

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

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ABSTRACT

Descriptive accounts and analysis of local seismograms establish that the epicentre of the 1934 March 5 M_s7.6 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 led early seismologists to name the earthquake after the town, but it has now been found that the highest intensities (MM9) occurred about 40 km to the east and 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 descriptions and isoseismal maps. A stable solution for the epicentre of the mainshock has been obtained by analysing phase arrivals read from surviving seismograms of the rather small and poorly equipped 1934 New Zealand network of twelve stations (two privately owned). The addition of some teleseismic P arrivals to this solution shifts the location of the epicentre by less than 10 km. It lies within, and to the northern end of, the MM9 isoseismal zone. Using local instrumental data larger aftershocks and other moderate magnitude earthquakes that occurred within 10 days and 50 km of the mainshock have also been located. Approximate locations of other associated moderate magnitude earthquakes until October 1934 have been identified by their maximum intensity and S-P intervals read from the Wellington Wood-Anderson seismograph records. 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 inquiries directed to old residents yield historical evidence of a surface fault rupture. Nevertheless, the strike-slip mechanism at 20 km depth determined by preliminary teleseismic body wave modelling of Doser and Webb suggests that rupture could have extended to the surface. Recent investigation of two of the freshest-looking, active faults that lie within the MM9 isoseismal by Schermer and others indicates that one of them could have ruptured in the 1934 Pahiatua earthquake.

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INTRODUCTION

In March 1934, northern Wairarapa, southern Hawke's Bay and Manawatu districts 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 $M_s 7.6 \pm 0.05$ [1], making it the fourth largest earthquake known to have occurred in New Zealand in the last 160 years. Since 1840, when organised European settlement began, New Zealand has experienced many large earthquakes. Most occurred before 1942, before the New Zealand seismograph network and knowledge of crustal structure and velocities were sufficient to allow calculation of reliable epicentres. For seismic hazard studies, it is desirable to have as complete and reliable a set of information about an earthquake as possible, including the epicentre, depth, source mechanism, surface faulting (if any), intensity and damage data. Since the end of 1942, not only have few large earthquakes occurred, but also those that have occurred have not been located close to large centres of population. Consequently, there are few recent well-constrained isoseismal maps with well-determined epicentral parameters for attenuation studies, and data on the performance of structures and services in urbanized areas at moderate to high intensities are particularly limited.

In contrast, New Zealand experienced eight shallow earthquakes (depth < 45 km) with magnitudes $M_s 6.9$ or greater [1] between March 1929 and September 1942. Two originated in sparsely populated areas of the South Island, but six occurred in more urbanized areas in one of the most seismically active regions of New Zealand, the east coast of the North Island. These earthquakes, each with the potential to provide much needed information on damage in high intensity near-source areas, are some of the largest in New Zealand's short, recorded history. Studies have been or are being initiated to refine our knowledge of their effects, epicentres, depths, magnitudes and source mechanisms, and hence to understand their tectonic significance. Re-analysis of seismogram records and collection and evaluation of the intensity and building damage data for the 1942 $M_s 7.2$ and $M_s 7.0$ Wairarapa earthquakes are in progress (by Downes and others [2]), following the same procedure as the present study. Collection and evaluation of the intensity and building damage data for the June 1929 $M_s 7.8$ Buller [3], the 1931 $M_s 7.8$ Hawke's Bay [4], the 1932 $M_s 6.9$ Wairoa [5] earthquakes are complete, or in progress. By modelling teleseismic body waves, Doser and Webb (pers. comm. 1997) have determined source mechanisms and moment magnitudes the 1929 Buller, and the March 1929 $M_s 7.1$ Arthur's Pass earthquakes as well as 15 other South Island earthquakes of lower magnitudes. Their modelling of North Island events, again including many of lower magnitudes than mentioned here, is progressing (Doser & Webb, pers. comm. 1997).

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 1934 Pahiatua earthquake in this important area has been uncertain for sixty years. In 1937, Hayes [6] located the epicentre offshore from Castlepoint (1934a, Figure 1) by using phase

arrivals from New Zealand's network of twelve stations. Bullen [7] found a similar location in 1936. In 1938 he incorporated some teleseismic data into his analysis [8], obtaining what he 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 assigned to stations. These epicentres are incompatible with Hayes' [6] isoseismal map. However, locating earthquakes instrumentally was difficult until the early 1940's because of the small number and poor quality of seismographs of the New Zealand network and because little was known about crustal structure and velocities of seismic waves in New Zealand. Most seismographs were quite simple instruments with very low magnification. Few had absolute time, or even reliable internal timing [9]. Using data from the large earthquakes of 1931-1934, Hayes [9] and Bullen [7, 8] attempted to identify crustal phases and to calculate their velocities at the same time as they determined epicentres, but having too many unknown parameters made solutions unreliable. Hayes [6] also located and listed magnitudes for other moderate to large earthquakes in 1934 (to October 25), including those closely related in time with the 1934 Pahiatua earthquake.

The only other study based on instrumental data was that of Gibowicz [10]. He calculated the b-value and the rate of decay of aftershocks in the 1934 Pahiatua earthquake, the 1931 Hawke's Bay and the 1942 Wairarapa earthquake sequences. 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. Gibowicz also examined the distribution of S-P intervals recorded on Wellington seismograms from which he concluded that the length of the zone containing 90% of the aftershocks was about 70 km.

No comprehensive account of the earthquake's effects on buildings and the environment has been published since Hayes' 1937 paper [6], in which there was only a brief description and isoseismal map (Rossi-Forel scale) based on newspaper reports, official felt reports from a network of observers and reports from one of the New Zealand Geological Survey's staff. More recently, Dellow [11] catalogued ground damage caused by the earthquake. In a catalogue of liquefaction effects caused by large New Zealand earthquakes Fairless & Berrill [12] list no reports for the Pahiatua earthquake.

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 [13]. Eiby used Bullen's [8] "1934c" epicentre and converted Rossi-Forel intensities from official felt reports in the Seismological Observatory's files to the Modified Mercalli scale. Eiby recognised that the conversion was inexact and unreliable and an interim measure until comprehensive studies could be completed. 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.

This paper describes the results of successfully combining re-reading and analysis of early seismograms with the analysis of a comprehensive collection of descriptive accounts to provide new locations for the 1934 Pahiataua earthquake, its major aftershocks and several other earthquakes in March

1934, a new isoseismal map and extensive information on the effects of the mainshock, in this way resolving previous uncertainties associated with this important earthquake sequence.

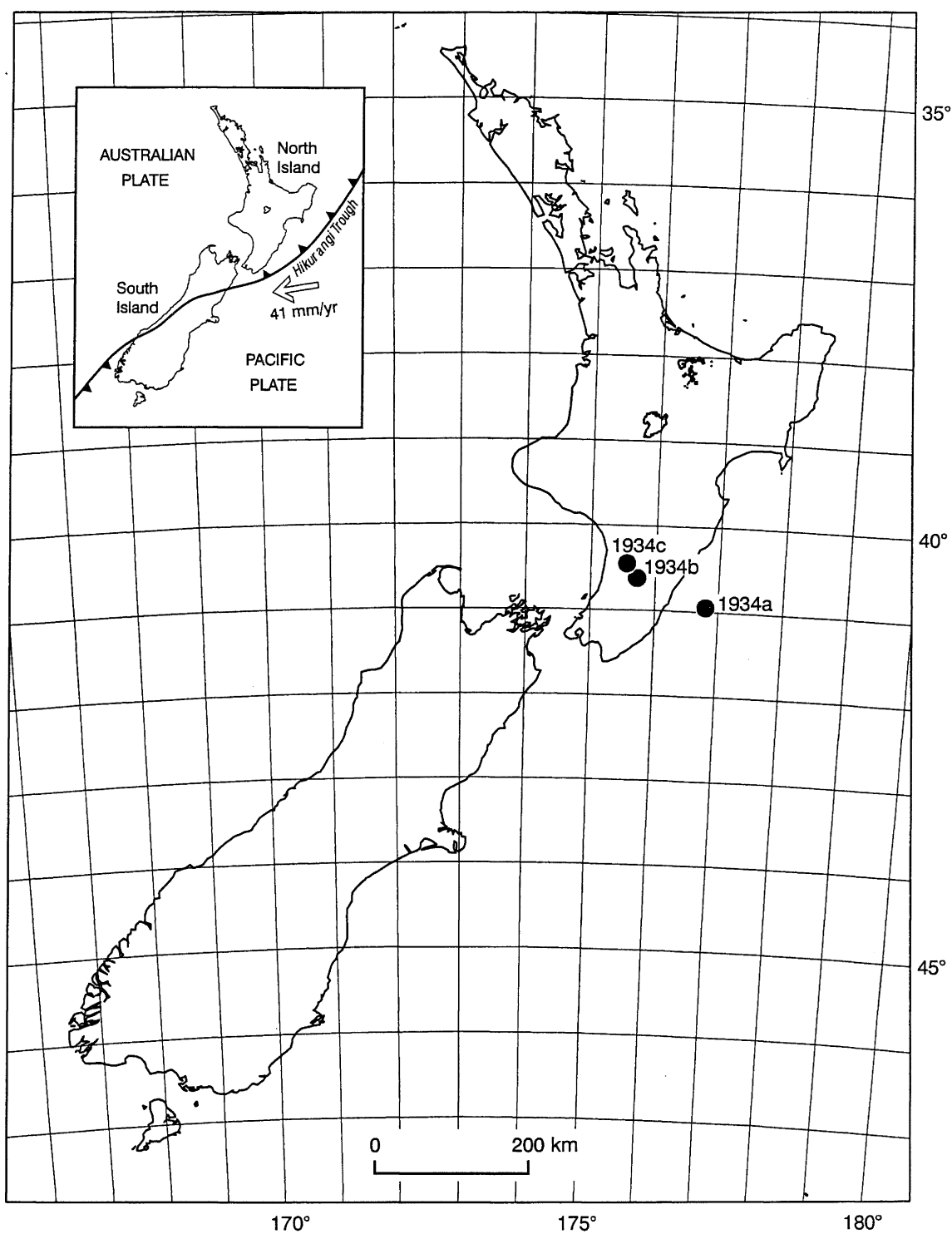


Figure 1. Map of New Zealand showing the 1934 Pahiataua earthquake epicentres determined by Hayes (1934a), and Bullen (1934b, c). The inset shows the main features of plate convergence.

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 in locating epicentres as determining an epicentre from instrumental data alone was rarely possible until the early-mid 1940s. The Observatory's file of newspaper cuttings supplemented the intensity questionnaires sent in by its network of reporters. Unfortunately, few of these early intensity questionnaires are useful today because of their formulation and use of the Rossi-Forel scale. The newspaper collection is more useful as many small town newspapers were included as well as the main provincial newspapers, but cuttings rarely extended more than a day or two after the main earthquake, and past experience has shown that useful material often appears days or weeks later.

The newspaper collection has now been made as complete as possible, primarily through the resources of the Alexander Turnbull Library (part of the National Library of New Zealand). Archives of the Palmerston North, Tararua, Masterton and Wellington City and District Councils, and the Department of Works files in the National Archives have been 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. These reports were considered confidential to building owners and not released publicly. Few other diary or journal accounts have been located, either in the Alexander Turnbull Library (manuscript section) or as a result of request for information in a January 1997 newspaper article in the *Bush Telegraph*, Pahiataua's local newspaper.

