THE 1942 WAIRARAPA, NEW ZEALAND, EARTHQUAKES: ANALYSIS OF OBSERVATIONAL AND INSTRUMENTAL DATA

G.L. Downes[1], D.J. Dowrick[1], R.J. Van Dissen[1], J.J. Taber[2], G.T. Hancox[1] and E.G.C. Smith[2]

ABSTRACT

In 1942, two large earthquakes, on June 24 (M_w7.2) and August 1 (UT) (M_w6.8), strongly shook the lower North Island, causing widespread moderate to severe damage. A third earthquake (M_s6.0) occurred in the same area on December 2.

These earthquakes have now been studied in detail by re-analysing seismograms from 1942 and by the collection and analysis of contemporary technical information and descriptive accounts from many sources. Results include new locations for the three main earthquakes and other moderate magnitude earthquakes in the sequence, summaries of building, lifelines and ground damage, new isoseismal maps and maps showing the distribution of landslides, liquefaction and other ground damage. The study has provided valuable information on the performance of buildings and lifelines in urban and small town environments at high intensities (MM8) and on the distribution of damaged buildings in central Wellington in relation to published ground shaking hazard microzoning maps and foreshore reclamation units.

An important result is that scarp-like features described after the June earthquake as surface fault rupture are probably landslide-related rather than tectonically produced. This result and the lack of evidence for any other surface fault rupture, the closeness in time and space of the earthquakes both within the sequence and with the 1934 Pahiatua earthquake, and the similarity of the sequence to the 1990 Weber earthquakes have important implications for seismic hazard assessment of this part of the Hikurangi Margin.

INTRODUCTION

The 1942 Wairarapa earthquakes marked the end of a remarkable 13-year period in New Zealand's historical earthquake record when eight magnitude M_s6.9+ shallow earthquakes (depth $\leq$ 45 km) occurred. The 1942 June 24 (M_w7.2 (Doser & Webb, pers. comm., June 1999); M_s7.2 [1]) and August 1 (UT) (M_w7.2 (Doser & Webb, pers. comm., June 1999); M_s7.0 [1]) earthquakes, strongly shook the Wairarapa, Manawatu and Wellington districts, causing moderate to severe damage. A third earthquake, of magnitude M_s6.0 [1], occurred in the same area on December 2. The June and August mainshocks were each preceded within a few hours by moderate magnitude earthquakes (June M_L5.3 (this paper); August M_w5.6 (Doser & Webb, pers. comm., June 1999), M_s5.3 [1]). The December shock initiated its own small aftershock sequence, renewing aftershock activity initiated by the June earthquake and extending the sequence well into 1943 [2].

A national network of eleven seismograph stations (plus a private station at Dunedin) (Figure 1a) meant that the main events in 1942 could be located at the time using graphical means. All were found to originate from the same location near Masterton in the Wairarapa district [3, 4] (Figure 1a). The June and December mainshocks were found to be "shallow", while the August mainshock was recognised as a deeper event [3]. The extent of building damage in Masterton and of ground damage near Tauweru to the east of Masterton (Figure 1b), and the discovery of what was interpreted to be a surface fault rupture a few kilometres north of Tauweru on June 29, confirmed the location of the June event for the seismologists and geologists of the day [3-7].

No fresh fault movement was found after the August shock [3]. However, in 1976, after comparing Ongley's 1930s geological field map with 1943-44 aerial photographs, Neef [8] concluded that a minor fault near Alfredton probably ruptured in the August earthquake. In addition, according to the recollections of an eye-witness, one of the 1942

[1] *Institute of Geological & Nuclear Sciences Ltd., Lower Hutt.*
[2] *Victoria University of Wellington, Wellington.*

earthquakes caused a scarp to form on what has subsequently been identified as a small fault in the Aorangi Ranges [9], over 60 km from Masterton and Tauweru. Dendrochronological dating confirmed that the growth of trees near the fault was disturbed within a year or two of 1942 [9].

