs of two brick buildings fell in, i.e. Yates' grocery and Hee's fruiterer, and both buildings were described as requiring complete rebuilding.

There appear to have been few, if any, reinforced concrete or steel framed buildings in Pahiatua (its population was only 1600). If there were any, none were reported to be damaged, despite the very detailed listings of damage given in the *Pahiatua Herald.*

Overall the damage in Pahiatua clearly indicates that intensity MM8 was reached. As there were no signs of MM9, the intensity for town is unequivocally MM8.

Although not actually in Pahiatua, the most notable case of an undamaged building in its vicinity and within the MM8 isoseismal is that of the five-storey Tui Brewery (Figure 4) which had been completed shortly before the earthquake. This building was located at Mangatainoka, 5 km northeast of Pahiatua, and hence is the same distance from the major axis of the isoseismals (Figure 2b). The brewery was built of brick-clad reinforced concrete and withstood the shock well. An inspection of the building by R T Hefford in June 1997 showed no signs of it having been cracked at any time. Its construction drawings show the beams and columns to have been only lightly reinforced. Its good performance is presumed to result from the combined action of frame and brickwork, its symmetry, and the small size and good positioning of its wall apertures. Such buildings also tend to do better at higher levels of shaking than implied by the corresponding descriptions of intensity. A two storey brick building, which is visible in an immediately pre-earthquake photograph but which no longer exists, was not reported as being damaged. Some of the other reinforced brick buildings at the Brewery (generally single storeyed) were cracked in the earthquake, but have remained in service until the time of writing, despite being subjected to strong shaking (probably MM7) again in the 1942 earthquakes.

In the MM8 and MM9 zones, there occurred small to moderate landslides, and cracking and slumping of weak soils including road fills. In the Makuri Gorge the road was blocked by landslides and the road itself was broken in numerous places, by cracks about one foot (300 mm) wide and two feet (600 mm) deep, while in a few places the whole road had dropped a foot or more. Estimates of the time required to repair the road varied up to as much as 100 man-weeks.

Reports of (apparently minor) cracking to roads came from many other localities, e.g. over a 20 kilometre length of road between Pongaroa and what was known as the Summit (near Coonoor), over a five kilometre stretch in the vicinity of Bideford, and on the Eketahuna to Alfredton, Pahiatua to Alfredton, Pongaroa to Akitio and Alfredton to Masterton roads. In the country between Tiraumea and Rakaunui the hills were badly cracked along the tops of the ridges.

Disruption to other lifelines was limited to a half a day's hold-up of the railway service between Masterton and Woodville, due to fall of rock at the bluff between Pahiatua and Mangatainoka and slightly twisted rails there and between Newman and Mauriceville. One water main was broken and there was the dislocation of the electricity supply and telephone service in the Pahiatua area.

According to reports to the Tararua Electric Power Board, electric power was lost in both the Pahiatua Borough and in surrounding country districts. Gales over the two days following the earthquake caused further problems and full restoration of power took some days to achieve. The worst effect of the earthquake on the power supply was the damage done in the Pahiatua main street to the overhead power lines which were broken by the falling fronts of some brick buildings.

While the telephones remained working without interruption locally in Pahiatua, most lines out to other centres were not operating for a day or so, because overhead telephone lines had crossed and tangled in many places.

Damage in other areas with intensities less than MM8

Consistent with the magnitude of this earthquake, minor chimney damage and breakage of household and shop goods extended as far as New Plymouth to the west, to Waipawa and Waipukurau to the north and Wellington to the south of the epicentral area. The townships of Dannevirke, Woodville, Masterton, Palmerston North, Foxton and Levin, all located within the MM7 zone, suffered heavy chimney damage as well as some damage to parapets and unreinforced brick walls. Parts of Wanganui also have been assessed as experiencing intensities of MM7. The uneven distribution of chimney damage in that town, heavy in some well-defined areas and light in others, was recognised in newspaper accounts and also by the City Engineer who submitted a sketch to the Council (Figure 5a). Among his accompanying comments, are that houses built on sand "came through with honours" and that the hill section of the city was noticeably little damaged. Although no account was taken of age or the type of construction by the engineer, the map may be useful for comparison with more recent studies estimating the effect of shaking enhancement on sites underlain by deep alluvium within the city.

Evidence of shaking enhancement can be found at other sites, with very localised damage occurring within areas of generally lesser or little damage. For example, Gladstone and Longbush, Moutua and Makerua have intensities MM8 assigned in an otherwise MM7 zone. In Petone, about 140 kilometres from the mainshock epicentre, 40 chimneys were damaged (i.e. MM7), 20 requiring demolition, in one small area of less than $0.5km^2$. Elsewhere in Petone, the intensity seems to have been MM6. In Lower Hutt also, where only a few chimneys were damaged or fallen, most were confined to a small area west of the Hutt River. This is in sharp contrast to Upper Hutt and Eastbourne where damage was slight and mostly confined to a few household items (MM5). Most of the Petone chimneys were reported to be old and built with lime mortar, but they were probably not the only ones of this type in Lower Hutt and Petone at this time. The areas of most damage in Petone and in Lower Hutt both lie in an area designated Zone 5, the highest shaking hazard zone, on the shaking hazard map of the Hutt Valley[16] (Figure 5b). Extensive areas of Zone 5 are also indicated on the shaking hazard map of Wellington[17], but fewer than 10 or 12 chimneys fell in the city and these were not reported as being restricted to any particular location. Stock was damaged in some shops in the city, and in private homes a few items were broken. Overall an intensity of MM6 is indicated, with some areas possibly experiencing MM5 only.

Sand and water ejections and other evidence of liquefaction occurred at several locations in the Wairarapa and Manawatu. At Foxton, extensive sand and water ejections were observed in the old bed of the Manawatu River. Differential subsidence and ground cracking occurred in the railway yards, resulting in the leaning of a goods shed and suspension of the railway line in places. Cracks also formed in river flats in Wanganui and the railway turntable was cracked. At Makerua (near Opiki) in the Manawatu and at Kahutara in the Wairarapa, stopbanks were badly fissured. Sand and water ejection also occurred at Makerua. Although the earthquake occurred at the end of summer, February's rainfall at Palmerston North, presumed to be representative of conditions at Foxton and Makerua, was 50% greater than average (NIWA unpubl. records).

The high rainfall in the month before and immediately after the mainshock may also have contributed to other ground damage. Landslides, slumps and associated road cracks, and rockfalls occurred over a large area, particularly within the MM9, MM8 and MM7 isoseismals and with isolated instances in the MM6 and MM5 zones (Figure 7). Most were relatively minor, those in road cuttings disrupting the traffic for no more than several days despite the widespread heavy rain following the mainshock. Electricity services were disrupted in many places in the lower North Island. Other than in the epicentral area, triggered circuit breakers were the main cause for the power outage. Two water mains were broken, in Wanganui and Pahiatua, although minor leaks occurred in several other places including one in the lower Hutt Valley.

Estimate of magnitude from the isoseismal map

Comparison of the radii of the isoseismal lines with other Ms6.9+ shallow earthquakes, i.e. the 1901 (Cheviot), 1929 (Arthur's Pass), 1929 (Buller), 1931 (Hawke's Bay), 1932 (Wairoa) and 1942 (Wairarapa) earthquakes is shown in Table

1. Estimating the magnitude from the isoseismal attenuation model of Dowrick[18] gives M_s 7.3-7.4 (regardless of mechanism).

Instrumental data

In the early 1930's, the network of seismographs in New Zealand was small (Figure 6) and poorly equipped. This resulted in few good data with which to calculate epicentres let alone attempting to interpret crustal structure and determine wave velocities. Our present understanding of these factors eliminates at least some of the problems experienced by Hayes and Bullen in their locations of the March 1934 earthquakes and it was expected that careful re-reading of phase arrivals from early seismograms and analysis with modern location methods should result in significant improvement in the solutions.

In 1934, a network of twelve seismographs, two of them privately owned and operated, was distributed over the central part of New Zealand, from Arapuni to Christchurch (Table 2 and Figure 6). New Zealand's first short period instrument, a Wood-Anderson seismograph, was installed in Wellington in January 1931 - in time to record the 1931 Hawke's Bay earthquake. It has been continuously in use until recently, although the magnification was doubled in the early 1940's. Christchurch received the second Wood-Anderson in July 1931. Other installations, one Imamura and a number of Milne-Jaggars, followed.

The Milne-Jaggar instrument was a simple design (see Eiby[19]) with virtually no magnification. Its circular smoked paper disk lasted three days, with one circuit being completed per hour. With a speed of 4-8mm per minute records are difficult to read to better than 2-5 seconds accuracy depending on which part of the circle is being read and whether the S arrival can be correctly identified. They had no absolute timing, nor an adequate time marking system, and the drum-rate was irregular at some stations. Nevertheless S-P intervals have been read from the Bunnythorpe and Hastings records.

According to Hayes[5], only Wellington records could be relied upon for consistently accurate absolute time (to 0.5sec), followed in reliability by Christchurch and then Arapuni. The accuracy of timing at Arapuni was limited by the Milne seismograph's inadequate time marking system. In contrast to the Wood-Anderson seismograph, which was designed for recording local earthquakes well, the Milne seismograph was better for recording teleseismic waves, with sensitivity to long period waves and with a recording speed of 4mm/minute. Errors in reading phase arrivals on this instrument are probably greater than the timing errors and could be as much as 5 seconds, whereas phase arrivals on Wellington can be read to within 0.5 sec (Wood-Anderson drum speed 30mm/minute; magnification 1400).