Several people who lived as children in the area of highest intensity have been contacted, one person supplying useful new information on the cracking of ridges near Tiraumea (place names mentioned in the text are shown on Figure 2), on landsliding on the eastern side of the Puketoi Ranges and to the east of Tiraumea, and most importantly, on the frequency of small aftershocks following 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 New Zealand 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 [14] (shown in Figure 6). According to Ongley, the damage was greatest to the east of Pahiataua, but everywhere it was less than that caused by the 1931 Hawke's Bay earthquake. Several newspaper articles written by special correspondents sent to survey the damaged area also recognised the greater severity of damage east of Pahiataua.

Using these resources a new isoseismal map of the $M_s 7.6$ 1934 March 05 Pahiataua earthquake has been compiled (Figure 3a, Figure 3b). Intensities and the effects on which the MM8 and MM9 intensities were based are listed by location in the appendix at the end of this paper. Intensities

were assigned using the 1992 version of the Modified Mercalli scale adapted for New Zealand conditions [15]. They were found to be compatible with the 1996 modifications proposed by Dowrick [16].

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 from just north of Waione to south of Bideford in the northern Wairarapa. Pahiataua and Eketahuna were the most severely damaged townships (MM8), but many other small towns and settlements in the Wairarapa, southern Hawke's Bay and Manawatu were also strongly shaken to intensity MM7 or MM8.

Damage and casualties in the highest intensity zones

Modified Mercalli intensities of MM8 or more occurred over an area of approximately 5000 km², the MM8 and MM9 isoseismals having lengths along their major axes of 124 km and 70 km respectively (Figure 3b). The total population within this high intensity region was fortunately modest (c. 23,000) as 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 Pahiataua, 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 and that most of their homes were timber-framed. If the earthquake had occurred in business hours the falling of brick gables and parapets of Pahiataua's commercial buildings was extensive enough that a modest number of casualties (a dozen or so?) could have been caused.

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 Pahiataua, with populations of about 9000 and 1600 respectively. Pahiataua experienced an intensity of MM8, Masterton MM7. Using the attenuation model of Zhao *et al* [17], estimates of peak ground acceleration (est. PGA) will be given for locations of interest in the following discussion. The building damage in Pahiataua (est. PGA 0.39g), as the town most severely damaged in the earthquake, is described below.

According to the remarkably detailed press reports of the time, most chimneys in Pahiataua fell. Two weeks after the earthquake (19 March) the *Pahiataua Herald* reported that there were 412 houses in the borough and 603 chimneys needed repair or rebuilding, consistent with intensity MM8.

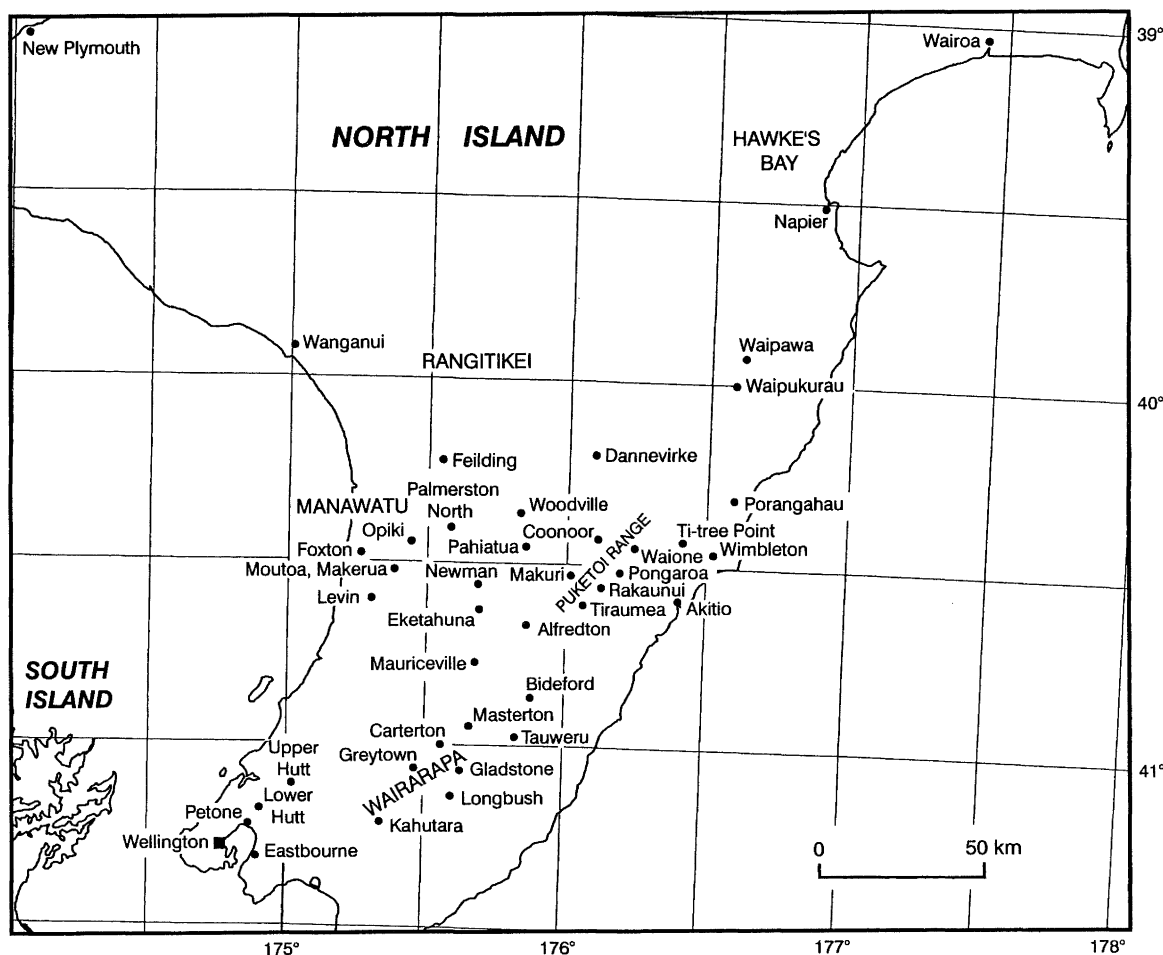


Figure 2. Map showing towns and districts within the MM6-9 zones.

Non-domestic buildings in Pahiatua were either one or two-storeyed. Considerable damage occurred to many of the brick buildings, with walls wholly or partly falling in a number of buildings. The upper storey front facade of the Wairarapa Farmer's Cooperative Association's general store fell into the main street (Figure 4). 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. 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 the town is unequivocally MM8.

One of the largest buildings within the MM8 isoseismal was the five-storey Tui Brewery at Mangatainoka (Figure 5) (est. PGA 0.39g), a small town about 5 km northeast of Pahiatua and hence about the same distance from the major axis of the isoseismals (Figure 3b) as Pahiatua. The Brewery, a brick-clad reinforced concrete building, which had been completed shortly before the earthquake, withstood the shock well. An inspection of the building by R T Hefford in June 1997 showed no signs of its 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 storied) 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.

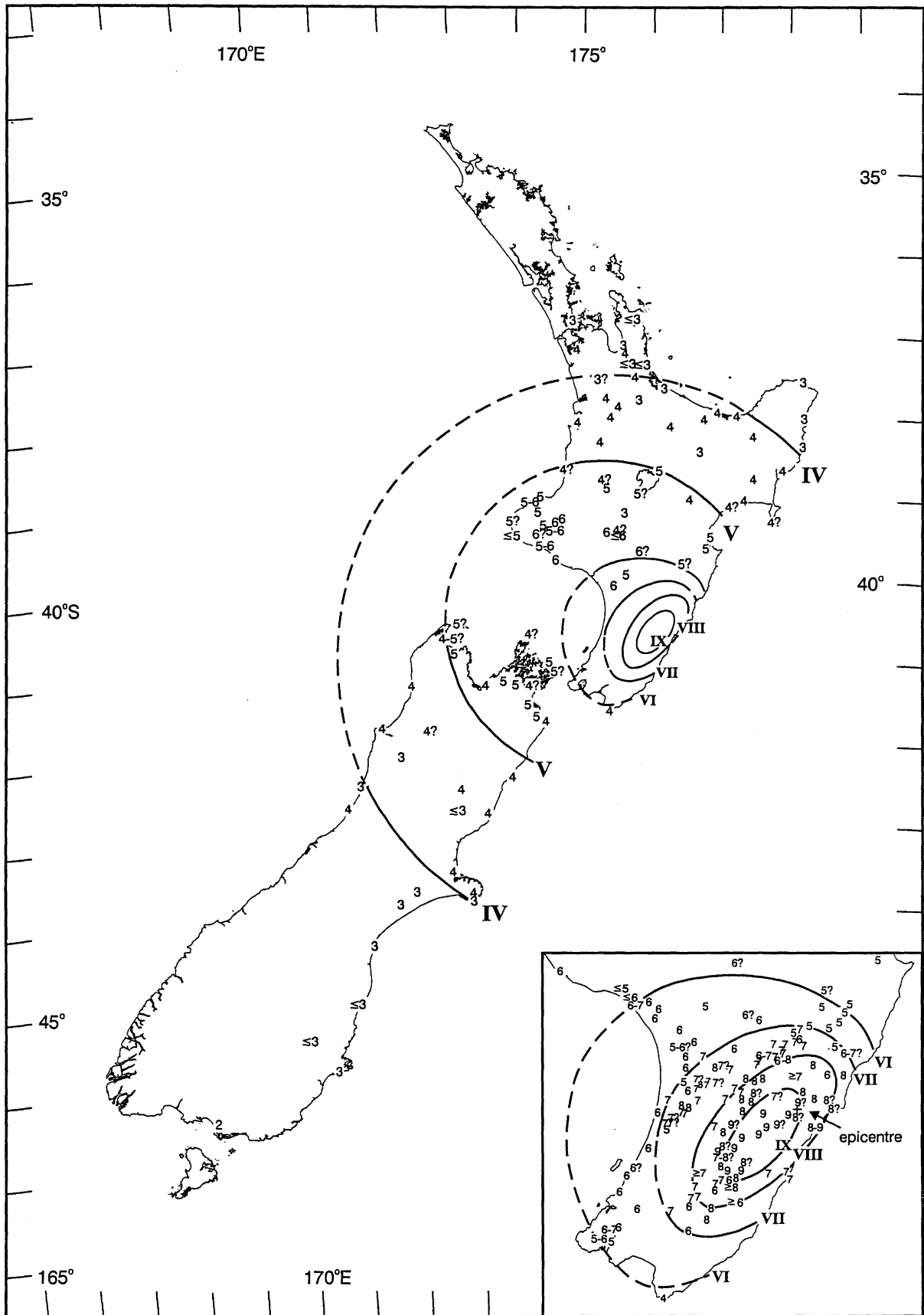


Figure 3. Isoseismal map of the 1934 Pahiatua earthquake. Inset: detailed map of the MM6-MM9 intensity areas and instrumental epicentre for the mainshock (+).