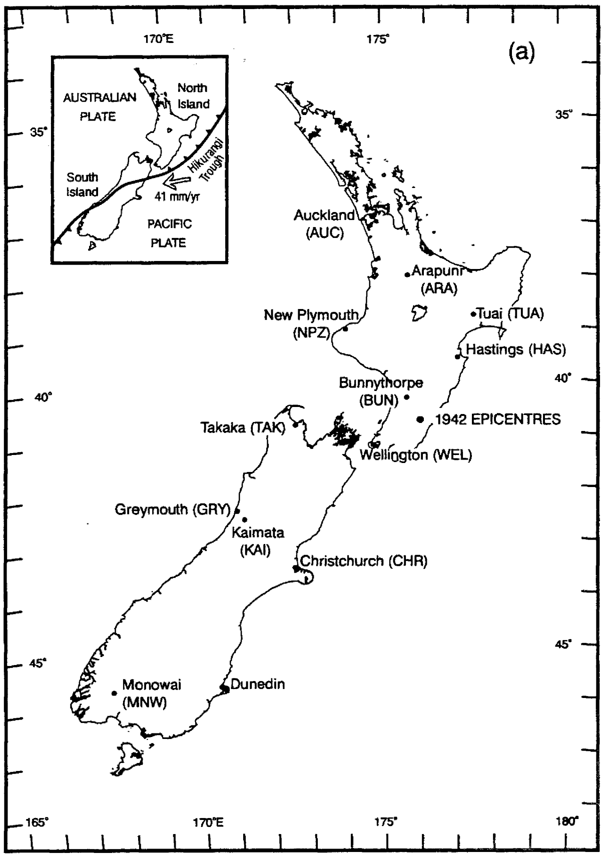

Figure 1:(a) Map of New Zealand showing the locations of seismographs in 1942, the main features of the convergent plate boundary through New Zealand (inset), and the epicentres of the 1942 Wairarapa earthquakes, all at the same location, determined by the Seismological Observatory in 1942.

The occurrence of the 1942 earthquakes during the Second World War years when labour and resources were directed elsewhere meant that the Seismological Observatory published no comprehensive account of the effects of the earthquakes nor their seismological aspects in the scientific literature, as had been done soon after the large earthquakes from June 1929 –1934 [for example, 10, 11]. Hayes wrote only brief accounts of the building and ground damage [3, 5], based on newspaper accounts and on observations during a 5-day reconnaissance trip to the Wairarapa immediately after the June earthquake with Dr Lillie and M. Ongley (New Zealand Geological Survey). Ongley [6] elaborated on the geological aspects of the June earthquake, including his field observations of ground damage and suspected "fault rupture".

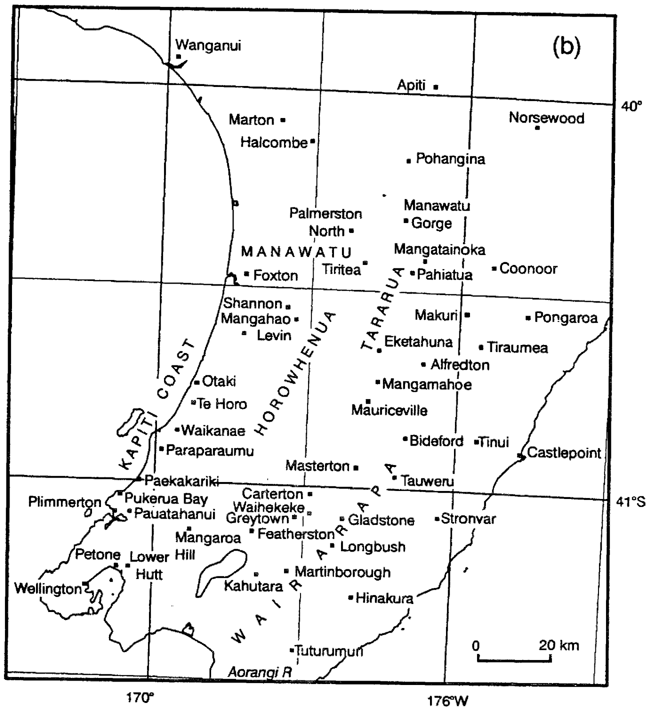

Figure 1: (b) Map showing the location of places mentioned in the text.

Only one account of the damage was published by a contemporary engineering observer. Aked's [12] analysis of damage to buildings in the City of Wellington was published in 1945. An unpublished report [13] by Luke, a Wellington City Council Engineer, covers much the same material as Aked, but the report also includes broad details on the distribution of chimney damage. In 1960, Johnston [14] made some useful comments in a brief discussion of buildings damaged, again in Wellington only, from his investigation of 900 buildings in the central city area. In conjunction with other geological, historical and modern instrumental data, these reports were used to help delineate areas in Wellington that might experience shaking enhancement or microzoning effects in future earthquakes [15-17].