The Seismological Observatory's archives contain many early seismograms. Phase arrivals have been re-read from those that could be found (see Table 2). Other phase arrivals were taken from the 1934 Seismological Reports[20], using S-P intervals when the P and S arrival times were obviously incorrect. As the Imamura record of the mainshock is missing, the S-P interval was read from a reproduction of the trace in Hayes[5]. At nearly all stations the amplitude of the motion beyond the first 10-15 seconds of the mainshock overloaded the instrument. At Bunnythorpe the displaced needle required manual replacement, losing 6 minutes of trace. After that, the drum rate seems to have become irregular and correlation of subsequent earthquakes with other stations is consequently difficult.

Despite these deficiencies, the old seismograms have been re-read. For the most part, the times of Wellington P-arrivals for well recorded events differ from 1934 readings by less than 1.0 sec (for one event, P and S arrivals differ by 19 sec, indicating reader error). S-arrivals differ by a greater amount, probably due to alternative interpretations. The most significant differences in readings are from Arapuni records, the P arrival being read 3 sec earlier than in 1934 for the mainshock and first major aftershock. In addition, this arrival is interpreted as P* (lower crustal P wave) rather than Pn as a means of recognising that the first arrival is likely to have been emergent and undetectable on a Milne records. For comparison, digital seismograms from the May 1990 Weber earthquake (just north of the new 1934 epicentre) from a station near Arapuni have been examined. These show an emergent arrival followed by a several stronger phases, the strongest of which may be the P* arrival.

The solution for the mainshock, which includes teleseismic data, and local station solutions for other major events are given in Table 3 and Figure 7. The estimated location error for any of the earthquakes is no less than 20km and possibly as great as 40km. Because of the good quality of readings on the Wellington Wood-Anderson instrument and the lesser quality of readings from Arapuni and Bunnythorpe, east-west control of the epicentres is poorer than north-south. Local magnitudes (M_L) of the earthquakes are derived from the Wellington Wood-Anderson records. The maximum amplitude for the mainshock, and possibly the aftershock at 1157, cannot be detected. Dowrick and Smith[1] give Ms7.6 for the mainshock magnitude.

Mainshock

The International Seismological Summary (ISS) for 1934 reports 62 teleseismic P readings from Australia, Asia and the Americas as well as 11 New Zealand observations for the March 5 mainshock. Residual times (observed arrival time-calculated arrival time) for these readings ranges from 1-3 seconds to as much as a few tens of seconds compared to modern P residuals of 1-2 seconds. The then greater observational errors arose from poorer clocks and slower rotating and lower-magnification seismographs.

The addition of the better teleseismic data to the local station data yields a solution for the epicentre (40.51S 176.29E; depth fixed at 12km; Figure 6 and 7), that differs, by less than 10km from the epicentre derived from local stations only. The mainshock epicentre is better constrained than any other earthquake in the sequence and the solution is not sensitive to the omission of any one local station. The epicentre lies within the highest intensity (MM9) isoseismal (Figure 7).

The data are too few and the nearest stations too distant to permit an estimate of the depth of the 1934 March 5 shock (or any other shock in March 1934) to be made that would be of a quality comparable to that of modern assessments. However, the arrival time data suggest that the earthquake was shallow, i.e. probably not deeper than about 25km. This conclusion is inferred from the "free depth" location using the best local and teleseismic data, which yielded a depth of 12km (formal standard deviation 7km). A shallow depth is consistent with the observed intensities.

A preliminary solution has been obtained by modelling teleseismic body waves (Doser, pers. comm. 1997). Strike-slip faulting at 20km ± 3km depth is indicated, with a near vertical nodal plane striking at 45° ± 8° preferred as the fault plane as it aligns with the MM9 isoseismal. However, the moment magnitude obtained was only 6.7 suggesting that significant energy was not recorded by the limited bandwidth instruments in use at the time.

Aftershocks and other related earthquakes

The highest magnitude aftershock within a month of the mainshock, $5.8 \geq M_L \geq 5.3$ occurred ten minutes after it. Phases are difficult to identify confidently for this earthquake as it is not only lost in the coda of the mainshock on many stations but also it seems to have been preceded by a smaller magnitude event (possibly M_L5.0). The highest amplitude that can be seen on the Wood-Anderson seismogram indicates a magnitude of M_L5.3 but it is possibly not the maximum, as comparison with the earthquakes on March 10 and 15 suggests that the magnitude should be greater, possibly as much as M_L5.8. The higher magnitude is consistent with press reports that the earthquake was widely felt from Wellington to New Plymouth, in the Waikato and in Wairoa. The local station solution places the epicentre about 30km southwest of the mainshock epicentre (Figure 6, 7; Table 3).

About thirty minutes after the mainshock two earthquakes occurred with only a few seconds between them (about M_L4.6 and M_L4.8). These were interpreted in 1934 as one larger event (M_L5.1). However, the amplitudes on the Hastings and Bunnythorpe records and the press reports are inconsistent with the higher magnitude. Interpreting phases for the two earthquakes from the seismograms is difficult and the locations are very uncertain as a consequence. The S-P intervals are similar to the largest aftershock.

It is possible that other large aftershocks are undetected in the mainshock coda. In particular, the Wellington Milne-Jaggar shows a burst of energy about 70 seconds after the beginning of the mainshock, which might be detectable on teleseismic records.

On March 6 1934, just over 24 hours after the mainshock, a moderate magnitude event (M_L5.2; Figure 6, 7) occurred offshore about 70km southeast of the mainshock. Another large event, located using teleseismic as well as local data, occurred 150km northeast of the mainshock on March 15 (M_L6.0, M_s6.5) (Figure 6). Both locations are consistent with their respective intensity distributions (March 6, this paper; March 15, Dowrick pers. comm.).

Further moderate magnitude earthquakes, the Porangahau earthquakes, occurred on March 10. Three earthquakes within an hour (M_L5.6, M_L4.6, M_L5.0) were responsible for damage to chimneys in Porangahau, stated to be comparable with the damage from the March 5 earthquake. The instrumental location of the first and largest event (ML5.6) is 30km south of Porangahau, while the solutions for second and third earthquake places them within 20-25km east-south-east of Porangahau. Because of their smaller magnitudes these events are not as well constrained as the March 5 mainshock and all are sensitive to phase identification at Arapuni. The lack of damage in Cape Turnagain communities, which are closer to the magnitude 5.6 event than Porangahau, suggests that at least the first earthquake may be mislocated by 20km or more.

Possible errors in location make it difficult to decide if the Porangahau events represent an extension of the mainshock rupture or are off-fault, possibly stress-triggered events. Historically, many events have occurred at locations distributed about Cape Turnagain, the latest being the 1990 Weber earthquakes, the earliest known in 1892 (Downes unpubl. data), and the most recent before 1934 in February 1930 (Downes unpubl. data).

Although many smaller aftershocks were recorded on Wellington Wood-Anderson records only the events already mentioned can be located. P and S arrivals or S-P intervals of all recognisable aftershocks until the end of March have been read where possible. Histograms of the S-P intervals after 24 hours, until March 10 (up to the Porangahau earthquakes), and to the end of March are shown in Figure 8. Gibowitz[9] gives similar diagrams. His distributions, however, included the March 6 and March 15 events and possibly several other events that did not have origins in the epicentral area.

The distribution of the mainshock and major aftershock epicentres and the NE-SW alignment of the inner isoseismals suggests possible NE-SW rupture. The distribution of the S-P intervals of the aftershocks might then be expected to define the extent of the rupture plane. Some aftershocks, particularly those with short S-P intervals, can be correlated with felt information and are consistent with epicentres about Bideford, i.e. they were noticed more around Masterton and the east of Masterton than in Dannevirke.

Gibowitz[9] concluded that 90% of all aftershocks (over more than six months) occurred in a zone about 70km long, which he took to represent the length of the mainshock rupture. Usually, the distribution of aftershocks in the first 24 hours is considered the best indicator of the mainshock rupture zone. The 24-hour S-P intervals, determined here, span about 5.5sec, suggesting a rupture length of about 50km. The 5-day intervals span about 11.5sec, or about 90km, with two events having S-P's greater (by 2.5-3sec) than the mainshock. At least one of the events had a similar S-P to the M_L5.2 earthquake offshore and occurred only six hours after it, and therefore may have been an aftershock of it. The histogram suggests that these two events and the Porangahau events with similar S-P intervals are probably not part of the mainshock rupture zone. However, they may be an extension of the main rupture or stress-triggered, off-fault earthquakes . By excluding them, the S-P intervals span just over

8sec or about 65km. It is concluded that the mainshock rupture was probably close to 50km long but may have extended to at most 65km.

Fault ruptures of this size are consistent with the estimated magnitude. Assuming a average stress drop of $3x10^6 N/m^2$ (30 Bar) and a fault width of 25 km (appropriate for a shallow strike-slip event above the plate interface) gives an M_w of 7.4 for a rupture length of 50 km or 7.6 for 65km. A higher stress drop or greater fault width would increase M_w.

The Wellington records show that about 30 aftershocks over magnitude 3.5 occurred in the first 24 hours. Comparison with the 24-hour aftershock numbers for the 1931 M_s7.8 Hawke's Bay earthquake (170 events with $M_L \geq 3.8$) and the June 1942 M_s7.2 earthquake (80 events with $M_L \geq 3.5$) (both numbers are from Gibowitz[9]) shows that the number of aftershocks in the Pahiatua earthquake aftershock sequence is somewhat small for a large shallow earthquake. Further, the number of aftershocks decreases rapidly after the first day and fewer than 80 magnitude 3.3 and above aftershocks (either of the Pahiatua mainshock or the Porangahau events) had occurred by the end of March.

In the eight months following the mainshock six earthquakes with magnitudes 4.0 -5.5 (Figure 7 and Table 4) were strongly felt at locations from just north of Masterton to near Ti-Tree Point and Wimbledon, the April 14 (M_L5.5) event bringing down some newly repaired chimneys at Ti-Tree Point. Their S-P intervals and available intensity data show that they were shallow and within or just outside the area defined by the aftershocks that occurred within the first month. Other events occurred in November and December, but the Wellington records have not been read for these events, as Observatory files of "felt" reports and newspaper clippings indicate no definite high MM intensity area to confirm their locations.