Figure 4. 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. (Reference no. P-A1 0832-021 -0, Alexander Turnbull Library, Wellington, New Zealand)

Small to moderate landslides occurred in the MM8 and MM9 zones, as did 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. Ongley [14] recorded many small slips and rockfalls east of Pongaroa (Figure 6), but suggested also that newspaper reports were exaggerated, especially with respect to the size of the landslides. Ongley also records the occurrence of small sand fountains on the river flats near Makuri. 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 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.

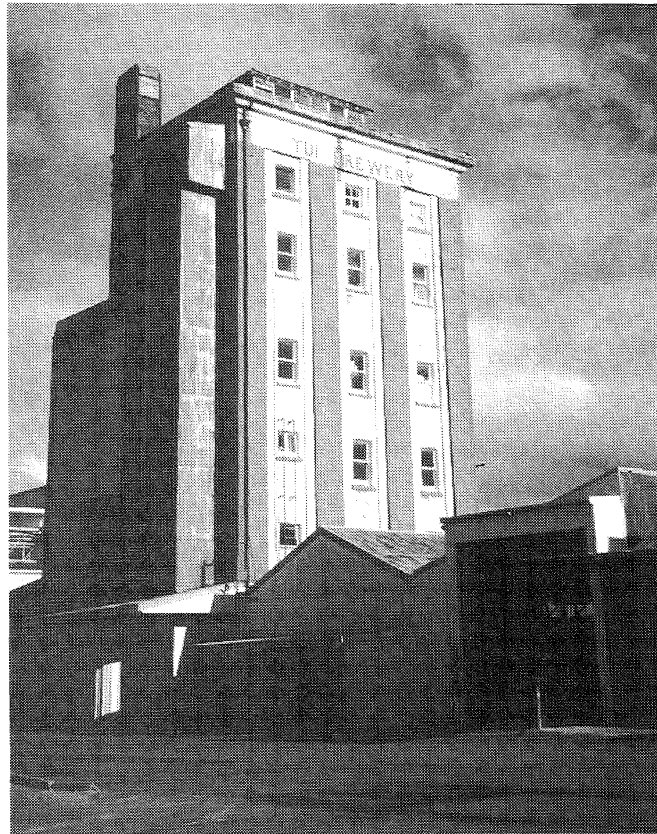


Figure 5. A view of the five-storey Tui Brewery building at Mangatainoka, near Pahiatua. This brick clad, reinforced concrete frame building was undamaged. (Photograph by R. T. Hefford, 1997).

Damage in other areas:

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 experienced intensity MM7. The uneven distribution of chimney damage in this 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 rough sketch to the Council (Figure 7a). Among his accompanying comments, were 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 the effects of other historical earthquakes, and other studies estimating the effect of shaking enhancement on sites underlain by deep alluvium within the city (such as Berryman *et al* [18]).

Evidence of shaking enhancement can be found at several other sites, with very localised damage occurring within areas of generally lesser or little damage. For example, Moutua and Makerua have intensities MM8 assigned in an otherwise MM7 zone. In Petone, about 140 kilometres from the

epicentre, 40 chimneys were damaged (i.e. MM7), 20 requiring demolition, in one small area of less than 0.5 km². Elsewhere in Petone, the intensity seems to have been MM6. In Lower Hutt a few chimneys were damaged or fallen and these were generally confined to a small area west of the Hutt River. This is in sharp contrast with 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 [19] (Figure 7b).

Extensive areas of Zone 5 are also indicated on the shaking hazard map of Wellington [20, 21], but fewer than 10 or 12 chimneys fell in the city and these were not notable for 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 apparently experiencing MM5 only. Gladstone and Longbush (MM8) may also have experienced shaking enhancement, as Masterton being closer to the epicentre experienced MM7 only. However, these settlements have been included within the MM8 isoseismal as it is not possible to delineate it well enough in this area.

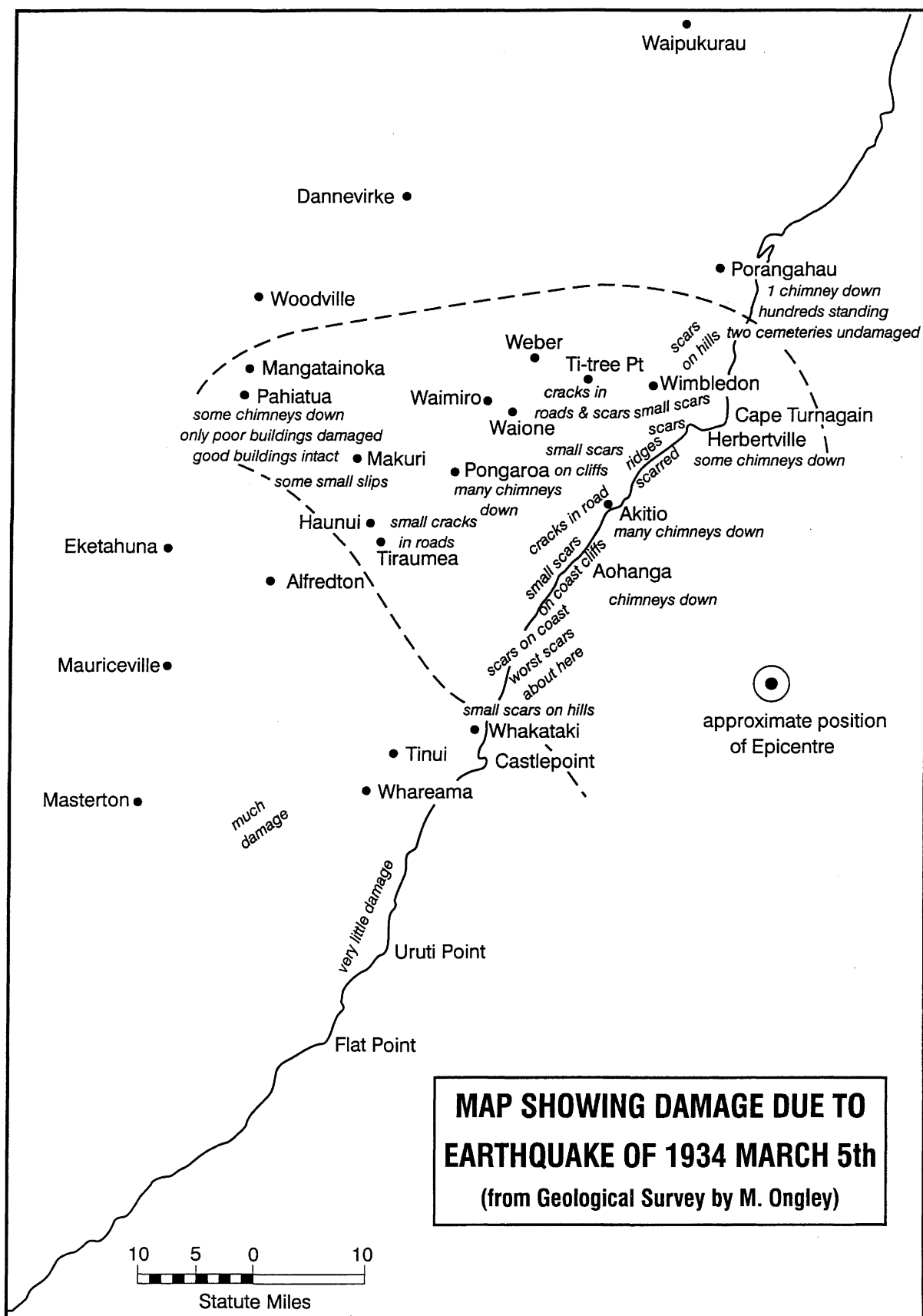


Figure 6. Scanned and redrafted sketch of the distribution of landslides in the epicentral area. Hayes probably drew the original from data supplied by Ongley [13] and located the epicentre shown in the sketch.

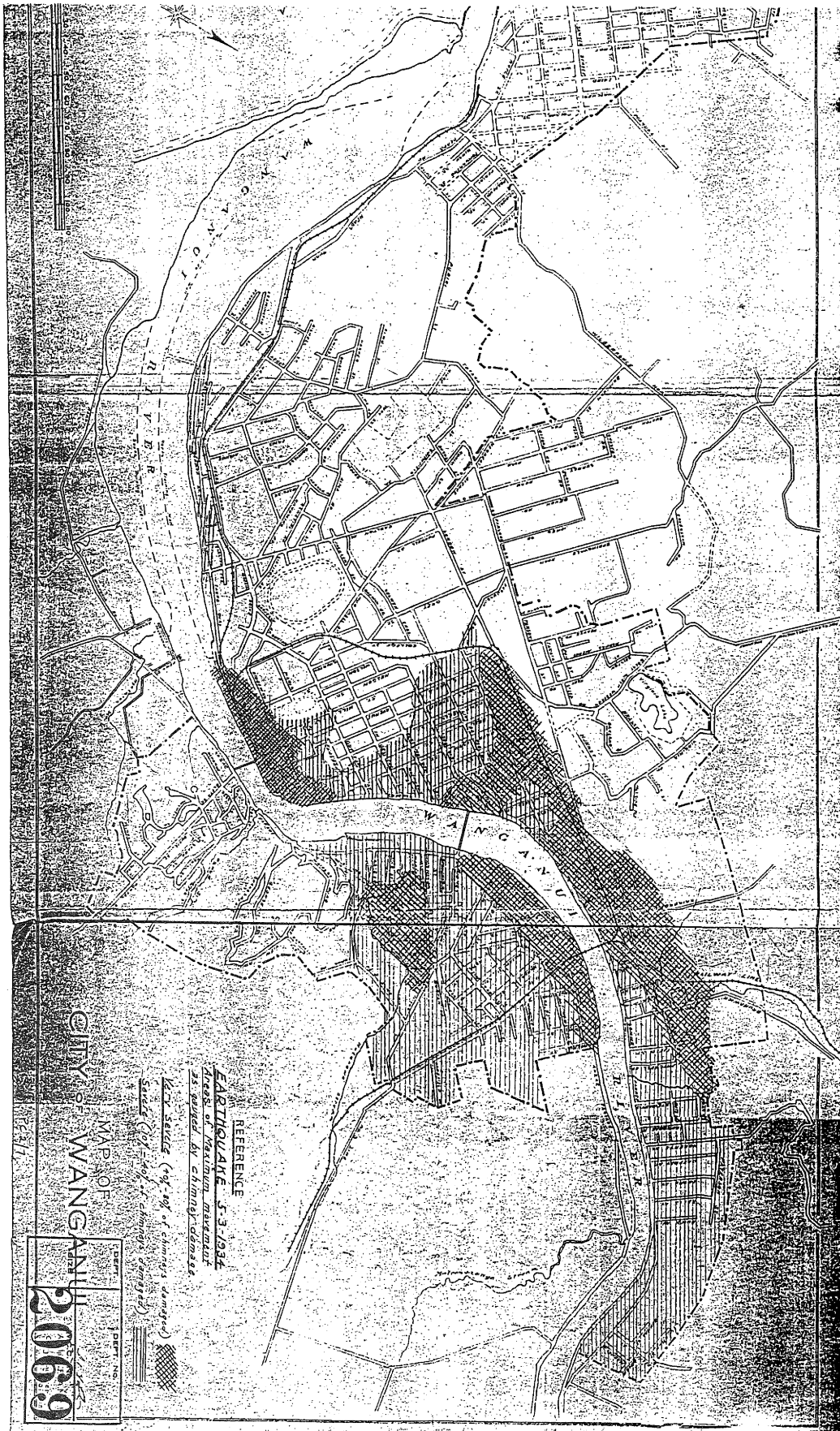


Figure 7. (a): Sketch of the distribution of chimney damage in Wanganui caused by the Pahiatua earthquake. The sketch was prepared for the Wanganui Council by the Council Engineer in March 1934. (Sketch courtesy of the Wanganui City Council Archives.)