Isoseismal maps for the earthquakes were published in 1943 [4], but were very small scale, did not show individual intensity observations and were based on the Rossi-Forel (R-F) scale. Various versions of the MM scale have been in use in New Zealand since January 1943 [GNS files]. The most recent version is that of Dowrick [18]. Eiby prepared new isoseismal maps for the 1942 June and August mainshocks based on R-F to MM scale conversion [19], so they could be used in attenuation of intensity studies. Although used for early attenuation studies [20, 21], these maps are now being replaced with new MM intensity maps based on comprehensive studies [for example, 22-24, this study]. These have been used to develop the most recent attenuation equations [25].

Studies based on instrumental records include statistical analysis of the aftershocks [2], and source mechanisms and depths of the June and August mainshocks from analysis of teleseismic wave forms recorded at Pasadena, California [26]. Teleseismic body wave modelling studies of large historical North Island, New Zealand, earthquakes by Webb & Doser [27], are in progress. Their studies will yield source mechanisms, moment magnitudes and depths for the June mainshock and the two August 1 earthquakes [pers. comm.].

Previous papers by the authors and others [22-24, 28] have demonstrated the benefits of comprehensive studies of large historical earthquakes for which there is short period local instrumental data and/or teleseismic data to establish locations, source mechanisms, depths, and surface wave and moment magnitudes. These investigations were undertaken to provide essential data for seismic hazard and intensity attenuation studies, data that had not been provided by more recent earthquakes because few large earthquakes have occurred from 1943-present, and few of the earthquakes that have occurred have been close to large towns. The purpose of the studies is to provide well-constrained isoseismal maps with well-determined epicentral parameters and source mechanisms, and to provide extensive data on the performance of structures and services in high density residential and business environments at moderate to high intensities and near source. Not only did the 1942 earthquakes occur very close to the town of Masterton, where there were many substantial non-domestic brick and concrete buildings, but also they provide the opportunity to document shaking-enhancement effects of a large distant shallow earthquake on reclaimed inner-city areas such as exist in Wellington. Further, the 1942 earthquakes occurred on the east coast of the North Island, an area which experiences moderate to high seismicity as a result of subduction of the Pacific Plate beneath the Australian Plate along the Hikurangi Trough (Figure 1a). Identifying the mechanisms and locations of these earthquakes within this zone is important for understanding how the relative movement of the plates is accommodated.

In this paper, the authors provide new instrumentally-derived locations for the 1942 Wairarapa earthquakes, their aftershocks and the two shocks that preceded the main events in June and August, new descriptive accounts and isoseismal maps, a detailed summary of lifelines damage, building damage at intensities of MM8, and a new map and description of the distribution of ground damage. Because of its importance in microzoning studies, Wellington City damage is summarised, and new information on the distribution of damaged commercial buildings is discussed. The lack of an identified surface fault rupture, the closeness in space and time of the earthquakes, both within the sequence and with the 1934 M_s7.6 Pahiatua earthquake, and the similarity of the sequence to the 1990 Weber earthquakes, are among the results discussed that have important implications for seismic hazard assessment of this part of New Zealand.

INSTRUMENTAL DATA

According to Eiby [29], the New Zealand Network of eleven stations (plus a private station at Dunedin) (Figure 1a) and the knowledge of New Zealand's crustal structure and velocities were developed enough by the early-mid 1940s that epicentres of magnitude 4.0 and above earthquakes between latitudes 38°S and 42°S could be calculated. An important proviso was that all stations were operating. However, the understanding of New Zealand's crustal and velocity structures were far less then than today, and moreover, epicentres could only be determined graphically. Based on the successful use of old records to relocate the 1934 M_s7.6 Pahiatua earthquake and other March 1934 earthquakes [24], the authors have re-read phase arrivals from as many seismograms of the larger 1942 earthquakes as could be located and analysed them using modern location methods and velocity models (for description, see [30]).

Although instrumentation had improved over that of 1934 with the installation of a Wood-Anderson at Tuai (TUA) and an Imamura strong motion recorder at Wellington, at least six stations still had no absolute timing, or had poor timing, and recording speeds that were too fast (commented on in [24]). Having New Plymouth (NPZ) Wood-Anderson records, Wellington (WEL) Imamura strong motion records and, in December, Imamura records from Bunnythorpe (BUN), none of which were available in March 1934, should have meant that the 1942 solutions would be better constrained than those for the 1934 earthquakes. However, while the network was adequate for locating isolated shocks the authors found that the resolution on individual records was not good enough for resolving locations when multiple shocks and/or very large shocks occurred.