Evidence for surface faulting and uplift

The magnitude of the Pahiatua earthquake and its preliminary depth and mechanism determined by Doser (pers. comm., 1997) suggest that rupture could have extended to the surface. However, no contemporary account nor any recent enquiries from old settlers indicates that any rupture was noticed. Further, Ongley, who was completing his survey of the east coast between Castlepoint and Cape Turnagain at the time of the mainshock, made a tour of the strongly shaken areas immediately after the first earthquake looking for a surface trace[13] without success. He also made enquiries about reported uplift of the coast around Cape Turnagain but replies on our files[13] from coastal station owners were inconclusive. Given the location, magnitude, depth and mechanism no uplift would be expected, nor would it be expected on the coast if the mechanism of the earthquake was thrust. There is no geological evidence of recent significant uplift in this region (Ota et al[21]).

Directivity

Based on the assumption that the highest intensity zone and the distribution of the mainshock and major aftershocks and S-P intervals in the first 24 hours are indicative of the location and extent of rupture in a large shallow earthquake, the March 5 Pahiatua earthquake rupture is oriented northeast-southwest and extends from 50km length (predicted from 24hour data) to no more than 65km length (predicted from 5 day data). The solution for the mainshock, which incorporates teleseismic and local instrumental data, places the epicentre at the northeastern end of the rupture zone, consistent also with its S-P interval being the highest in the first 24 hours. If this location is less in error than the analysis of location error would suggest, then it could be concluded that the rupture proceeded from northeast to southwest and that evidence of directivity might be found in the intensity data or the teleseismic records.

However, the evidence for directivity in the intensity pattern is not strong. Although the MM9 isoseismal (Figure 7) shows strong NE-SW elongation with an along strike length of 70km, this length is 20km more than the minimum rupture length (50km) but only marginally more than the inferred maximum rupture length (65km). The fact that the MM8 isoseismal does not parallel the MM9 isoseismal, i.e. there is little MM8 zone in the southwest, could suggest that the MM9 isoseismal is extended relative to the MM8 zone, reflecting directivity. However, directivity should be reflected in all inner isoseismals.

Other evidence may be found by plotting the centres of symmetry of the MM4-MM9 isoseismals, measured along strike of the MM9 isoseismal. These indicate a slightly more rapid decay to the northeast than to the southwest (more noticeable in the MM4-MM6 isoseismals).

There is also some evidence that ground damage and/or shaking enhancement is more prevalent and more significant to the southwest (and west) of the rupture zone than to the north or northeast, whereas equally susceptible areas exist in both directions. For example, landslides and instances of liquefaction occurred fairly symmetrically in the 1904 M_s6.9 Cape Turnagain earthquake (Downes[22]) whose epicentre was about 40km east of the Pahiatua earthquake. As environmental effects are a less definitive criteria when assigning intensity the severity of ground damage is not always apparent in intensities on an isoseismal map. Also not apparent in the intensities allocated is the nature of the shaking described in written accounts. This indicates a dominance of long period waves to the northeast of the 1934 epicentre.

Directivity may be seen in the pattern of M_s observations at individual instrumental stations, these being, potentially, higher in the direction of rupture than in other directions. The teleseismic stations reporting M_s for the 1934 earthquake show no such effect. However, they are very poorly distributed to do so, with no observations at all at azimuths approximately NE or SW.

Discussion

This study on the Pahiatua earthquake has been successful in achieving its objectives of providing reliable and extensive data on both the location and the effects of the mainshock and other related shocks. Given the modest quality and small number of early seismograms leading to an estimated epicentral location error of 20-40km, such good agreement of the instrumentally derived epicentres of the March 1934 earthquakes with their respective zones of highest intensity is encouraging. Indeed, the epicentres and the S-P data from Wellington are sufficiently consistent in their locations that inferences can be made about the location and extent of the rupture, and the distribution of aftershocks.

The fortunate location of the Wellington seismograph almost along strike to the southwest of the inferred rupture zone provided an opportunity to examine the distribution of aftershocks—an opportunity that would be rare in an era of such poor instrumentation. The close relationship between the Pahiatua earthquake and the Porangahau earthquakes five days later has always aroused curiosity. The close proximity in space and time of the Porangahau earthquakes suggests that they were almost certainly triggered, although whether along strike or off-fault is uncertain because of location error. The histogram (Figure 8) shows the growth of the aftershock zone with time, with apparently more events occurring towards the southwest than to the northeast. However, the record of the more distant northeast events may not be complete. Some of the late aftershocks, occurring up to 5 months later, are well located by their felt information (Figure 7), which also indicates that they are probably quite shallow. When the teleseismic studies of the mainshock are complete and the source mechanism is known, the distribution of the aftershocks may be of interest for comparison with stress triggering models of King *et al*[23].

Of perhaps even greater interest will be the relationship of the 1942 Wairarapa earthquakes to the 1934 earthquake. A possible surface rupture in the June 1942 earthquake (Ongley[24]) is less than 30km from the largest aftershocks of the 1934 shock and within 10km of the some of its later aftershocks (Figure 7). Source mechanisms of the three 1942 earthquakes (June Ms7.2, August Ms7.0 and December Ms6.0) from continuing studies of Doser and Webb and planned seismological and engineering studies of the same earthquakes will contribute greatly to our understanding of the tectonics of the sequence from 1934 to 1942.

When the depth of the mainshock and its source mechanism have been determined with more certainty, discrepancies in magnitude (M_s, M_w, M (from attenuation models)) will need resolution. Although the instrumental location determined in this paper indicates that the mainshock occurred at shallow depth, teleseismic body wave modeling of Doser and Webb will give a more accurate estimate and the location of the earthquake within the upper part of the subducted plate or within the overlying Australian Plate will be able to be determined. At present, the preliminary solution of a strike-slip mechanism at 20km depth, makes the recent recognition by Berryman *and others* (unpubl. data) of a fresh-looking, active fault close to the inferred rupture zone (Figure 7) exciting but further studies will need to be initiated to determine whether the latest movement was in 1934. Shallow strike-slip faulting in this region of the east coast is consistent with the model of slip partitioning along the Hikurangi margin (e.g. Webb & Anderson[25]).

Acknowledgements

This research has been jointly funded by the Earthquake Commission and the Foundation for Research, Science and Technology. We would like to thank Dick Hefford for inspection and photograph of Tui Brewery, Mangatainoka, Carolyn Hume for her careful execution of the diagrams, and Terry Webb and Martin Reyners for helpful comments which have improved the text.

References

1. Dowrick, D. J., Smith, E. C. G. 1990. Surface wave magnitudes of some New Zealand earthquakes 1901-1988. *Bulletin of the New Zealand National Society for Earthquake Engineering* 23: 198-210.

2. Dowrick, D. J. 1994. Damage and intensities in the magnitude 7.8 1929 Murchison, New Zealand, earthquake. *Bulletin of the New Zealand National Society for Earthquake Engineering* 27: 190-204.

3. Dowrick, D. J. In preparation. Damage and intensities of the magnitude 7.8 Hawke's Bay, New Zealand, earthquake of 1931.

4. Dowrick, D. J. In preparation.

5. Hayes, R. C. 1937. The Pahiatua earthquake of 1934 March 5. *New Zealand journal of science and technology* 19: 382-388

6. Bullen, K. E. 1936. On near earthquakes in the vicinity of New Zealand. *New Zealand journal of science and technology* 18 493-507.

7. Bullen, K. E. 1938. On the epicentre of the 1934 Pahiatua earthquake. *New Zealand journal of science and technology* 20: 62-66.

8. Hayes, R. C. 1935. Seismic waves and crustal structure in the New Zealand region. *New Zealand journal of science and technology* 17: 519-528.

9. Gibowitz, S. J. 1973. Variation of the frequency-magnitude relation during the 1931 Hawke's Bay, 1934 Pahiatua, and 1942 Wairarapa aftershock sequences. *New Zealand journal of geology and geophysics* 16: 1009-1045.

10. Downes, G. L. 1995. Atlas of isoseismal maps of New Zealand earthquakes. *Institute of Geological & Nuclear Sciences monogragh 11.* Institute of Geological & Nuclear Sciences Ltd., Lower Hutt, New Zealand.

11. Dellow, G. D. 1988. Earthquake generated landslides in the Wellington-Lower Hutt area. *MSc Thesis*. University of Canterbury, Christchurch, New Zealand.

12. Fairless, G. J., Berrill, J. B. 1984. Liquefaction during historic earthquakes in New Zealand. *Bulletin of the New Zealand National Society for Earthquake Engineering* 17: 280-291.

13. Ongley, M. 1934. (Unpublished) Collection of Ongley's letters and sketches relating to the 1934 Pahiatua earthquake to the Director of the Geological Survey. File also includes letters to the Geological Survey from coastal landowners regarding coastal uplift. Institute of Geological & Nuclear Sciences Ltd. files

14. Study Group of the New Zealand National Society for Earthquake Engineering 1992. A revision of the Modified Mercalli seismic intensity scale. *Bulletin of the New Zealand National Society for Earthquake Engineering* 25: 345-356.

15. Dowrick, D. J. 1996. The Modified Mercalli earthquake intensity scale - revisions arising from recent studies of New Zealand earthquakes. *Bulletin of the New Zealand National Society for Earthquake Engineering* 29: 92-106.

16. Van Dissen, R. J., Taber, J. J., Stephenson, W. R., Sritheran, S., Read, S. A. L., McVerry, G. H., Dellow, G. D., Barker, P. R. 1992. Earthquake ground shaking hazard assessment for the Lower Hutt and Porirua areas, New Zealand. *Bulletin of the New Zealand National Society for Earthquake Engineering* 25: 286-301.