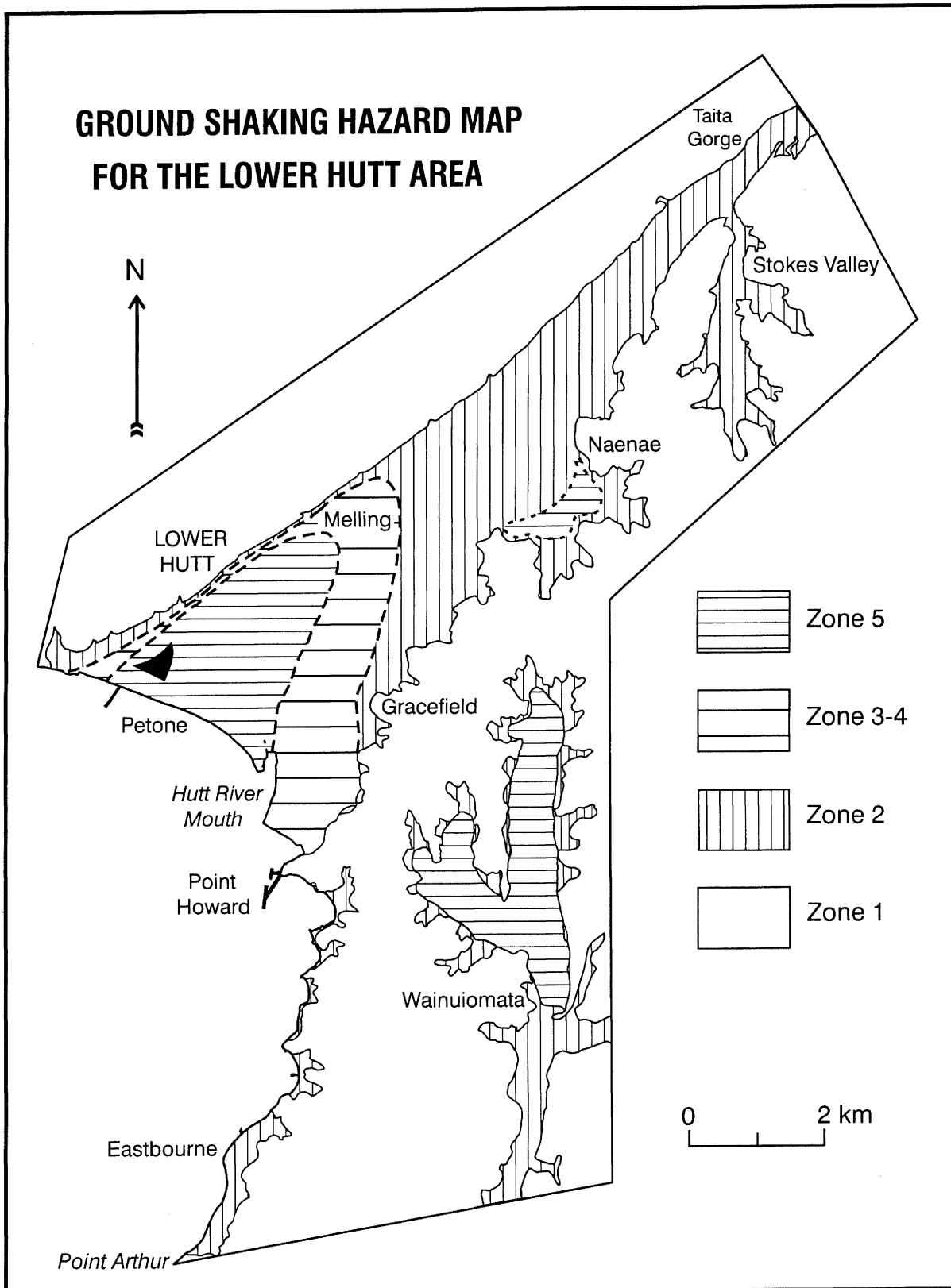


Figure 7. (b): Location of heavy chimney damage in Petone within Zone 5 of the Ground Shaking Hazard map for the lower Hutt Valley area (after Van Dissen et al [16]).

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 settlement and ground cracking occurred in the nearby railway yards, resulting in the racking 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, probably as a result of subsidence. At Makerua (near Opiki) in the Manawatu and at Kahutara in the Wairarapa, stopbanks were badly fissured. Sand and water ejection occurred at Makerua also. 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 unpublished records). At Napier the rainfall was twice the average (presumably since records began).

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, but with isolated instances in the MM6 and MM5 zones (Figure 9). 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. Triggered circuit breakers were the main cause for the power outage outside the epicentral area. A water main was broken in Wanganui and minor leaks occurred in several other places, including the lower Hutt Valley.

Estimate of magnitude from the isoseismal map:

Comparison of the radii of the isoseismal lines with other $M_{6.9+}$ shallow earthquakes, i.e. the 1901 Cheviot (Dowrick unpublished data), 1929 Arthur's Pass (Dowrick unpublished data), 1929 Buller [3], 1931 Hawke's Bay [4], 1932 Wairoa [5] and 1942 Wairarapa (Dowrick & Downes unpublished data) earthquakes is shown in Table 1. Estimating the magnitude from the isoseismal attenuation model of Dowrick [22] gives $M7.3 - 7.4$ (regardless of mechanism).

INSTRUMENTAL DATA

In the early 1930's, the network of seismographs in New Zealand was small (Figure 8) and poorly equipped (Table 2). This resulted in few good data for seismologists of the day to calculate epicentres and attempt to interpret New Zealand's crustal structure and 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 we expected that careful re-reading of phase arrivals from early seismograms and analysis with modern location methods would result in significant improvement over their 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 8). New Zealand's first short period

instrument, a Wood-Anderson seismograph, was installed in Wellington in January 1931. Its magnification was 1400. An Imamura strong motion instrument was installed at Takaka in the same month and Wood-Anderson seismographs at New Plymouth and Christchurch, and Milne-Jaggard instruments at several other locations were installed later in the same year [23].

The Milne-Jaggard instrument was a simple design (see Eiby [24]) with virtually no magnification. Its circular smoked paper disk lasted three days, with one circuit being completed per hour. With a speed of 4 - 8 mm 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, these records are important to our analysis and S-P intervals (time between the P and S arrivals) have been read from the Bunnythorpe and Hastings records.

According to Hayes [6], only Wellington records could be relied upon for consistently accurate absolute time (to 0.5 sec), 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 4 mm/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 30 mm/minute, magnification 1400).

The Seismological Observatory's archives contain many early seismograms. Phase arrivals have been re-read from those that could be found (Table 2). Other phase arrivals were taken from the 1934 Seismological Reports [25], using S-P intervals when the absolute P and S arrival times were obviously incorrect through bad timing or reader error. As the Imamura record of the mainshock is missing, the S-P interval was read from a reproduction of the trace in Hayes [6]. 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 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 has been interpreted as P* (lower crustal P wave) rather than P_n as a means of recognising that the first arrival is likely to have been emergent and undetectable on a Milne

record. 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 several stronger phases, the strongest of which may be the P* arrival.

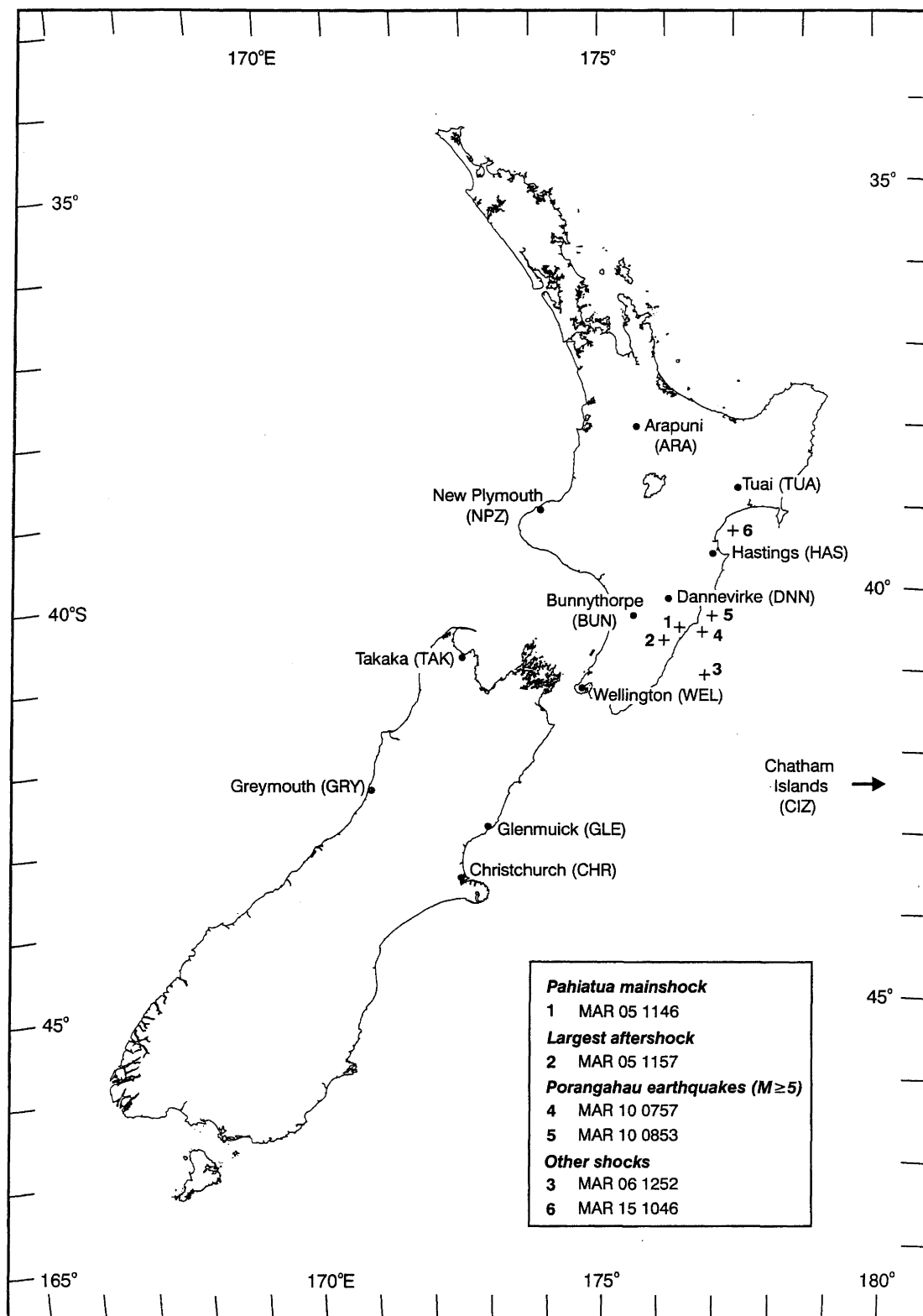


Figure 8. Map showing the locations of seismographs in 1934 and instrumentally derived epicentres of the Pahiatua earthquake, its largest aftershock, the Porangahau earthquakes and other nearby large earthquakes in March 1934.