Phase arrivals for the mainshocks, the shocks preceding the mainshocks and significant aftershocks were read from North Island seismograms that could be found in the Seismological Observatory's archives (i.e. all except TUA). Reliable amplitudes, and S-P intervals (time between the arrival of the P- and S- waves) or P and S arrivals, at other stations were added from readings tabulated by Eiby from the analysts' working books (Eiby, working papers in GNS files). Reread arrival times differ from 1942 readings by up to 3sec., some of the differences being attributable to the better magnifying equipment, which allows one more significant figure to be read than done in 1942.

Locations for the mainshocks, two shocks preceding the June and August mainshocks and larger aftershocks ($M_L \geq 4.9$) calculated from these data are shown in Table 1. The estimated location error for any of the earthquakes is about 20 km. Because of the few stations constraining the epicentres, most are sensitive to the omission of any of the key stations (WEL, NPZ, HAS, BUN). M_w (Doser & Webb, pers. comm., June 1999) and M_s [1] are given where available, while local magnitudes (M_L) of other located earthquakes are derived from the WEL, CHR (using 1942 readings) and NPZ Wood-Anderson records.

Epicentres of the June, August and December mainshocks and their preceding shocks:

Except for the first earthquake on August 1, all the locatable earthquakes in the sequence, including major aftershocks, are found to cluster about Masterton and within about 35 km of each other (Figure 2). They are also west of, and within about 19-42 km of, the epicentres calculated in 1942 [see 3, 4].

Table 1. Instrumentally derived epicentres for the 1942 June 24, August 1 (UT) and December 2 Wairarapa earthquakes, the June 24 foreshock, the August 1 Makuri earthquake and major locatable aftershocks of the June 24 mainshock. The epicentres are based on New Zealand data only. The Makuri earthquake has been assigned a location based on intensity data.

Year	Date	Time (UT)	Lat °S	Long °E	Depth (km)	Magnitude	Max. MM intensity	
1942	Jun 24	0814	41.04	175.60	12R	M_L5.3	MM5	foreshock
	Jun 24	**1116 30**	**40.96**	**175.69**	**12R**	**M_L~6.5**		**Wairarapa I, sub-event 1**
	Jun 24	**1116 36**	**40.96**	**175.67**	**12R**	**M_s7.2[1], M_w7.2[2]**	**MM9**	**Wairarapa I, sub-event 2**
	Jun 24	1129	41.15	175.52	12R	M_L4.9		aftershock
	Jun 24	1309	40.92	175.68	5R	M_L5.3		aftershock
	Jun 24	2031	40.96	175.43	12R	M_L5.0		aftershock
	Jun 29	0702	41.13	175.54	12R	M_L5.1		aftershock
	Aug 01	**0447**	**40.5**	**176.1**	**12R**	**M_s5.3[1], M_w5.6[2]**	**MM7?**	**Makuri earthquake**
	Aug 01	**1234**	**41.01**	**175.52**	**40R**	**M_s7.0[1], M_w6.8[2]**	**MM8**	**Wairarapa II**
	Dec 02	**0013**	**41.08**	**175.58**	**20R**	**M_L6.0, M_s6.0[1]**	**MM7**	**Wairarapa III**

[1] – Dowrick & Rhoades 1998
[2] – Doser & Webb pers. comm.