17. Wellington Regional Council. 1992. Seismic Hazard Map Series: Ground shaking hazard. Map sheet 1 Wellington (1st edition) 1:20000 with notes. Compiled by Kinsbury, P. A.; Hastie, W. J.

18. 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.

19. Eiby, G. A. 1982. New Zealand Seismological Report 1948-49-50. *Seismological Observatory [New Zealand] Bulletin E-164.*

20. *Dominion Observatory (New Zealand) bulletin E40.* Seismological Reports for January, February, March 1934.

21. Ota, Y., Berryman, K., Fellows, D., Hull, A.., Ishibashi, K., Iso, N., Miyauchi, T., Miyoshi, M., Yamashina, K. 1990. Sections and profiles for the study of Holocene coastal tectonics, Gisborne - Cape Palliser, North Island, New Zealand. *New Zealand journal of geology and geophysics* 38: 269-282.

22. Downes, G. L. In preparation. The 1904 Cape Turnagain, New Zealand, earthquake.

23. King, G. C. P., Stein, R. S.,Lin, J. 1994. Static stress changes and the triggering of earthquakes. *Bulletin of the Seismological Society of America* 84: 935-953.

24. Ongley, M. 1943. Wairarapa earthquake of 24th June, 1942, together with a map showing surface traces of faults recently active. *New Zealand journal of science and technology* B25: 67-78.

25. Webb, T. H., Anderson, H. Focal mechanisms of large earthquakes in the North Island of New Zealand: Slip partitioning at an oblique active margin. *Geophysical Journal International.* (submitted)

Figures

Figure 1. Map of New Zealand showing the locations of large earthquakes 1840-1996. The map includes epicentres determined by Hayes (a), and Bullen (b,c) but not that determined in this study. The inset shows the main tectonic features of plate convergence.

Figure 2. **a.** Isoseismal map of the 1934 Pahiatua earthquake. **b.** Detailed map of the MM6-MM9 intensity areas. The map also shows the instrumental epicentre for the mainshock (+). **c.** Map showing locations mentioned in the text.

Figure 3. View along the main street of Pahiatua, showing the collapse of the brick facade of the upper storey of the Wairarapa Farmer's Cooperative Association store. (Reproduced by courtesy of the Alexander Turnbull Library, NLNZ, Wellington, New Zealand)

Figure 4. A view of the five-storey Tui Brewery building at Mangatainoka, near Pahiatua. This brick clad, reinforced concrete frame building was undamaged. (Photograph by R. T. Hefford, 1997)

Figure 5. (**a**) Sketch of the distribution of chimney damage in Wanganui in the Pahiatua earthquake, prepared for the Council by the Council Engineer in March 1934. (Sketch supplied by the Wanganui City Council Archives.) (**b**) Location of chimney damage in Petone within Zone 5 of the Ground Shaking Hazard map fro the Lower Hutt area (after Van Dissen *et al*[16])

Figure 6. Map showing the locations of seismographs in 1934 and instrumentally derived epicentres of the Pahiatua and Porangahau earthquakes in March 1934.

Figure 7. Map showing the instrumental locations of the Pahiatua and Porangahau earthquakes, major aftershocks and later aftershocks in relation to the MM6-MM9 isoseismals. The map also shows the location of Berryman *et al*'s recently recognised active fault and the location of the only reliable surface rupture in the June 1942 earthquake. The shaded area shows the distribution of ground damage.

Figure 8. Histograms of S-P intervals on the Wellington Wood Anderson seismograms; after 24 hours; after 5 days (i.e. until the occurrence of the Porangahau earthquakes); until the end of March 1934.

Tables

Table 1. Comparison of the isoseismal "radii" of the 1934 March 5 Pahiatua earthquake with other Ms6.9+ New Zealand shallow strike-slip events. The values listed are d_s (semi-axis along strike) and d (mean horizontal radius).

Table 2. The New Zealand Network of seismographs, 1934. * - indicates records that have been re-read.

Table 3. Instrumentally derived epicentres for the 1934 March 5 Pahiatua earthquake, its major aftershocks and the 1934 Porangahau earthquakes. Location of the March 5 event includes teleseismic data as well as local station data.

Table 4. Wellington S-P intervals and maximum MM intensities and their location for well recognised later aftershocks (March -October) of the Pahiatua earthquake.

Table 1.

MMI	d_s						
	1901 M6.9	1929 7.1	1929 7.8	1931 7.8	1932 6.9	1942 7.2	1934 (Prelim) M?
4	256	360	-	749	378	407	373
5	180	244	431	315	230	239	238
6	128	96	281	216	94	146	102
7	64	-	185	150	-	87	69
8	32	28	98	96	50	44	48
9	-	-	40	43	20	-	35

MMI	$\bar{d}$						
	1901 M6.9	1929 7.1	1929 7.8	1931 7.8	1932 6.9	1942 7.2	1934 (Prelim) M?
4	-	-	-	-	-	377	393~370
5	162	198	-	-	-	233	266~260
6	101	84	243	165	93	135	114~117
7	44	-	157	108	-	77	75~66
8	21	20	82	68	34	39	40~36
9	-	-	27	34	25	-	21~26

Table 2.

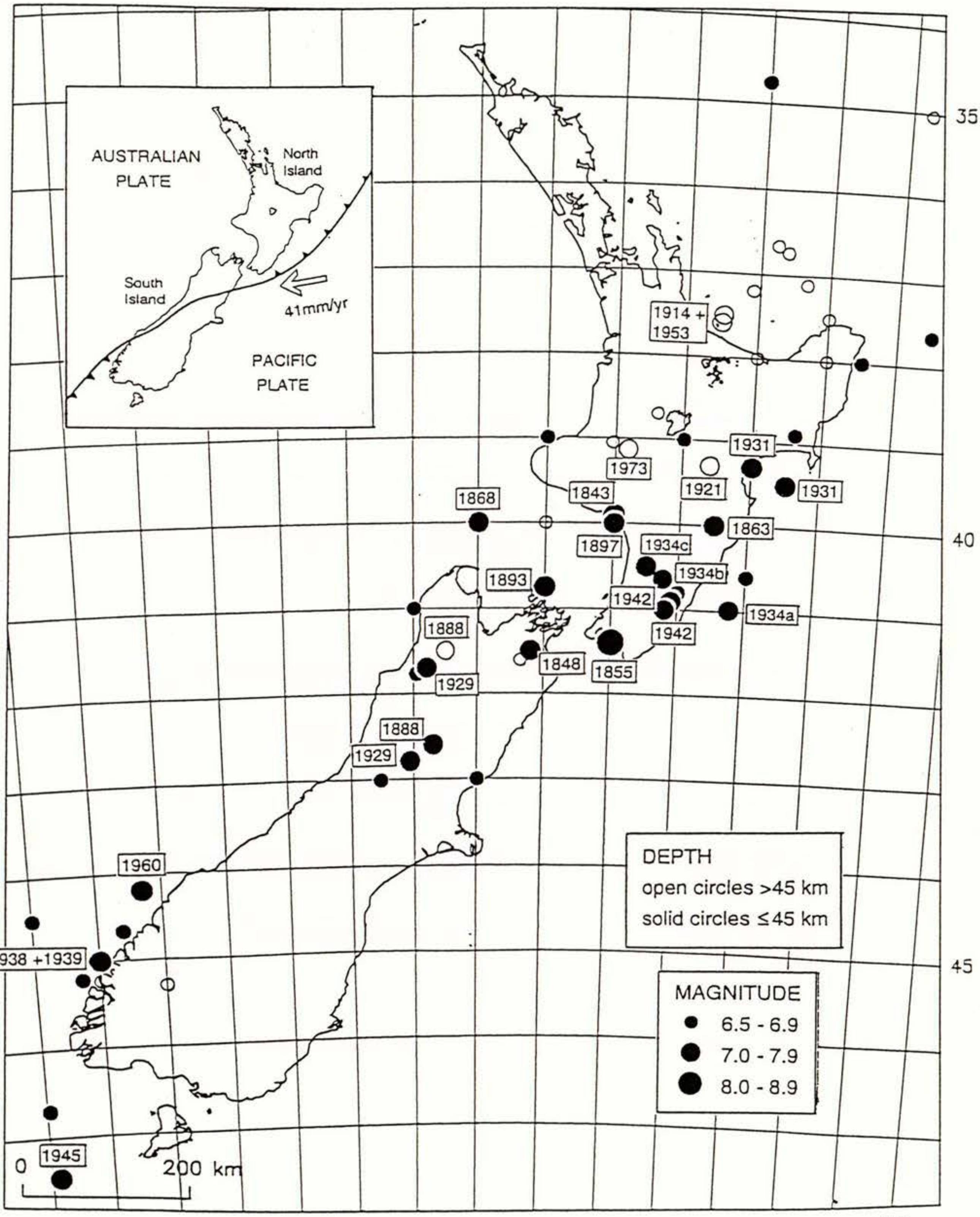
Station	Instrument	Drum rate	Records available
Arapuni (ARA)	Milne	4mm/minute	all
Tuai (TUA)	Milne-Jaggar	variable, from 4-10mm/minute	
New Plymouth (NPZ)	Wood-Anderson	30mm/minute	
	Milne-Jaggar		Mar 15 only
Hastings (HAS)	Milne-Jaggar		all
Dannevirke (DNN)*	Milne-Jaggar		
Bunnythorpe (BUN)	Milne-Jaggar		all
Takaka (TAK)	Imamura		except March 5
Wellington (WEL)	Wood-Anderson		all
	Galitzin-Wilip		all
	Milne-Shaw		all
	Milne-Jaggar		all
Greymouth (GRY)	Milne-Jaggar		
Glenmuick (GLE)*	Inverted pendulum		
Christchurch (CHR)	Wood-Anderson		
	Galitzin-Wilip		
Chatham Islands	Milne		from March 15

Table 3

Year	Date	Time (UT)	Lat °S	Long °E	Depth	Magn.	Max. MM intensity	Location
1934	Mar 05	1146 13	40.5	176.3	12R	M_s7.6, M_w6.9 (prelim.)	MM9	Approx. Waione to Bideford
		1157 42	40.7	176.0	12R	about Ml5.8		
		1221 20	40.7	176.0	12R	Ml4.8		
	Mar 06	1252 24	41.1	176.4	12R	Ml5.2	MM4	Widely felt in southeast North Island
	Mar 10	0757 11	40.6	176.7	12R	Ml5.6	MM7	Porangahau
	Mar 10	0803 43	40.4	176.9	12R	Ml4.6		Porangahau
	Mar 10	0853 53	40.4	176.8	12R	Ml5.0		Porangahau

Table 4.