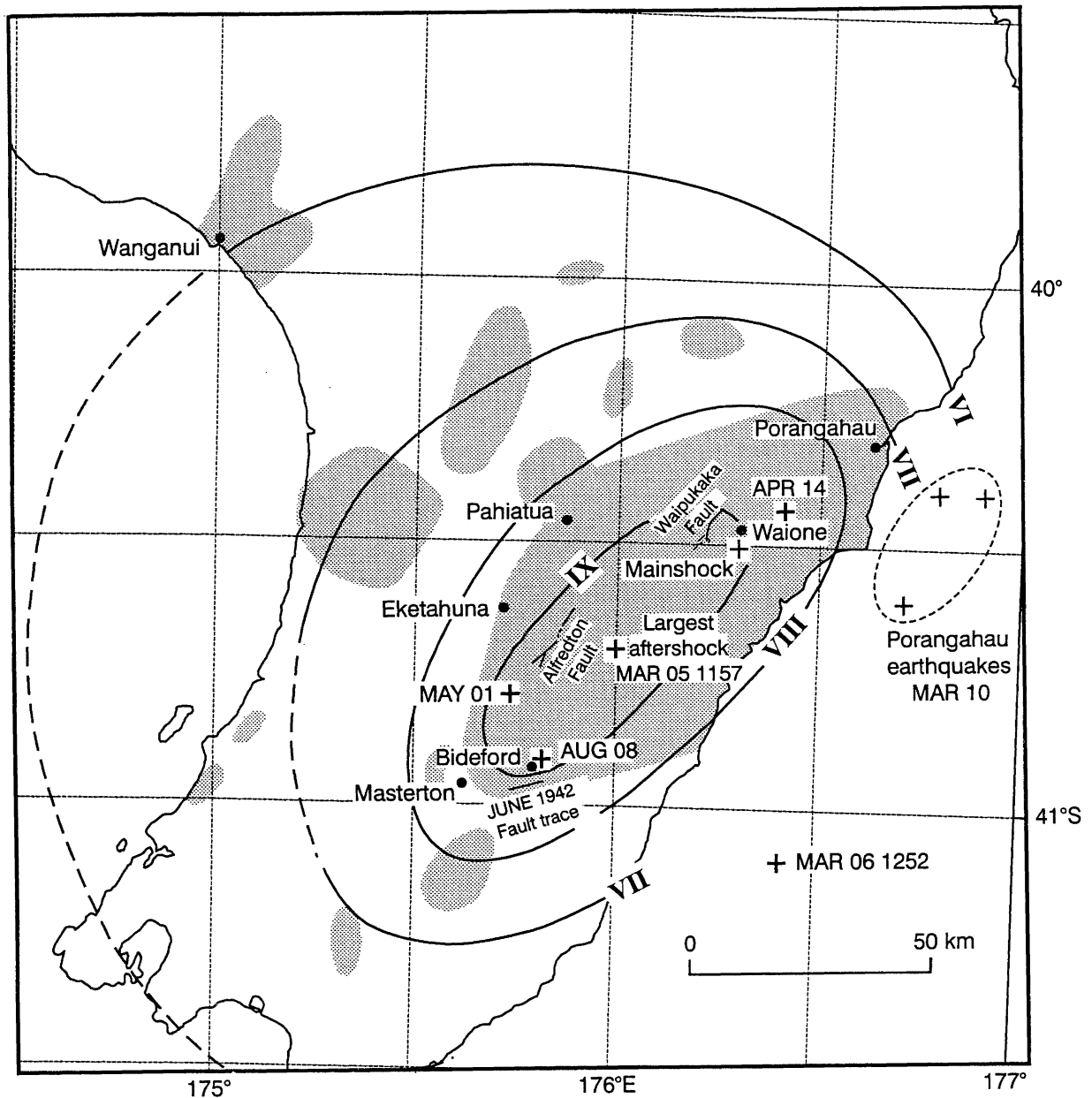


Figure 9. Map showing the instrumentally derived epicentres of the Pahiatua earthquake, its largest aftershock, well-identified later aftershocks and the Porangahau earthquakes in relation to the MM6-MM9 isoseismals. The map also shows the location of surface rupture in the June 1942 earthquake [31], and, within the MM9 isoseismal, two areas containing two fresh-looking faults that were investigated by Schermer et al [29]. The shaded areas show the approximate distribution of reported ground damage (landslides, ground cracking and liquefaction).

The solution for the mainshock, which is the only event to include teleseismic data, and local station solutions for other major events are given in Table 3 and Figure 9. The estimated location error for any of the earthquakes is no less than 20 km and possibly as great as 40 km. 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 Rhoades [1] give $M_s 7.6 \pm 0.05$ 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 range 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 because of poorer clocks, and slower rotating and lower-magnification seismographs.

Table 1. Comparison of the isoseismal "radii" of the 1934 March 5 Pahiataua earthquake with other $M_s6.9+$ New Zealand shallow strike-slip events. The values listed are d_s (semi-axis along strike) and \bar{d} (mean horizontal radius). M_s are from Dowrick & Rhoades [1].

MM intensity	d_s						
	1901 $M_s6.9$	1929 7.1	1929 7.8	1931 7.8	1932 6.9	1942 7.2	1934 $M_s7.6$
4	256	300	-	449	378	400	360
5	180	224	431	315	230	239	220
6	128	94	281	216	94	136	111
7	64	-	185	149	-	65	75
8	32	34	98	101	48	38	62
9	-	20	50	47	22	-	35

MM intensity	\bar{d}						
	1901 $M_s6.9$	1929 7.1	1929 7.8	1931 7.8	1932 6.9	1942 7.2	1934 $M_s7.6$
4	-	-	-	-	-	~380	~380
5	162	172	-	-	-	236	240
6	101	79	243	165	97	142	117
7	44	-	157	107	-	65	70
8	21	23	82	67	39	31	41
9	-	12	34	34	18	-	22

Table 2. 1934 New Zealand Seismograph Network. * indicates privately owned stations; # indicates seismograms re-read.

Station	Instrument	Drum (or recording) rate	Records available
Arapuni (ARA)	Milne	4 mm/minute	all#
Tuai (TUA)	Milne-Jaggar	variable, from 4-10 mm/minute	-
New Plymouth (NPZ)	Wood-Anderson	30 mm/minute	-
	Milne-Jaggar	variable, from 4-10 mm/minute	Mar 15 only#
Hastings (HAS)	Milne-Jaggar	variable, from 4-10 mm/minute	all#
Dannevirke (DNN)*	Milne-Jaggar	variable, from 4-10 mm/minute	-
Bunnythorpe (BUN)	Milne-Jaggar	variable, from 4-10 mm/minute	all#
Takaka (TAK)	Imamura	20 mm/minute	all, March 5 from Hayes [5]#
Wellington (WEL)	Wood-Anderson	30 mm/minute	all#
	Galitzin-Wilip		all
	Milne-Shaw		all
	Milne-Jaggar	variable, from 4-10 mm/minute	all#
Greymouth (GRY)	Milne-Jaggar	variable, from 4-10 mm/minute	-
Glenmuick (GLE)*	Inverted pendulum		-
Christchurch (CHR)	Wood-Anderson	30 mm/minute	-
	Galitzin-Wilip		-
Chatham Islands	Milne	4 mm/minute	from March 15#

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 12 km; Figures 8 and 9) that differs, by less than 10 km from the epicentre derived from local stations only. The mainshock epicentre is better constrained than that of any other earthquakes 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 9).

The data are too few and the nearest stations too distant to reliably calculate the depth of the 1934 March 5 shock (or any other shock in March 1934). However, the arrival time data suggest that the earthquake was shallow, i.e. probably not deeper than about 25 km. This conclusion is inferred

from the "free depth" location using the best local and teleseismic data, which yielded a depth of 12 km (formal

standard deviation 7 km). A shallow depth is consistent with the observed intensities.

Table 3. Instrumentally derived epicentres for the 1934 March 5 Pahiataua earthquake, its major aftershocks and the 1934 March 10 Porangahau earthquakes. Teleseismic data as well as local station data were used to locate the mainshock.

Year	Date	Time (UT)	Lat °S	Long °E	Dept h	Magnitude	Max. MM intensity	Location
1934	Mar 05	1146 13	40.5	176.3	12R	$M_s7.6$, $M_w7.4$ (prelim.)	MM9	Approx. Waione to Bideford
		1157 42	40.7	176.0	12R	about $M_L5.8$		
		1221 20	40.7	176.0	12R	$M_L4.8$		
	Mar 06	1252 24	41.1	176.4	12R	$M_L5.2$	MM4	Widely felt in southeast North Island
	Mar 10	0757 11	40.6	176.7	12R	$M_L5.6$	MM7	Porangahau
	Mar 10	0803 43	40.4	176.9	12R	$M_L4.6$		Porangahau
Mar 10	0853 53	40.4	176.8	12R	$M_L5.0$	Porangahau		

Modelling of teleseismic body waves (Doser pers. comm. 1997) has yielded a preliminary mechanism for the earthquake. Strike-slip faulting at $12 \text{ km} \pm 5 \text{ km}$ depth is indicated, with a near vertical nodal plane striking at $16^\circ \pm 6^\circ$, this being the preferred fault plane as it aligns with the MM9 isoseismal. The moment magnitude (M_w) obtained was 7.4 compared with the surface wave magnitude $M_s7.6$.

Aftershocks and other related earthquakes:

The highest magnitude aftershock ($5.8 \geq M_L \geq 5.3$) occurred ten minutes after the mainshock. Phases for this earthquake are difficult to identify confidently as the trace 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 $M_L5.0$), further obscuring arrivals. The highest amplitude that can be identified on the Wood-Anderson seismogram indicates a magnitude of $M_L5.3$. However, comparing seismograms at various stations with those for the earthquakes on March 10 and 15, whose magnitudes are well determined, suggests the highest amplitude detectable on the Wellington record is not the maximum and that the earthquake had a magnitude possibly as high 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 within the MM9 isoseismal and about 30 km southwest of the mainshock epicentre (Figure 8, Table 3).

About thirty minutes after the mainshock two earthquakes occurred with only a few seconds separating 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, however, are similar to the largest aftershock.

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

On March 6 1934, just over 24 hours after the mainshock, a moderate magnitude event ($M_L5.2$; Figures 8 and 9) occurred offshore about 70 km southeast of the mainshock. Another large event, located using teleseismic as well as local data, occurred 150 km northeast of the mainshock on March 15 ($M_L6.0$, $M_s6.5$) (Figure 8). Both locations are consistent with their respective intensity distributions (March 6, this paper; March 15, Dowrick, unpub. data).