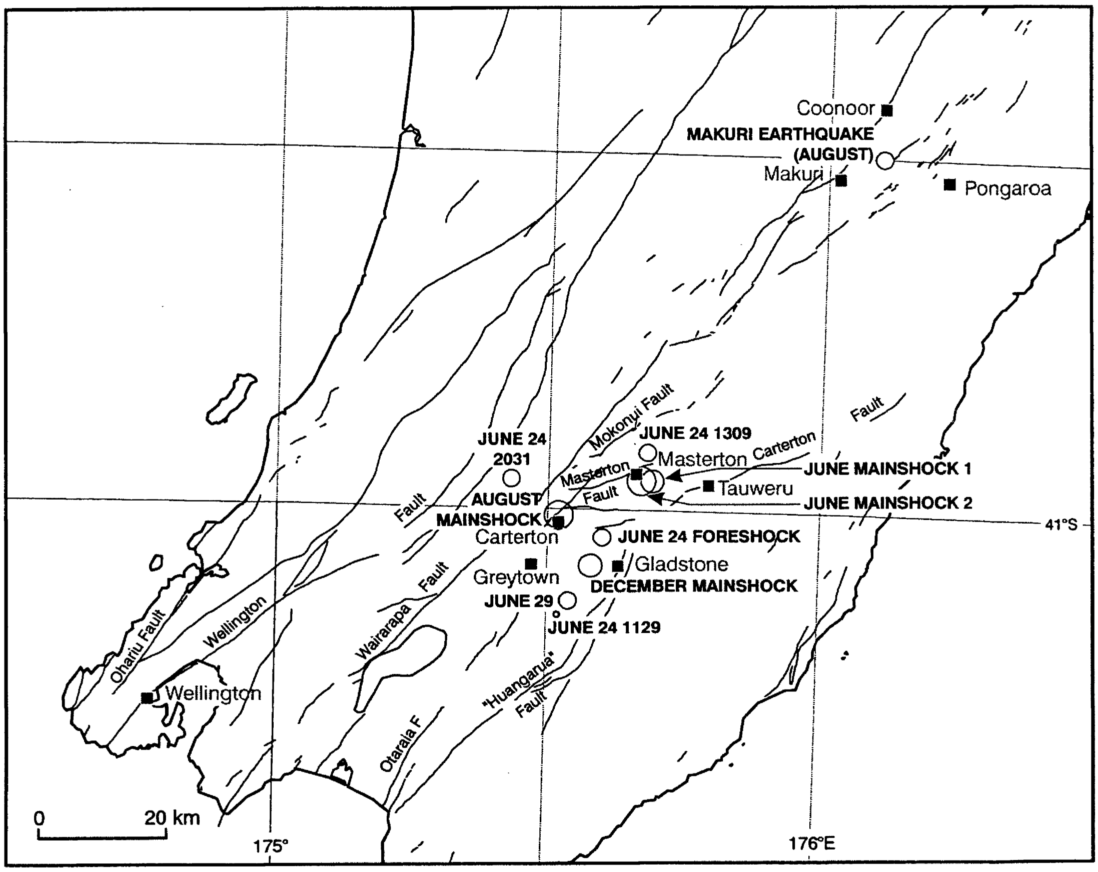

Figure 2: Map showing the locations of instrumentally derived epicentres of the 1942 June 24, August 1 and December 2 mainshocks, June 24 foreshock, their major aftershocks and the August 1 Makuri earthquake. Also shown are major onshore faults, including the Wellington, Wairarapa, Carterton and Masterton Faults.

The earthquake at 8.14pm on the evening of June 24 was a shallow, moderate magnitude M_L5.3 earthquake, too small to be recorded teleseismically. The local station solution fits phase arrivals, including later crustal phases (for example, Pg), fairly well. For CHR and TAK the first arrivals were taken to be P* rather than Pn. Because of its unreliability (no absolute timing and poor quality record), BUN is not included in the solution, although including it changes the epicentre by about 5 km only, from close to the December epicentre to nearer the June and August mainshock epicentres. The epicentre would still lie within the cluster, however. Hence, because of its close relationship in time and space, the earthquake can truly be considered as a foreshock of the earthquake that occurred 3 hours later, and it will be referred to as such for the rest of this paper. Its location is compatible with the highest intensity of MM5 occurring in Masterton (see Table 5).

Using the WEL Imamura records, the June 24 mainshock can be separated into two major sub-events six seconds apart, the first sub-event being about magnitude 6.4-6.5, based on the ratio of its S-wave amplitude with that of the following sub-event, which is presumed to be M_w7.2. Doser & Webb's body wave modelling (pers. comm., June 1999) also indicates two sub-events separated by about six seconds. The authors have attempted to locate both events using the local records, and the depth given by Doser & Webb (pers. comm.), but separating the events on stations other than WEL is difficult. The solutions for the events are highly reliant on the depth chosen and on which stations are included, and vary by up to 15 km. The solutions listed are considered to fit the data best, including crustal phases, and the first sub-event is more reliably located than the second sub-event. In the following sections the main shock is referred to as though it were a single event at the location of the first sub-event (which is within 5 km of the second sub-event).