Year	Date	Time (UT)	Wellington S-P interval	Magn.	Max MM intensity	Location
1934	Apr 14	0818	10.6	Ml4.2	MM4	Masterton
	Apr 14	0848	20	Ml5.5	MM7	Ti Tree Point, Wimbledon
	Apr 20	1658	15	Ml4.7	MM4	Masterton, Pahiatua, Dannevirke
	May 01	0941	9.2	Ml4.8	MM6	Mauriceville
	Aug 08	0005	10.8	Ml4.0	MM5	Bideford (possibly two events)
	Aug 08	2030	11.2	Ml4.5	MM4	Masterton



AUSTRALIAN PLATE
North Island
South Island
41mm/yr
PACIFIC PLATE
35
40
45
170
175
180
1914 + 1953
1973
1931
1931
1921
1843
1868
1897
1863
1934c
1934b
1893
1942
1942
1934a
1888
1848
1855
1929
1888
1929
1960
1938 +1939
1945
0
200 km
DEPTH
open circles >45 km
solid circles ≤45 km
MAGNITUDE
6.5 - 6.9
7.0 - 7.9
8.0 - 8.9

Fig 1

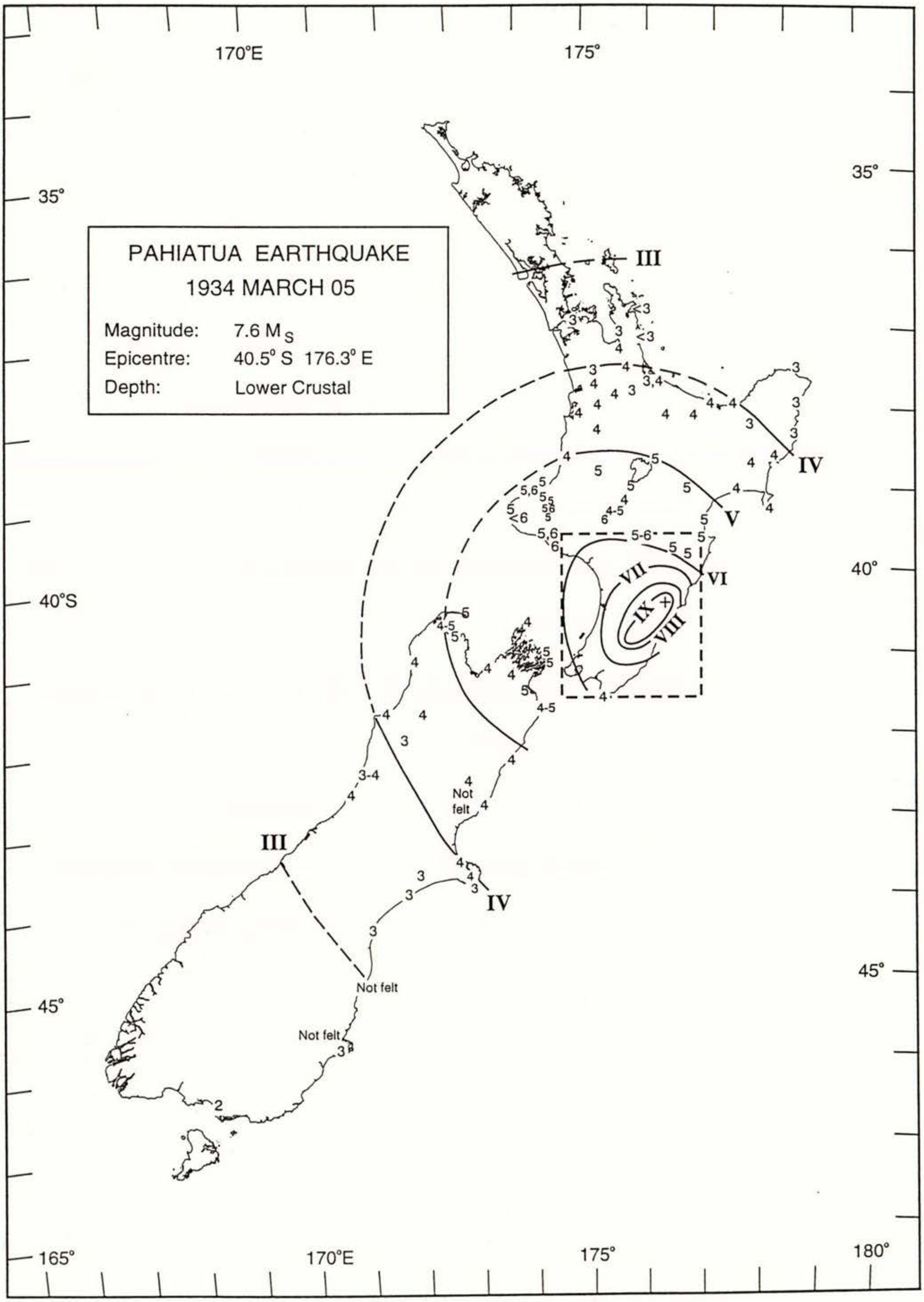

PAHIATUA EARTHQUAKE
1934 MARCH 05
Magnitude: 7.6 M S
Epicentre: 40.5° S 176.3° E
Depth: Lower Crustal
170°E
175°
35°
40°S
40°
45°
165°
180°
III
IV
V
VI
VII
VIII
IX
Not felt