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, reported to be comparable with the damage from the March 5 earthquake. The instrumental location of the first and largest event ($M_L5.6$) is 30 km south of Porangahau, while the solutions for second and third earthquake places them within 20-25 km 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 at 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 20 km or more.

Possible errors in location make it difficult to decide if the Porangahau events represent an extension of the mainshock

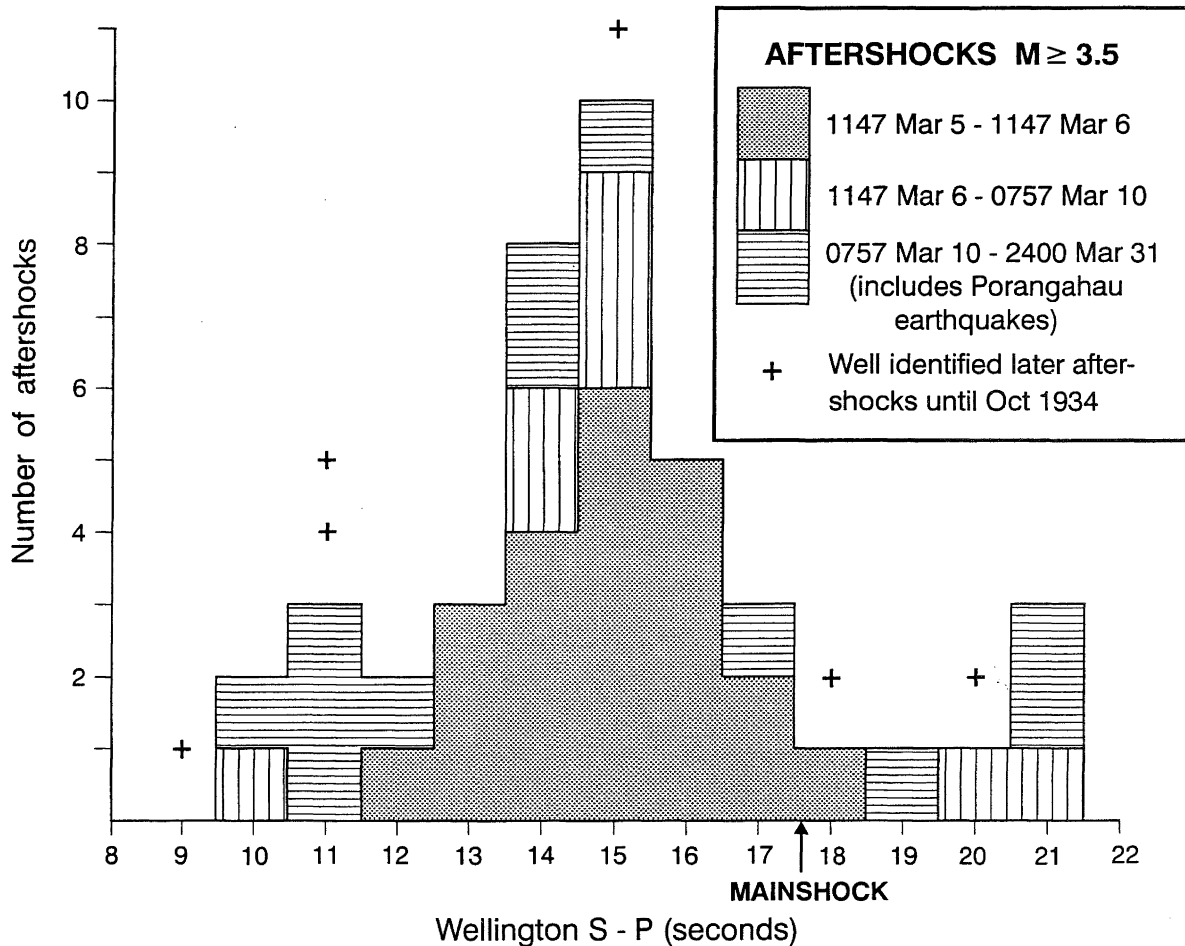


Figure 10. Histogram of S-P intervals ($l_s = 9$ km approx.) read from Wellington Wood-Anderson seismograms for $M \geq 3.5$ aftershocks after 24 hours, after 5 days (i.e. up to the occurrence of the Porangahau earthquakes) and until the end of March 1934. Also shown are well-identified later aftershocks until October 1934.

rupture or are off-fault, possibly stress-triggered events. Historically, many events with $M \geq 6.0$ have occurred within 20-30 km of 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). The 1990 Weber earthquakes were located within 15 km ($M_L 6.1$; Feb 19) and 25 km ($M_L 6.2$; May 13) [26] of the 1934 mainshock epicentre.

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. Some aftershocks, particularly those with short S-P intervals, can be correlated with felt information. Histograms of the S-P intervals after 24 hours, until March 10 (up to but not including the Porangahau earthquakes), and to the end of March are shown in Figure 10. Gibowicz [10] gave similar diagrams. His distributions, however, included the March 6 and March 15 events and possibly several other events (aftershocks of the March 15 event) that did not have origins in the epicentral area.

The distribution of the mainshock, major aftershock and identifiable (by felt information) minor aftershock epicentres and the NE-SW alignment of the inner isoseismals and the preliminary focal mechanism suggest possible NE-SW rupture and hence, the distribution of the S-P intervals of the aftershocks might be expected to define the extent of the rupture plane.

Gibowicz [10] concluded that 90% of all aftershocks (over more than six months) occurred in a zone about 70 km long and this he took to represent the length of the mainshock rupture. The distribution of aftershocks in the first 24 hours is now considered a more reasonable indicator of the mainshock rupture zone. The 24-hour S-P intervals, determined in this paper, span about 5.5 sec., suggesting a rupture length of about 50 km. The 5-day S-P intervals (excluding the Porangahau earthquakes) span about 11.5 sec., or about 90 km, with two events only having S-P's greater (by 2.5 - 3 sec) than the mainshock. At least one of these events had a similar S-P to the $M_L 5.2$ earthquake offshore and occurred only six hours after it, and therefore may have been an aftershock of it. The histogram suggests that both these events and the later Porangahau events with similar S-P intervals are probably not part of the mainshock rupture zone. By excluding them, the 5-day S-P intervals span just over 8

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

Fault ruptures of this size are consistent with the estimated magnitude. Assuming a average stress drop of 3×10^6 N/m² (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 65 km. A higher stress drop or greater fault width would increase M_w .

Comparison of the 24-hour aftershock numbers of the Pahiatua earthquake with those of other large shallow (upper plate) earthquakes in the region shows that the number of aftershocks in the Pahiatua earthquake sequence is somewhat small. The Wellington records show that about 30 aftershocks with $M_L \geq 3.5$ occurred in the first 24 hours, whereas the 1931 $M_s 7.8$ Hawke's Bay earthquake produced 170 events ($M_L \geq 3.8$), the June 1942 $M_s 7.2$ earthquake, 80

events ($M_L \geq 3.5$) [10] and the more recent May 1990 $M_L 6.2$ Weber earthquake produced 60 events ($M_L \geq 3.5$) [26]. The number of aftershocks decreased rapidly after the first day and fewer than 80 magnitude 3.5 and above aftershocks (including the Porangahau events) had occurred by the end of March (26 days). However, in the five months following the mainshock six earthquakes with magnitudes 4.0 - 5.5 (Figure 9 and Table 4) were strongly felt at locations from just north of Masterton to near Ti-Tree Point and Wimbledon, the April 14 ($M_L 5.5$) 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 three weeks. Other events may have occurred in the same area in November and December, but felt intensity data do not indicate a specific highest intensity area which would identify probable locations for the earthquakes.

Table 4. Locations, maximum MM intensities and Wellington S-P intervals of well-identified later aftershocks (April - October) of the Pahiatua earthquake.

Year	Date	Time (UT)	Wellington S-P interval (sec.)	Magnitude	Max MM intensity	Location
1934	Apr 14	0818	10.6	$M_L 4.2$	MM4	Masterton
	Apr 14	0848	20	$M_L 5.5$	MM7	Ti Tree Point, Wimbledon
	Apr 20	1658	15	$M_L 4.7$	MM4	Masterton, Pahiatua, Dannevirke
	May 01	0941	9.2	$M_L 4.8$	MM6	Mauriceville
	Aug 08	0005	10.8	$M_L 4.0$	MM5	Bideford (possibly two events)
	Aug 08	2030	11.2	$M_L 4.5$	MM4	Masterton

GEOLOGICAL SETTING AND POST-EARTHQUAKE OBSERVATIONS

The epicentral region of the 1934 earthquake lies within the East Coast Deformed Belt (ECDB) [27], the onshore manifestation of the deformation at Pacific-Australia plate boundary in the North Island. The epicentral region also straddles two of the major structural domains of the geology of eastern North Island [28]. To the east of a structural line approximately between Tiraumea and Pongaroa the geological sequence includes Mesozoic bedrock greywacke overlain by a complexly deformed early Cretaceous sequence of sedimentary rocks and a less deformed late Cretaceous-Paleogene sequence. To the west of this structural line the basement greywacke is overlain by late Miocene rocks of slope basin affinity related to the Hikurangi subduction margin. This structural line therefore marks the hinge-line between an outer part of the region that was sedimentary basin through the late Cretaceous and early Tertiary, and an inner part that was initially uplifted and eroded, but which later subsided as the Hikurangi subduction margin continued to evolve.

Present-day active faulting in the region is represented by a developing oblique and strike-slip phase that is well expressed along the Wairarapa-Alfredton-Makuri zone to the west of the epicentral area, but is only now becoming established in the Pongaroa-Tiraumea area [29]. Active faults in the epicentral area are characterised by short traces, often only a few to ten kilometres long, with weak geomorphic expression, often due to rapid rates of surface processes in weak rock types. The active faults have not accumulated sufficient total displacement to significantly modify the geomorphology of the region. Movement on the faults has not yet formed distinctive hills and basins, or diverted or modified the drainage pattern, even though many of the faults appear to have rates of movement of the order of several metres per thousand years [29]. 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 [30]).

The large magnitude of the Pahiatua earthquake and its preliminary depth and source mechanism determined by Doser (pers. comm. 1997) suggest that rupture could have extended to the surface. However, no contemporary account

nor recent enquiries among old settlers indicates that any rupture was noticed. Further, Ongley, who was conducting a field survey of the east coast between Castlepoint and Cape Turnagain at the time and was at Mauriceville at the time of the earthquake immediately made a tour of the strongly shaken areas surveying damage as well as looking for a surface trace [14]. None was found nor was any reported to him. However, his coverage of the area was restricted because of his mode of transport, either on a bicycle or as a passenger in a courier or mail van. Ongley passed through Pongaroa but did not go south to Alfredton, possibly because he was not aware of the Alfredton Fault at the time. He examined the Alfredton Fault for the first time in December 1935 [31]. The geology of the Pongaroa area was probably not examined by Ongley or other Geological Survey staff in any detail until after the earthquake also.

Ongley made inquiries about reported uplift of the coast around Cape Turnagain but written replies [14] from coastal station owners were inconclusive. Given the location, magnitude, depth and mechanism of the earthquake no uplift would be expected and there is no geological evidence of recent significant uplift in this region (Ota *et al* [32]).