The M_w5.6 earthquake on the afternoon of August 1, previously thought to be in the same area as the June and August mainshocks, seems to be two earthquakes a few seconds apart at different locations. Neither of the earthquakes can be located instrumentally. The first earthquake is probably related to the June sequence. The location of the second, and larger, of the two earthquakes is identified by felt intensity data, that is, by the fall of many chimneys at Makuri and Coonoor, the fall of a few chimneys at Pongaroa, and by an anomalous large amplitude on HAS. The HAS record is similar to that of a 1934 Pahiatua earthquake aftershock [24] that was located about 15 km south east of Makuri. Therefore, the second earthquake appears to have originated about 50 km north east of the June mainshock and the M_w6.8 earthquake that occurred some eight hours later, and hence is not a foreshock of the latter event. About an hour after the M_w5.6 earthquake near Makuri (now to be referred to as the Makuri earthquake), a small earthquake (M_L~3.8) was recorded on WEL with an S-P interval appropriate to its occurring near Makuri also. Hence, it may have been an aftershock. Until August 4, there is one other possible aftershock (noting that aftershocks smaller than M_L~3.8 would not be identifiable).

The August mainshock (M_w6.8) is deeper than the June mainshock, as was recognised in 1942 [3], and the best fit location is within 15 km southwest of either sub-event in June. Although the depth is fixed at Doser & Webb's preliminary body wave modelling depth of 40 km (pers. comm., June 1999), the best fit is shallower, at 33 km. The solution does not converge unless the depth is fixed, and it is highly sensitive, within 10-15 km, to the inclusion of BUN. The inclusion of TUA moves the epicentre well to the east, but as the timing on TUA appears to be incorrect by 3.5-4 sec. for the well-constrained December shock and is not available for the June shock, the TUA P arrival has not been used to derive the location.

The December mainshock epicentre is reasonably well-constrained. A reliable S-P interval from the BUN Imamura contributes stability to the solution whereas for the earlier earthquakes BUN had only Milne-Jaggar records, which are difficult to read accurately and overloaded within 5-8sec. A depth of 12 km is obtained from the free depth solution, but the small area over which MM7 was experienced suggests the depth was greater. Varying the depth from 12 to 30 km changes the epicentre by at most 10 km, the epicentre remaining within the highest intensity isoseismal (see Figure 5). The best fit location is within five kilometres of the June foreshock, although probably at greater depth than this event, and within 20 km of the June and August mainshocks.

Teleseismic data for June, August and December mainshocks:

The International Seismological Summary (ISS) for 1942 reports more than 90 P arrivals for many stations around the world for the June and August mainshocks. Fewer P arrivals are listed for the December main shock because of its smaller magnitude. Residual times (observed arrival times minus calculated arrival times) for the three mainshocks range from near zero to tens of seconds (one almost certainly misread by a minute). For the June mainshock some arrivals are recorded as emergent and have a six second residual, which may represent the arrival of the second and larger earthquake. Including a selection of arrivals (from differing azimuths) with less than 3 sec. residual from the local solution changes the epicentre for the June mainshock by up to 10 km and for the August mainshock, up to 30 km, depending on the stations used. Including two Australian stations (RIV and SYD) for the December shock moves the location by 1 km only.

Some of the large residuals for the 1942 earthquakes may be the result of the situation during the Second World War, with station operators and analysts possibly lacking sufficient training or facilities, including well-controlled timing, to perform their tasks. Some strategically located stations around the Pacific were almost certainly closed down, at least temporarily, as some stations that recorded the 1931-1934 shocks were not listed in 1942.

Modelling of teleseismic body waves (Doser & Webb pers. comm., June 1999) has yielded a preliminary mechanism for the June earthquake of predominantly right-lateral strike-slip faulting at 12 ± 6 km depth on a near vertical nodal plane striking at 20° ± 19°. This plane is preferred as it aligns most closely with the known major geological features of the area. The moment magnitude (M_w7.2) obtained is the same as the surface wave magnitude.

Doser & Webb's mechanism for the August earthquake (M_w6.8) is normal faulting at a depth of 40 ± 4 km on a near vertical nodal plane striking at 28° ± 15°. This mechanism is compatible with the earthquake's location in the upper part of the subducting plate, the top of which is at a depth of about 19-20 km [31].

Aftershocks:

Six aftershocks with magnitudes $M_L \geq 4.8$ occurred in the month following the June earthquake. Four were able to be located and all were within 25 km of each other and within 25 km of the mainshock (Figure 2). Their S-P intervals on WEL varied from 9.2-10.2 sec. whereas the mainshock S-P interval on WEL was 10.7 sec. and the foreshock, 10.4 sec.). The range spanned by the S-P intervals at Wellington of all recognisable aftershocks within the first 24 hours after the earthquake was 8.2-12.0 sec. The extremes of S-P intervals, that is, 8.2 sec. and 12.0 sec, both occurred within 1.5 hours of the mainshock, and the range does not change significantly up to the time of the August foreshock [2], nor after it.