FIG 2a

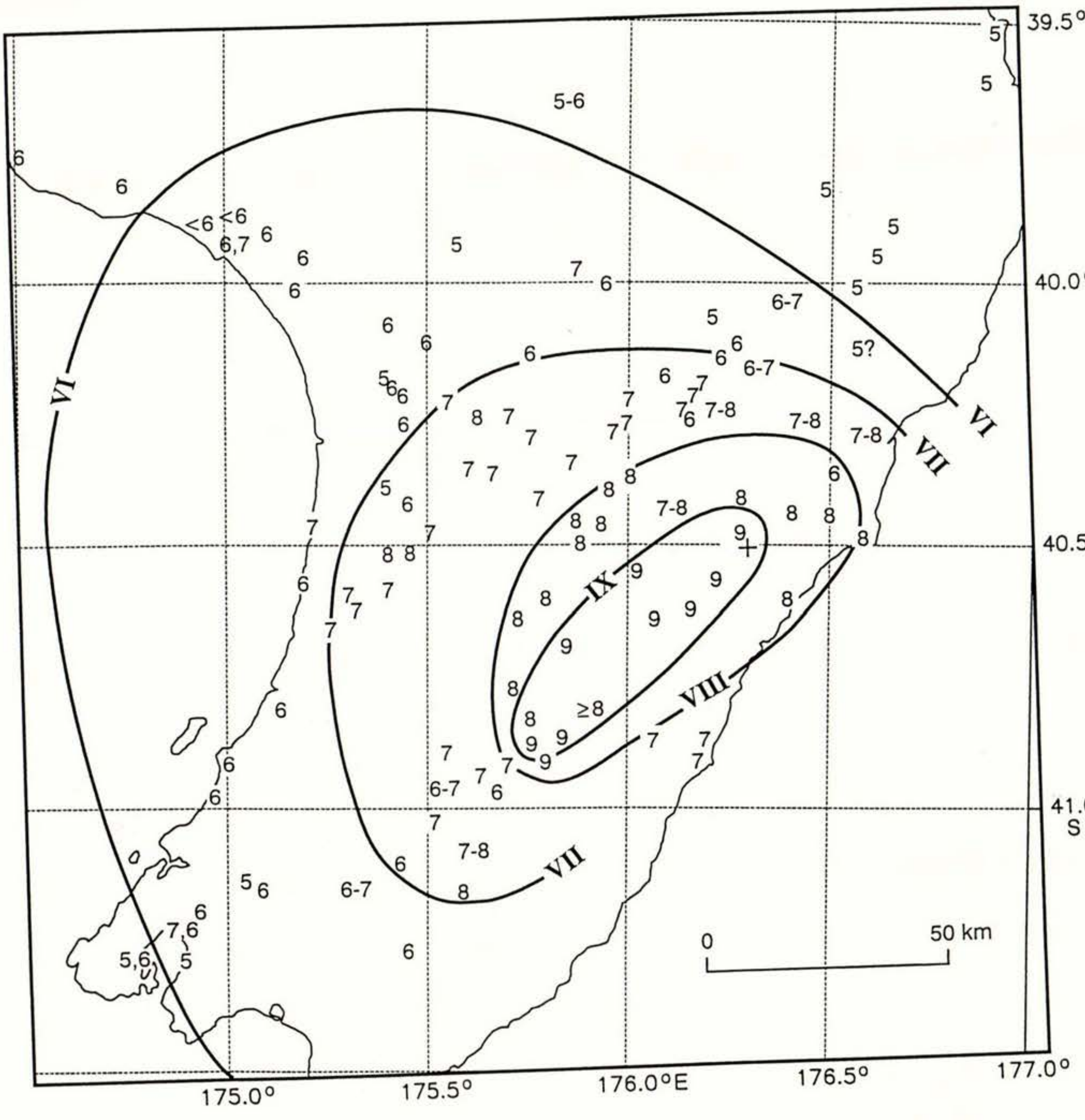
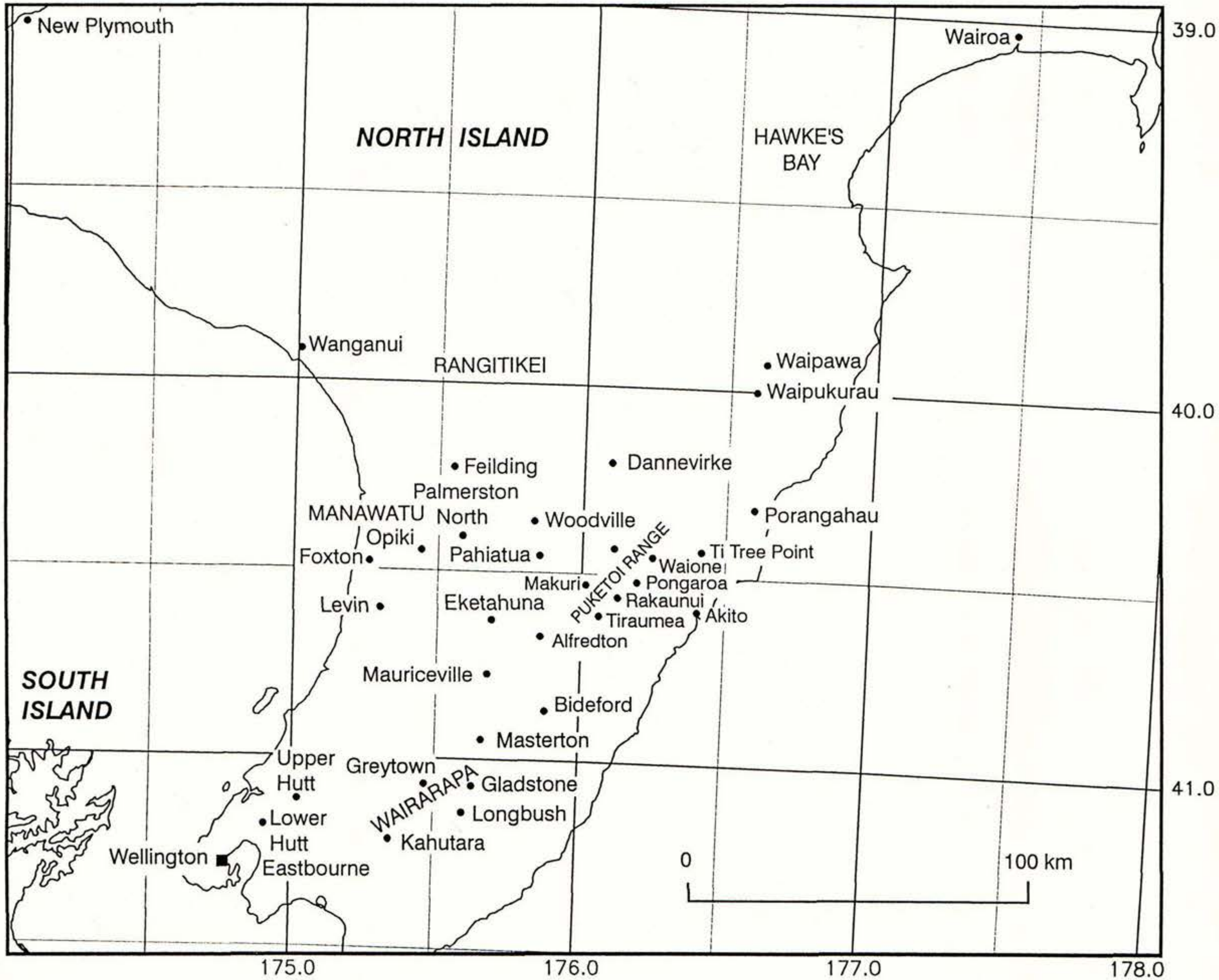


FIG 2b

gaye/1934/detail2



New Plymouth
NORTH ISLAND
HAWKE'S BAY
Wairoa
39.0
Wanganui
RANGITIKEI
Waipawa
Waipukurau
40.0
Feilding
Dannevirke
Palmerston North
MANAWATU
Woodville
Porangahau
Opiki
Foxton
Pahiatua
PUKETOI RANGE
Ti Tree Point
Waione
Makuri
Pongaroa
Rakaunui
Levin
Eketahuna
Tiraumea
Akito
Alfredton
SOUTH ISLAND
Mauriceville
Bideford
Masterton
Upper Hutt
Greytown
Gladstone
WAIRARAPA
41.0
Lower Hutt
Longbush
Kahutara
Wellington
Eastbourne
0
100 km
175.0
176.0
177.0
178.0