DISCUSSION

This study has been successful in achieving its objectives of providing reliable and extensive data on both the location of the epicentres and the effects of the mainshock and other related shocks in March 1934. Given the modest quality and small number of early seismograms, agreement of the instrumentally derived epicentres with their respective zones of highest intensity is excellent, despite an estimated error in the epicentral locations of about 20-40 km. Indeed, the locations of the instrumentally derived epicentres and distribution of S-P intervals from Wellington are sufficiently consistent that inferences have been made about the location and extent of the rupture of the 1934 Pahiatua earthquake, and the distribution of its aftershocks. The fortunate location of the Wellington seismograph almost along strike of the inferred rupture zone and 120 km southwest of it provided this opportunity to examine the distribution of aftershocks - an opportunity that would be rare in an era of such poor instrumentation.

The incidence of damage was typical of that for a large earthquake centred in rural New Zealand in an era when brick buildings and timber buildings with brick chimneys predominated. Despite much falling masonry, casualties were negligible almost certainly because the main shock occurred late at night when most people were inside their robust timber houses and not in the streets of Pahiatua where falling of masonry was sufficiently extensive to have caused injuries and possibly several deaths.

The closeness in time between the Pahiatua earthquake and the Porangahau earthquakes five days later has always aroused curiosity. Their close proximity in *space* as well as in time suggests that they were part of the Pahiatua earthquake sequence. Although probably not part of the mainshock rupture zone, they were almost certainly triggered. Whether they were along strike of the mainshock rupture or off-fault is uncertain because of the location errors.

The aftershock zone clearly shows growth with time, mainly to the southwest, although the record of the more distant northeast events may not be complete. The aftershock sequence was protracted and lasted for at least five months, similar to the nearby 1990 Weber earthquake sequence with four M 5.5+ earthquakes over more than a year and within 15km of each other. Unlike the 1990 Weber sequence, which had one earthquake M 6.2 in the upper plate and three earthquakes with $M \geq 5.5$ in the lower plate, all the aftershocks (including those up to 5 months later) that can be unequivocally associated with the 1934 earthquake seem to have occurred at shallow depths, as identified by their magnitudes and felt information. It may be of interest to compare the distribution of the Porangahau earthquakes, later aftershocks, and possibly the 1942 Wairarapa earthquakes (June M_s7.2, August M_s7.0 and December M_s6.0) with stress triggering models of King *et al* [33] when the teleseismic studies of the Pahiatua mainshock (Doser & Webb, pers. comm.) are complete and the source mechanism is known. The small, possibly secondary, surface rupture accompanying the June 1942 earthquake (Ongley [34]) is less than 30 km from the largest 1934 aftershocks and within 10 km of the some of the later aftershocks (Figure 9). The 1934 data presented here, the seismological and engineering studies of the 1942 earthquakes in progress, and the source mechanisms from continuing studies of Doser and Webb (pers. comm.), will provide the necessary data for investigating the tectonics of this interesting and important 1934-1942 sequence of earthquakes.

Teleseismic body wave modelling by Doser and Webb will also give a more accurate estimate of the depth of the 1934 earthquake than can be determined from the local seismographic data used in this paper. At present, the preliminary solution of a strike-slip mechanism at 12 km depth suggests that surface rupture could have taken place. Schermer and others [29] present new data on two fresh-looking faults within the MM9 isoseismal and close to the inferred rupture zone (Figure 9). Their data confirm that rupture on the Waipukaka Fault has occurred since European settlement of the area, and that the most probable earthquake to have caused that rupture was the 1934 Pahiatua earthquake.

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APPENDIX :

March 05 1934 Pahiatua earthquake MM intensities listed by location. A brief summary of damage to structures, services and to the environment for MM8 and above is given after the table. Note that the wording used reflects that in historical accounts especially with regard to numbers of chimneys damaged.

INTENSITIES (in alphabetical order; MM8 and above in bold font)

<i>North Island</i>	Kairanga - MM7?	Patumahoe - MM4	Waipiro Bay - MM3
Akaroa (near Pongaroa) - MM8?	Kaituna - ≥MM7	Patea - MM6	Waipukurau - MM5
Akitio - MM8-9	Karioi - ≤MM6	Petone - MM6, MM7 in some areas	Wairoa - MM4
Alfredton - MM9	Kawhia - MM4	Piripiri - MM7	Waitara - MM5
Aokautere - MM7?	Kiritaki - MM7	Pohangina - MM6	Waitarere - MM6
Apiti - MM6?	Kohinui - MM8?	Pongaroa - MM9	Wallingford - MM6-7?
Ashhurst - MM7	Koputaroa - MM7?	Porangahau - MM8	Wangaehu (Wairarapa)-MM8
Auckland - MM3	Kumeroa - MM8	Portland Is. Lighthouse - MM4?	Wanganui - MM6, MM7 in some areas
Awakino - MM4?	Levin - MM7	Raetihi - MM6	Wanstead - MM5
Awapuni - MM7	Longburn - MM8	Rakaunui - MM9?	Wararoa - MM5
Bagshot - MM9	Longbush - MM8	Rangiotu - MM6	Weber - MM8
Ballance - MM7	Lower Hutt - MM6	Rangitumau - MM8	Wellington - MM5, MM6 in places
Bideford - MM9	Maharahara - MM7	Raumati (Hawke's Bay) - MM7	Westmere (near Wanganui)- ≤MM6
Brancepeth - ≥MM6	Makerua - MM8	Rongomai - MM9?	Whakataki - MM7
Bulls - MM5, MM6? in places	Makomako - MM7	Rongotea - MM6	Whakatane - MM4
Bunnythorpe - MM8	Makotuku - MM7	Rotorua - MM4	Whangaeu - MM6
Cambridge - MM4	Makuri - MM9	Sanson - MM6	Whetukura - MM7
Cape Egmont Lighthouse - MM5?	Mangamahoe - MM8?	Shannon - MM7	Whitianga - ≤MM3
Cape Palliser Lighthouse - MM4	Mangaone - MM8	Stratford - MM5	Wimbledon - MM8?
Carrington - MM7	Mangaorapa - MM6	Strathmore - MM6	Woodville - MM8
Carterton - MM7	Mangatainoka - MM7	Taihape - MM6?	
Castlepoint - MM7	Martinborough - MM6	Taikorea - MM5	<i>South Island</i>
Chateau Tongariro - MM3	Marton - MM6	Takapau - MM5	Akaroa - MM4
Coonoor - MM7?	Masterton - MM7	Tarawera (Hawkes Bay)- MM4	Akaroa Lighthouse - MM3

Dalefield - MM7	Matamata - MM3	Taumarunui - MM5	Ashburton - MM3
Dannevirke - MM7	Matamau - MM7	Taupo - MM5	Blenheim - MM5
Douglas - MM6	Mauriceville - MM7, MM8? in places	Tauranga - MM3	Cape Campbell Lighthouse - MM4
Eastbourne - MM5	Mauriceville West - MM9	Tauweru - ≥MM8	Cape Jackson Lighthouse - MM5
Eketahuna - MM8	Mohaka - MM4?	Te Aroha - MM4	Cheviot - MM4
Eltham - MM6?	Motea - ≥MM7	Te Awamutu - MM4	Christchurch - MM4
Featherston - MM7	Motu - MM4	Te Kuiti - MM4	Collingwood - MM4-5?
Feilding - MM7	Moutoa - MM8	Te Ore Ore - MM7	Culverden - ≤MM3
Fordell - MM6	Murupara - MM3	Te Rehunga - MM6-7	Dunedin - MM3
Foxton - MM7	Napier - MM5	Te Teko - MM4	Farewell Spit - MM5?
Gisborne - MM4	New Plymouth - MM5, MM6 in places	Te Uri - MM8	Greymouth - MM3
Gladstone - MM8	Ngaere - MM5, possibly MM6 in places	Thames - MM3	Hanmer Springs - MM4
Glendonald - MM8?	Ngaturi - MM8	Ti Tree Point - MM8	Havelock - MM5
Greytown - MM6	Nireaha - MM7	Tiakitahuna - MM7	Hokitika - MM4
Halcombe - MM6	Norsewood - MM5	Tikokino - MM5?	Invercargill - MM2
Hamilton - MM4	Ohakune - MM4?	Tinui - MM7	Kaikoura - MM4
Hastings - MM5	Okahukura - MM4?	Tiniroto - MM4	Karamea - MM4
Hatuma - MM5	Okoia - MM6	Tipapakuku - MM6	Middlemarch - ≤MM3
Haunui - MM9	Ongaonga - MM5	Tiratu - MM8	Murchison - MM4?
Hawera - MM5, MM6 in places	Opotiki - MM4	Tiraumea - MM9	Nelson - MM4
Herbertville - MM8?	Opunake - ≤MM5	Tokaanu - MM5?	Oamaru - ≤MM3
Hicks Bay - MM3	Ormondville - MM6	Tokomaru - MM7	Picton - MM4?
Hiwinui - MM7?	Otaki - MM6	Tolaga Bay - MM3	Rai Valley - MM5
Homebush - MM6	Otane - MM5	Turua - MM4	Rakaia - MM3
Hopelands - MM8	Otawhao - MM7	Umutaoroa - MM7	Reefton - MM3
Hunterville - MM5	Paekakariki - MM6	Umutoi - MM6	Seddon - MM5
Huntly - MM3?	Paeroa - ≤MM3	Upper Hutt - MM6	Stephens Is. Lighthouse - MM4?
Ihakara - MM7?	Pahiatua - MM8	Waihi - ≤MM3	Takaka - MM5
Ihuraua Valley - MM9	Palmerston North - MM7	Waikanae - MM6?	The Brothers Lighthouse - MM5?
Inglewood - MM5	Paraparaumu - MM6	Waione - MM9?	Timaru - MM3
Kai iwi - ≤MM5	Parkvale (near Carterton) - MM7	Waipawa - MM5	Westport - MM4

INTENSITIES ≥ MM8 (in alphabetical order):

Akaroa Quarry - MM8?

At Akaroa Quarry there was some damage to machinery. Cracks formed in concrete walls and foundations and there was extensive ground cracking round buildings.

Akitio - MM8-9

Considerable damage occurred at Akitio Homestead with all chimneys fallen, breaking through the roof in places. The private power plant (hydro?) was totally destroyed. Many houses in the Akaroa-Akitio area, i.e. east of Pongaroa, were rendered uninhabitable, some being more affected than others, and many people had to resort to cooking on open fires.

Alfredton - MM9

Most chimneys fell. Twenty or more houses were damaged structurally. A small concrete bridge on the Alfredton-Masterton Road was cracked and shifted from its foundations and fissures appeared in the road nearby.

Bagshot - MM9

One house had doors and woodwork smashed. In a woolshed studs and floor joists were broken. Small branches fell from pine trees. Nearby flat land was badly cracked.

Bideford - MM9

There was considerable structural damage to at least two houses, which were racked and distorted. The verandah was wrenched from one and the chimney foundations sunk a metre or more. Outbuildings at the second property were extensively damaged and the woolshed thrown from its piles. Nearby a landslide estimated to be 5 acres in extent came down. Tanks were thrown down. In many places there were cracks in the road (30 between the 6-9 mile pegs) and some landslides.