Although there are too few locatable aftershocks to define the strike of the rupture zone, the zone encompassing them and the June mainshock is compatible with the preliminary source mechanism of Doser & Webb referred to above. Because of the orientation of Doser & Webb's strike with respect to Wellington, the range of S-P intervals (1 sec equates to about 8 km) on Wellington records probably does not fully reflect the length of the rupture. Hence the minimum length of the fault rupture zone is estimated to be no less than about 35 km and probably no more than about 45 km.

According to Gibowicz [2], 644 aftershocks ($M_L \geq 2.9$) occurred up to July 31. Three aftershocks reached magnitude 5 or greater (June 24 1309 M_L5.3, June 24 2031 M_L5.0, Jun 29 0702 M_L5.1). The August mainshock initiated a small aftershock sequence at a rate of about 7 per day ($M_L \geq 2.9$) on the first day, compared to a rate of 82 per day on the first day after the June mainshock and 28 per day after the December mainshock [2]. As no aftershocks of the August mainshock exceeded magnitude 5.0, and hence none were locatable, it is not known whether the aftershocks were at the same depth as the mainshock, or whether the aftershocks represent a reactivation of the June rupture zone.

The December mainshock initiated its own sequence of aftershocks (about 250 in 58 days with $M_L \geq 2.9$). None of the three largest events (all M_L4.7) could be located. The WEL S-P intervals for the aftershocks to the end of December spanned 8-11 sec., most of them being between 9-10 sec. [2]. The June foreshock also initiated a small aftershock sequence with ten events ($3.3 \geq M_L \geq 2.9$) with similar S-P intervals (10.4 sec. ± 0.5 sec.) occurring in the three hours between the foreshock and mainshock.

DAMAGE AND INTENSITY DISTRIBUTION

Collecting felt reports from Post Office and lighthouse operators, and newspaper clippings on an earthquake's effects was still an important task of the Seismological Observatory in 1942. Improvements in the instrumental network meant that intensity assessments were less necessary for locating epicentres of large earthquakes than previously, but information on building damage was more needed for the development of better building standards, as it is today. Unfortunately the early intensity questionnaires or "felt reports" were not well formulated and generally only those that included comments are now useful.

For this study, the newspaper collection was augmented and made as complete as possible. Relevant city and district council archives, National Archives, Government Department files, School Jubilee Booklets and records and reports of the Wellington Port Authority were searched for information and photographs. Some oral history tapes at Wairarapa Archive were listened to (enough to realise that gathering information from this source was time consuming and not very useful!) and eyewitness accounts sought from several people, and from diary accounts in the Alexander Turnbull Library. Public Works Department Engineers' building-by-building reports for all the larger Wairarapa towns significantly damaged in the earthquake were found at the Wairarapa Archive. The detail on buildings will be analysed in greater depth in a subsequent paper (by Dowrick). Another resource is a set of 420 building-by-building reports of damage to Wellington buildings (at Wellington City Council Archives).

Using these resources, new isoseismal maps have been compiled for the 1942 June 24, August 1 and December 2 mainshocks (Figures 3-5). Intensities assigned for these shocks, the June foreshock and the Makuri earthquake are summarised in Tables 2-6. Intensities were assigned using the 1996 modifications of the Modified Mercalli scale for New Zealand proposed by Dowrick [18].

THE M_W7.2 JUNE 1942 EARTHQUAKE

The earthquake of June 24 was shallow enough (centroid depth h_c=12 km) and, with a magnitude of M_w7.2, large enough to cause considerable damage, despite being centred away from large cities. It was felt over a large part of the North and South Islands, from Auckland to Dunedin (Figure 3, Table 2). The zone of heaviest damage, inside the MM8 isoseismal, covered an area of about 4,000 km^2 and encompassed six small towns and a total population in 1942 of about 24,000 people. The intensity reached a maximum of MM9 at a few locations near Masterton.

Inside the MM8 zone there were only two casualties, despite the fact that parts of about 50 brick buildings and thousands of brick chimneys fell and many windows were smashed. In Masterton, two were injured, one with a cut arm, and the other was serious enough to be admitted to hospital. Outside the MM8 zone, one woman broke her leg when she jumped from a hotel window in Otaki, and one man died in Wellington (MM6 and MM7) from carbon monoxide poisoning as a result of damage to gas fittings (Coroner's report). Otherwise, only a few minor cuts or bruises were reported. The few deaths and injuries may be attributed to the earthquake occurring at 11.16 pm when most people were inside timber houses.