FIG 2c

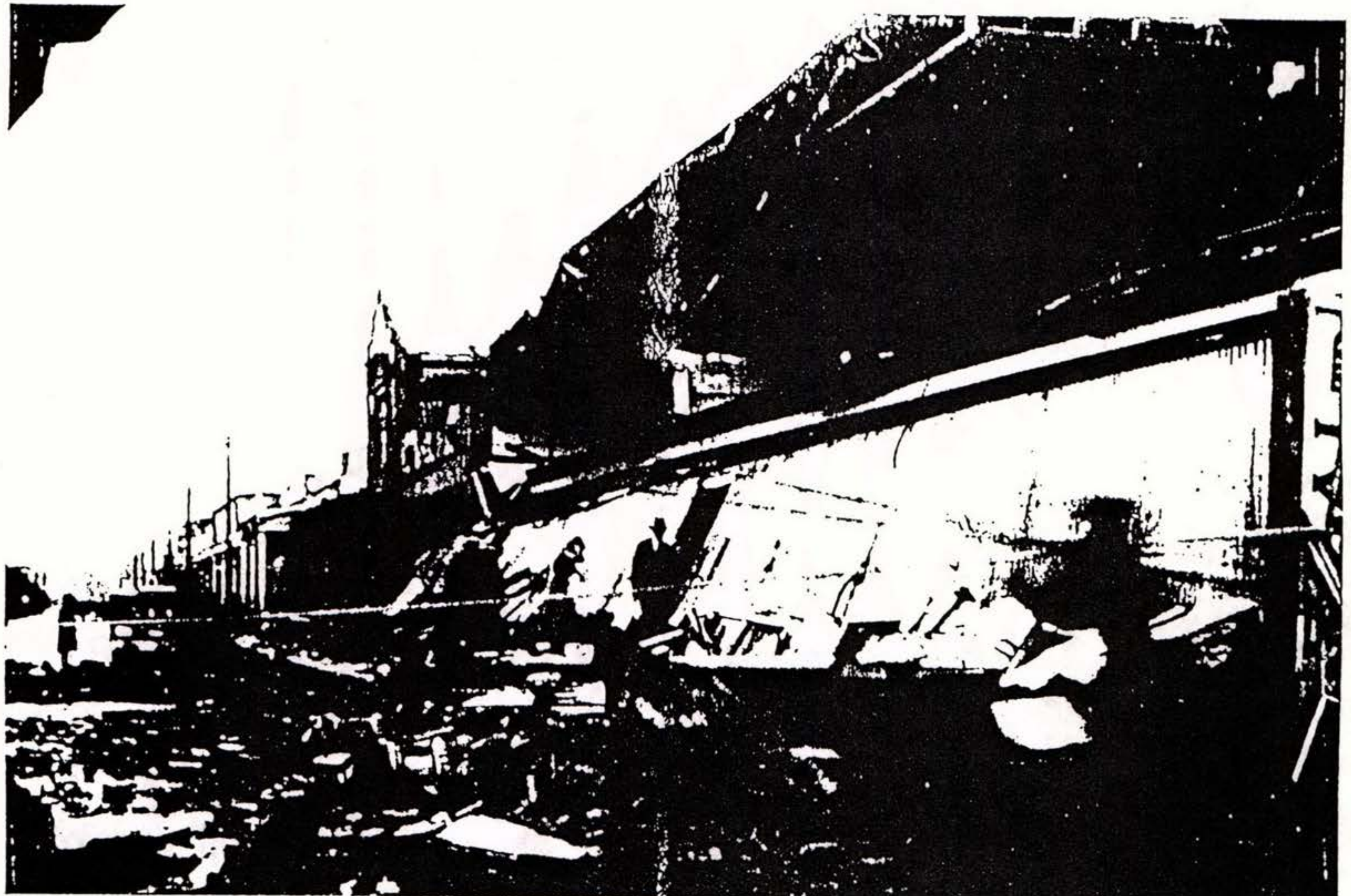


FIG 4

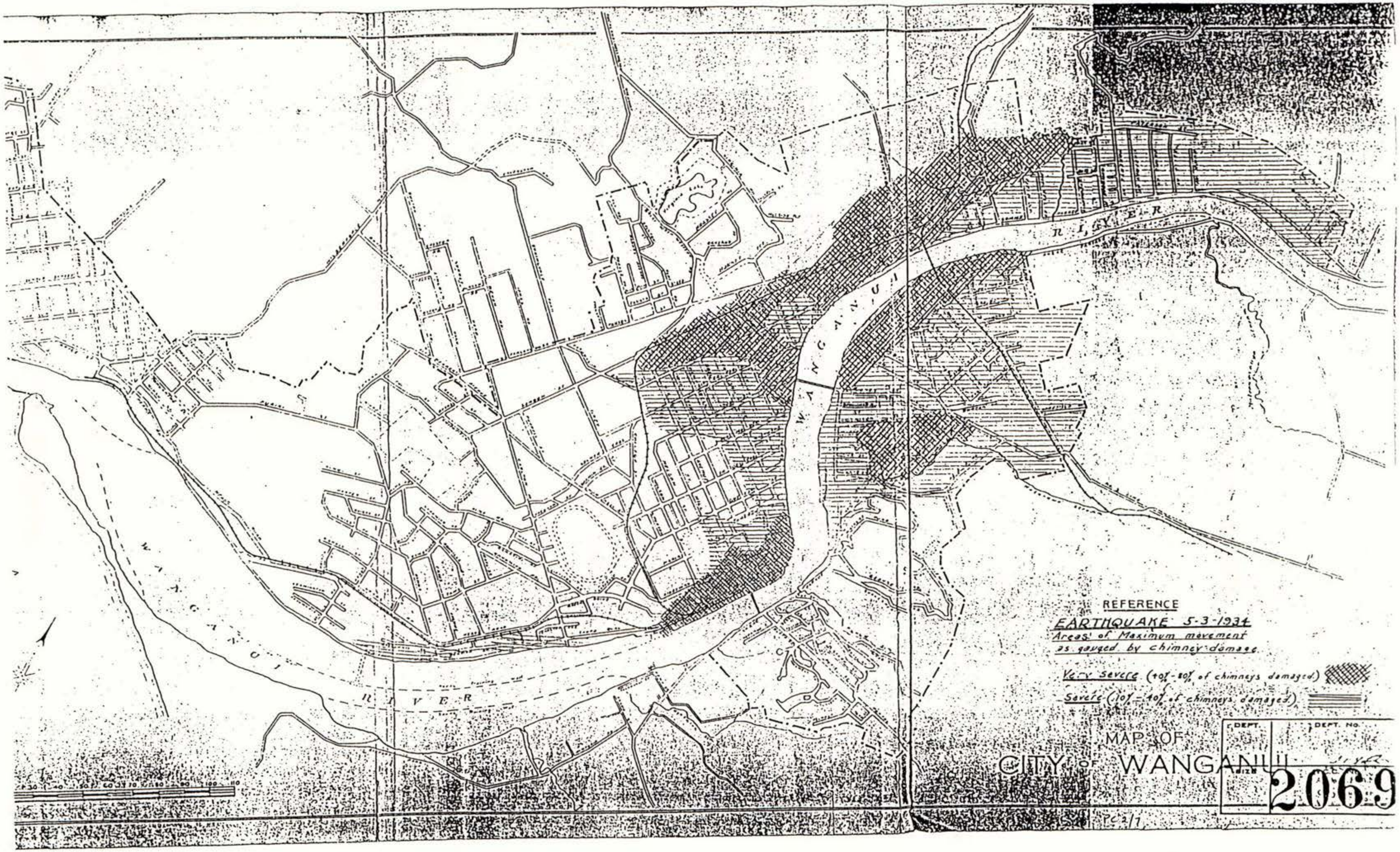

WANGANUI
RIVER
REFERENCE
EARTHQUAKE 5-3-1934
Areas of Maximum movement
as gauged by chimney damage.
Very severe (40% - 80% of chimneys damaged)
Severe (10% - 40% of chimneys damaged)
MAP OF
CITY of WANGANUI
DEPT.
DEPT. NO.
2069
PC 2/7

FIG 5a

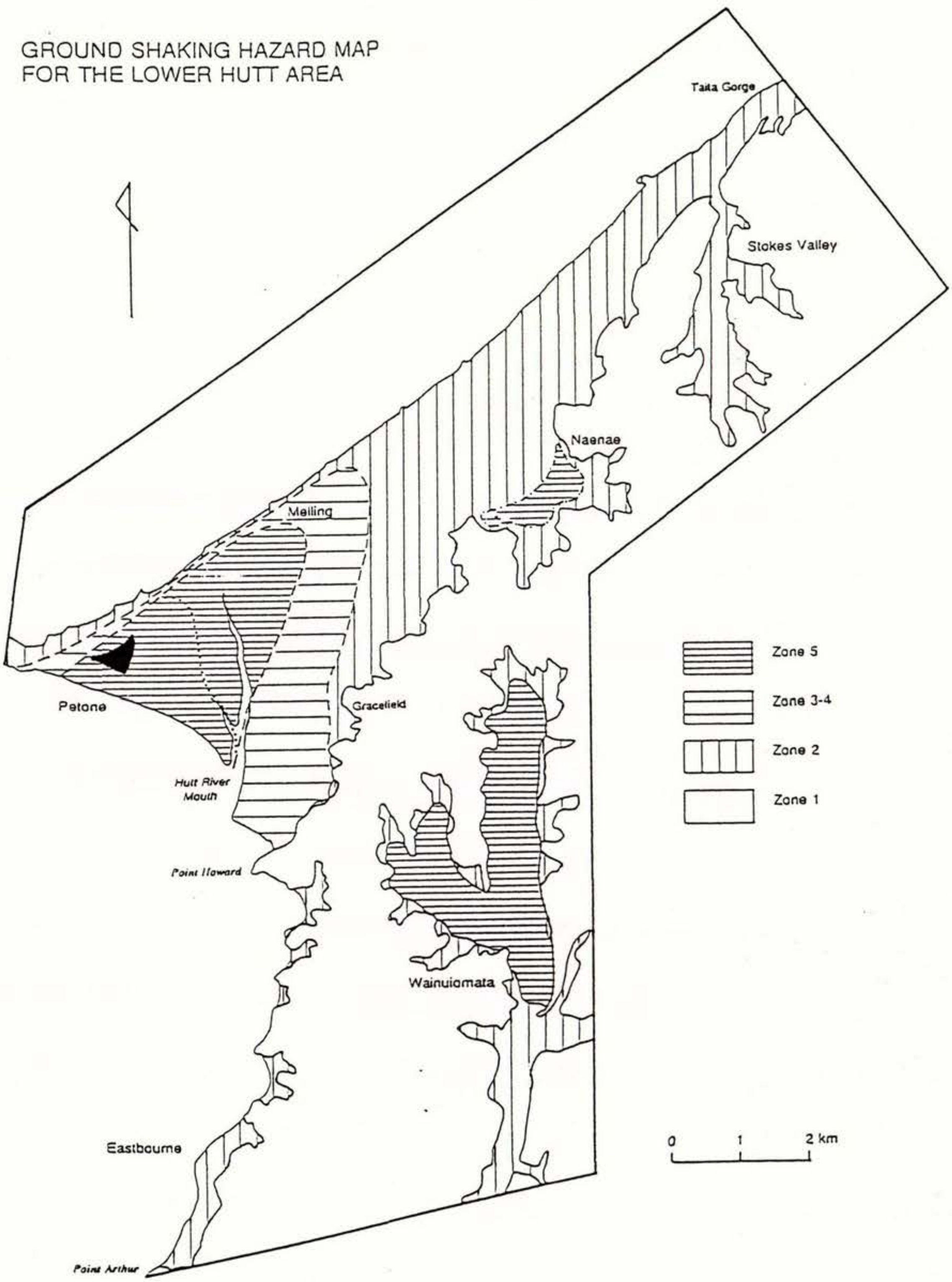
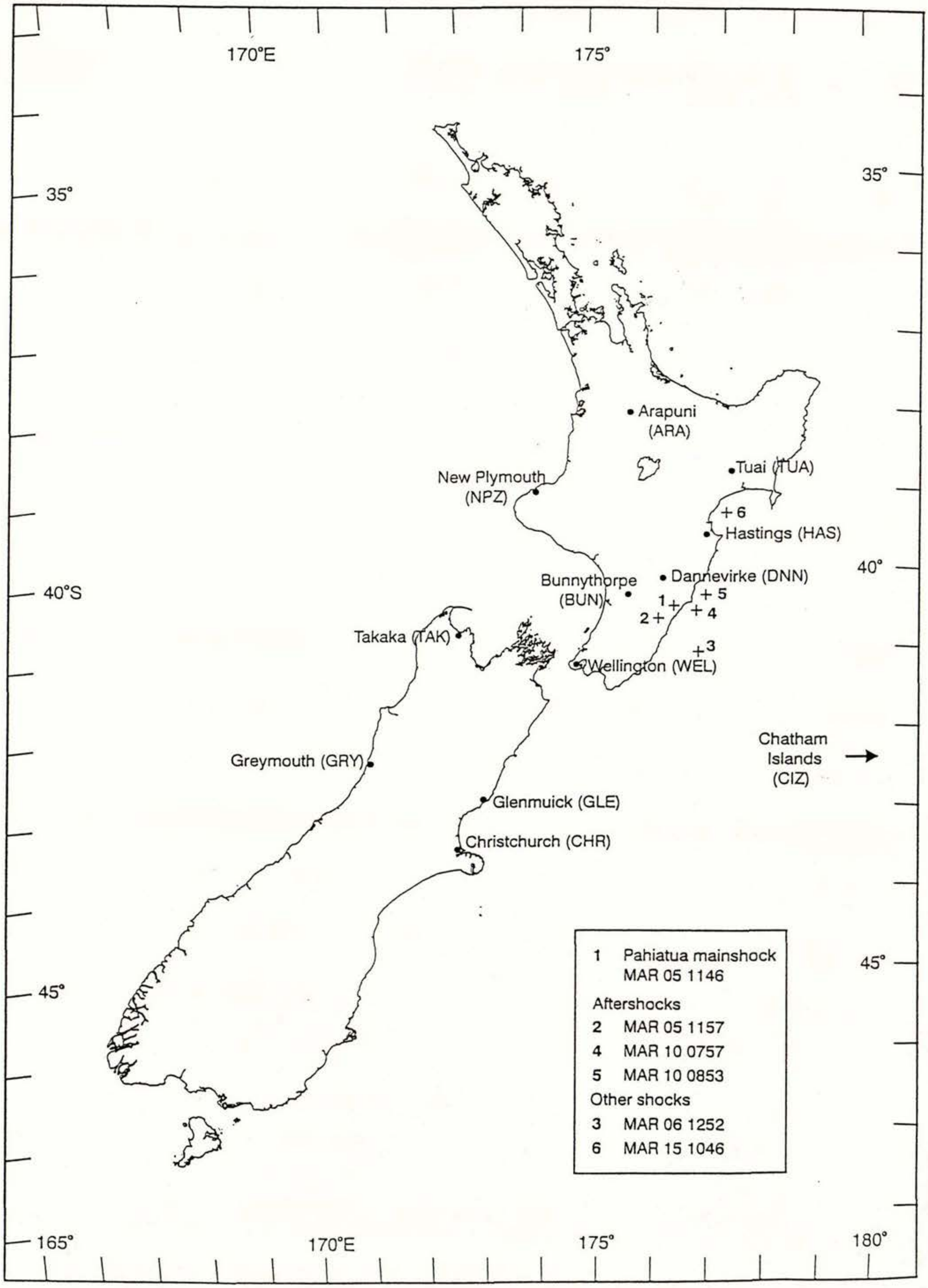