Bunnythorpe - MM8

Many, or nearly all, chimneys fell, plate glass windows broke and stock was thrown about in shops. The brickwork and foundations of the sub-station were badly cracked. The touching of power wires tripped switches.

Eketahuna - MM8

No buildings collapsed, but several brick walls leaned and some parapets and foundations were cracked and broken, more damage becoming obvious with thorough inspection. 75% of chimneys were thrown down, while the rest were twisted and badly damaged (later estimates indicate that up to 90% were damaged in some way, i.e. 1000 chimneys). Heavy furniture was moved and there was heavy damage to stock in shops.

Damage to services:

Damage to power board lines similar to that reported in Dannevirke, i.e. many twisted lines tripping switches during the earthquake with other faults, accentuated by wet weather, appearing over the next few days. Slips affected the railway line at Eketahuna and Hukanui.

Gladstone - MM8

The earthquake said to be severe. Most chimneys and tanks were brought down and many roofs were damaged through falling bricks. Cracks appeared in at least one road.

Glendonald - MM8?

Chimneys (no details) fell, houses were damaged, and cracks were caused in some of the roads in the area.

Haunui - MM9

There was severe damage to at least one house (no details).

Herbertville, Wimbledon - MM8?

Some chimneys fell and others were cracked. A heavy stove was wrenched from a chimney. These areas (including Weber) were said to have more damage than Porangahau.

Hopelands - MM8

One house of concrete blocks was so badly damaged that it was declared unsafe. Other houses were badly damaged from falling chimneys and in some cases rafters were broken and interior walls torn apart. Equipment in milking sheds was damaged. Preliminary estimate of damage, £14,000.

Ihuraua Valley - MM9

Practically all chimneys were brought down, being shaken right to the base. Almost without exception houses were twisted to some extent, furniture thrown about and water tanks ruined. Several houses required complete re-wallpapering. Roads were badly cracked.

Kohinui - MM8?

School chimney was half shaken down. Tank stand was shifted 4ft (1.2 m) from a wall.

Kumeroa - MM8

Most chimneys fell and there were many household articles broken. One concrete house was so badly cracked that it was considered unsafe by the owners and they abandoned it. Roads cracked in many places.

Longburn - MM8

In a small area between Palmerston North and Longburn, every chimney fell.

Longbush - MM8

The earthquake said to be severe. All chimneys fell and interior walls were distorted in at least one instance. Furniture as well as crockery was damaged and broken. There were also cracks up to a 10 m long and 300 mm wide in several places. A landslide blocked the Whakaroa Creek.

Makerua, Moutua - MM8

On the low lying land in these two areas almost every chimney fell down and on the land near the river, long, wide cracks, more than 40 m long and up to 300 mm wide formed. There was evidence of large sand fountains, which continued

to ooze for several days, and differential settlement with some strips of land having sinking 300-450 mm. Deep fissures cut through the stopbank at Coley's Bend while smaller cracks in the stopbank were evident elsewhere. Other fissures ran along the river banks.

Makuri - MM9

Almost every chimney collapsed. Many houses suffered interior structural damage, for example, collapse and racking of interior walls. At least one of the badly damaged houses was close to a creek, which went "suddenly dry" during or just after the earthquake. One large house at Te Rata was shifted from its piles. At the school, windows were broken, the water tanks and stands were badly damaged, chimneys were destroyed and pantry shelves emptied. Numerous slips were visible in the nearby countryside and large boulders were displaced. Landslides of up to 100 tonnes were dislodged. Roads were cracked parallel with and across the road, with slumping in parts. The Makuri Gorge Road was blocked by a landslide. In the township the bridge approaches subsided and cars could barely cross.

Mangamahoe - MM8?

Many chimneys were brought down, but the area "escaped worst of shock" (in comparison to Ihuraua).

Mangaone - MM8

Two houses were said to be considerably damaged. There were numerous cracks in the road from Mangaone to Pongaroa.

Mauriceville - MM7, possibly MM8 in places

Parts of Mauriceville were severely affected, other parts "almost entirely escaping damage". The approaches to a small railway bridge subsided with the result that the railway line was suspended for about 10 m. Between Mauriceville and Mangamahoe the railway track was put out of alignment and there were subsidences north and south of Mauriceville station. The road to Masterton was cracked.

Mauriceville West - MM9

Few chimneys were left standing, doors in homes were jammed (i.e. racking) and many windows shattered.

Moutua - MM8

Refer to Makerua.

Ngaturi - MM8

No chimneys were left standing. There was minor damage to structures, including bridges, and a few very small slips occurred.

Pahiatua - MM8

Many chimneys, walls, verandahs and parapets collapsed in the business centre. A number of business premises were subsequently condemned. Few chimneys in homes were left intact and many roofs were damaged by falling chimneys. Over 600 chimneys in 412 houses in the Pahiatua Borough needed repairs. The War memorial was displaced but did not fall.

Services:

A water main burst in King St. The railway line between Mangatainoka & Hukanui was buckled in several places.

Road damage in Pahiatua County (i.e. includes area east of Pahiatua)

Road damage was most evident in the Puketoi Ranges and Akaroa Peak areas.

Wellington-Napier road: some damage

Pahiatua-Pongaroa road: One abutment on Allen's bridge was badly damaged. 40 slips and extensive cracking of the road surface between the 8 & 11.5 miles. Road blocked by slip in the Makuri Gorge for 36 hours. There were bad cracks on Makuri side of Pongaroa Hill, both across and parallel to the road.

Makuri-Mangatoro road: subsidence in several places

Pahiatua-Mangaone road: Some subsidences occurred and there were slips on the Mangamarama and Kaitawa hills.

Pahiatua Gorge bridge road: some slips

Tiraumea Valley road: abutment at Whitcoull's(?) bridge slightly damaged

Pongaroa-Akitio Main road: batter slips and cracking between 1 & 4 mile pegs. Heavy falls of rock in Marainanga Gorge

Pongaroa-Akitio road: Many minor slips and cracks at Beach Hill

Glenora Road: falls of rock and earth from high batters

Akitio River road: some heavy slips in upper section?

Towai Road: batter slips and cracking. Subsidence at Wolfs drop.

North Range Road: blocked by earth and rock falls and very serious cracking (all earthquake?)

Waipatakaka road: batter slips. Road partially blocked at Bowie's Bluff.

Tiraumea-Pongaroa road: particularly badly cracked at Kaitawa.

Alfredton-Pongaroa road: cracked in many places.

Pongaroa - MM9

All chimneys and tanks were brought down and some houses were distorted. Earliest comments after the earthquake suggested much less damage. i.e. that chimneys were damaged, but damage to stock in shops not particularly great.

Later comments in newspapers recognise that the effects of the earthquake were greater to the east of the Summit of the Puketoi Ranges, presumably referring to Pongaroa, Tiraumea, Waione, etc., than to the west. A special correspondent sent to the area wrote that,

"bad as Pahiatua was, the damage to the back country was even worse. The roads to the coast are cracked and slips common and in some instances the roads are reported unsafe for traffic. In places telephone poles have been snapped off at ground level and services interfered with. Settlers homes suffered considerable damage and in a very wide area there is scarcely a chimney standing. In several instances wooden homes are unsafe for habitation. The severity of the shake in this location may be gauged from the fact that chimneys in nearly every case have been completely shattered from top to bottom, it being possible to place one's hands in the cracks and crevices around the kitchen ranges.... Where houses have been constructed on high piles the buildings have been twisted and badly strained, it being possible to place one's fist down into the ground alongside the piles where the shaking of the structure has loosened the earth. In a

number of cases great holes have been torn in the roofs where chimneys have crashed through and tanks have been thrown to the ground by the collapse of stands. Windows were broken in a number of houses. Woolsheds suffered in like manner, some being badly twisted with consequent snapping of rafters and struts." (Manawatu Herald Mar 13).

Porangahau - MM8

In the town and surrounding area many chimneys fell, water tanks were damaged or overturned and household articles were broken. Ongley [13] suggests that the newspapers greatly exaggerated the chimney damage in Porangahau (see comment for Herbertville). Several cracks appeared in the river banks and there was a break in main water supply pipe.

Rakaunui - MM9?

Damage to household items was greater than in Pongaroa.

Rangitumau - MM8

Only two or three chimneys were not demolished.

Rongomai - MM8, possibly MM9

Roads were cracked badly, many chimneys were brought down and some outbuildings collapsed.

Tauweru - ≥MM8

The damage was said to be most severe (considerably greater than at Tinui, MM7), with all chimneys brought down. Approaches to the Tauweru Bridge subsided up to 70 mm. Big landslides were reported to be evident at many places near Tauweru and Bideford and there were deep cracks in the roads.

Te Uri - MM8

Most chimneys fell or were extensively damaged.

Ti Tree Point - MM8

Chimneys fell and tanks were broken.

Tiratu - MM8

Few chimneys were not cracked or fallen.

Tiraumea - MM9

Several homes were abandoned. One Haunui Road house, which was built low to the ground was shifted from its piles, wooden ceilings were torn down, windows broken, doors jammed and water pipes torn apart. Water tanks were thrown from piles. Another house, in Waihoki Road, was racked and distorted. Two other houses were also reported as badly damaged.

Waione - MM9?

Damage to household items greater than in Pongaroa (no details).

Wangaehu (Wairarapa)- MM8

A large number of chimneys and tank stands fell. Fireplaces were shifted out of alignment. At least one house (fairly new) was so extensively damaged that it required rebuilding. The walls were twisted and wrenched, the chimneys were brought down and doors jammed. At the same place one outbuilding was shifted from its foundations while the garage and

woolshed leaned. Nearby on the entrance road there were numerous ground cracks. Elsewhere one or two cracks were made in the roads. Damage was noticeable from junction with Bideford Road northwards. There was some damage at bridge approaches. Small branches were dislodged from trees and telephone wires were dislocated in Wangaehu Valley.

Weber - MM8

All the chimneys fell, many water tanks were damaged, a number of roads were cracked and bridges were damaged.

Wimbledon - MM8?

Refer to Herbertville.

Woodville - MM8

90% of chimneys either snapped off at the roof line, broken at the roof line and sitting askew, or completely demolished. Other chimneys were cracked. A number of parapets fell, one up to 30 m long, (another article in Levin Chr Mar 8 states every parapet damaged). On thorough inspection a number of walls not thought to be damaged at first were found to be badly cracked and requiring rebuilding. This applied equally to parapets. The majority of shop windows were damaged, heavy furniture and other articles were moved and there was extensive stock damage. At the Cemetery several tombstones fell and others were loosened, mainly in the older area of the grounds. Preliminary estimate of damage in Woodville, £6,000.

Services in Woodville area:

Cracks, mostly fairly minor and quickly repaired, were made in many country roads, including Druce's Road near Kumeroa, Otawahao, Jackson's and Davies Roads, as well as the main road near the eastern end of the Manawatu Gorge (approx. 800 m of cracking and slight subsidence), and at Ballance and Papatawa. A minor slip occurred on Holder's Bluff Road. There was no damage to the gas reticulation and one very minor leak in a water pipe. There was subsidence at a railway bridge near Woodville on the Masterton-Woodville line.