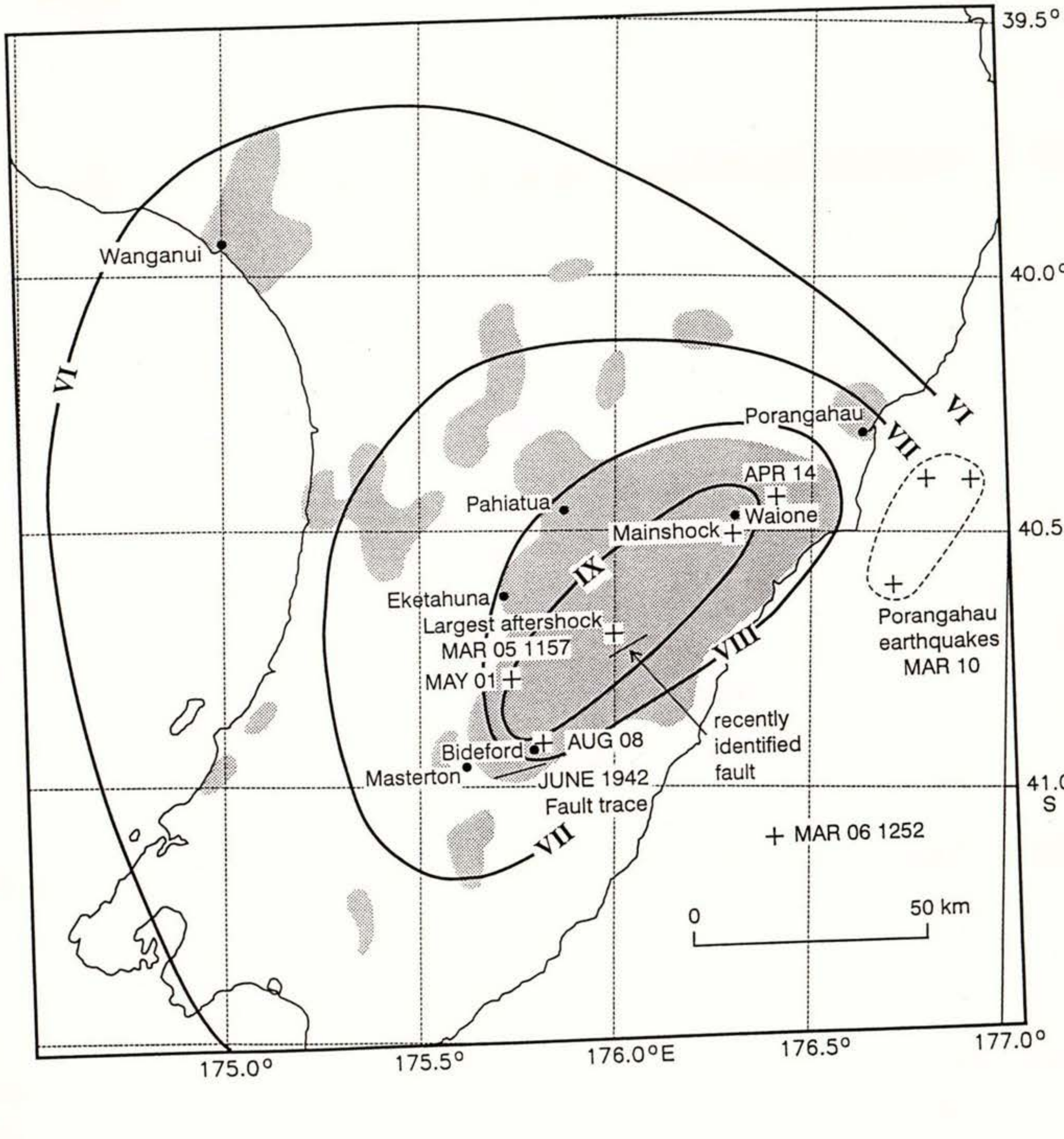
Figure 5. Ground shaking hazard map for the Lower Hutt area.

FIG 5b



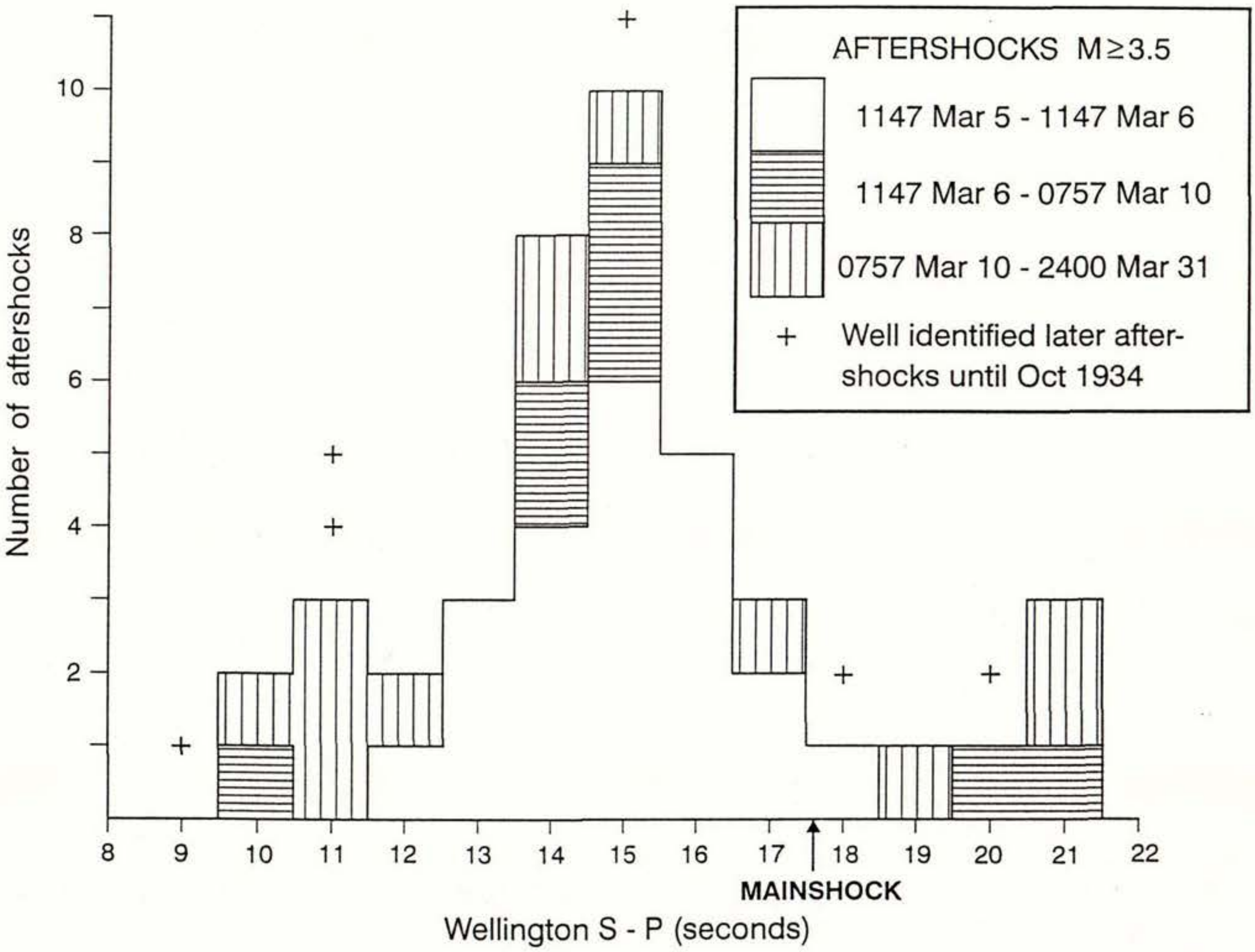
170°E
175°
35°
35°
40°
40°S
45°
45°
165°
170°E
175°
180°
Arapuni
(ARA)
Tuai (TUA)
New Plymouth
(NPZ)
+6
Hastings (HAS)
Bunnythorpe
(BUN)
Dannevirke (DNN)
+5
1+
2+
+4
+3
Takaka (TAK)
Wellington (WEL)
Chatham
Islands
(CIZ)
Greymouth (GRY)
Glenmuick (GLE)
Christchurch (CHR)
1 Pahiatua mainshock
MAR 05 1146
Aftershocks
2 MAR 05 1157
4 MAR 10 0757
5 MAR 10 0853
Other shocks
3 MAR 06 1252
6 MAR 15 1046

FIG 6



gaye/1934/shading

FIG 7



gaye/1934/hist

FIG 8