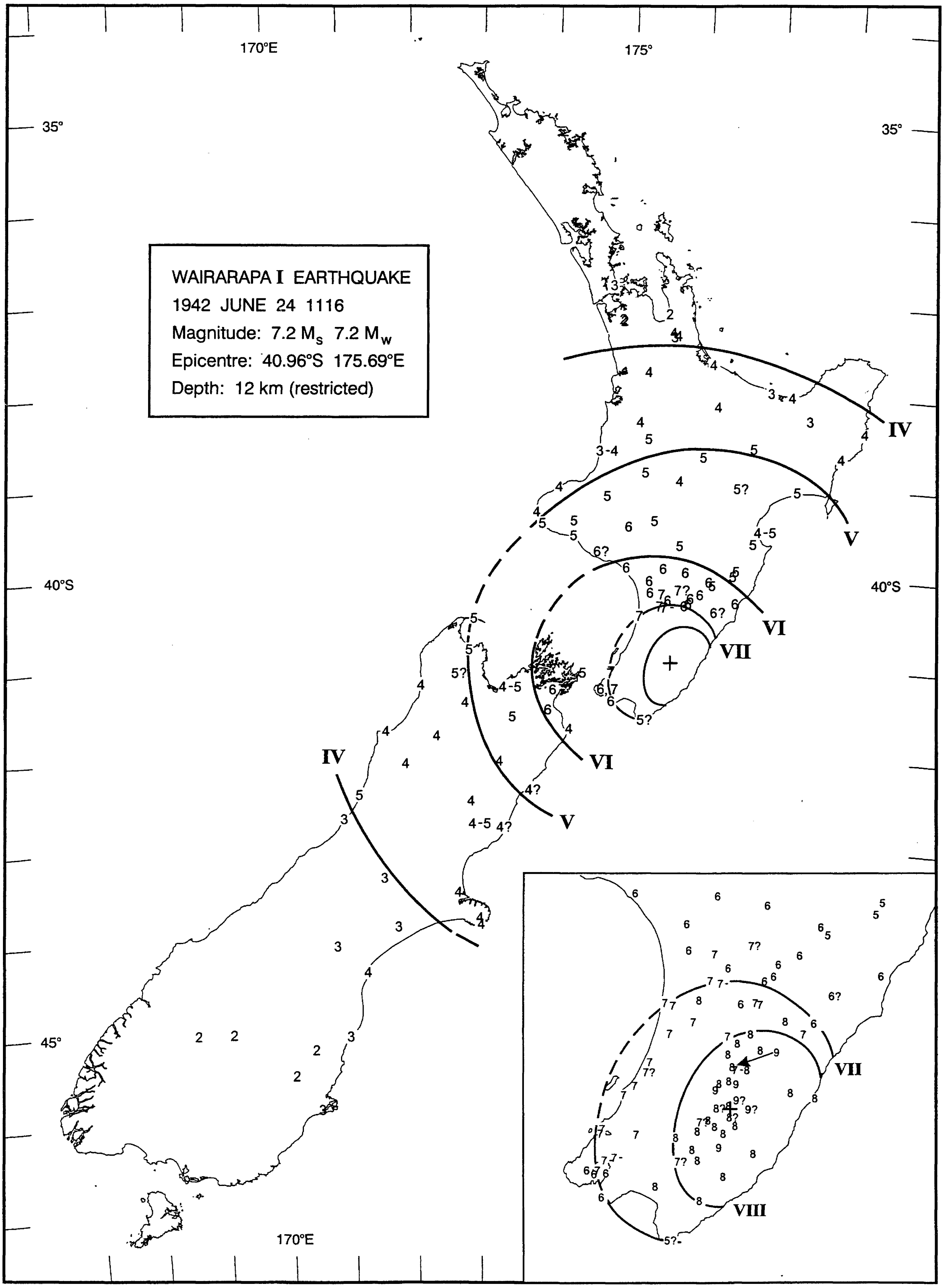

Figure 3: Isoseismal map of the 1942 June 24 M_w7.2 Wairarapa earthquake (Wairarapa I). Inset shows detail within the inner isoseismals. "+" denotes epicentre determined in this paper.

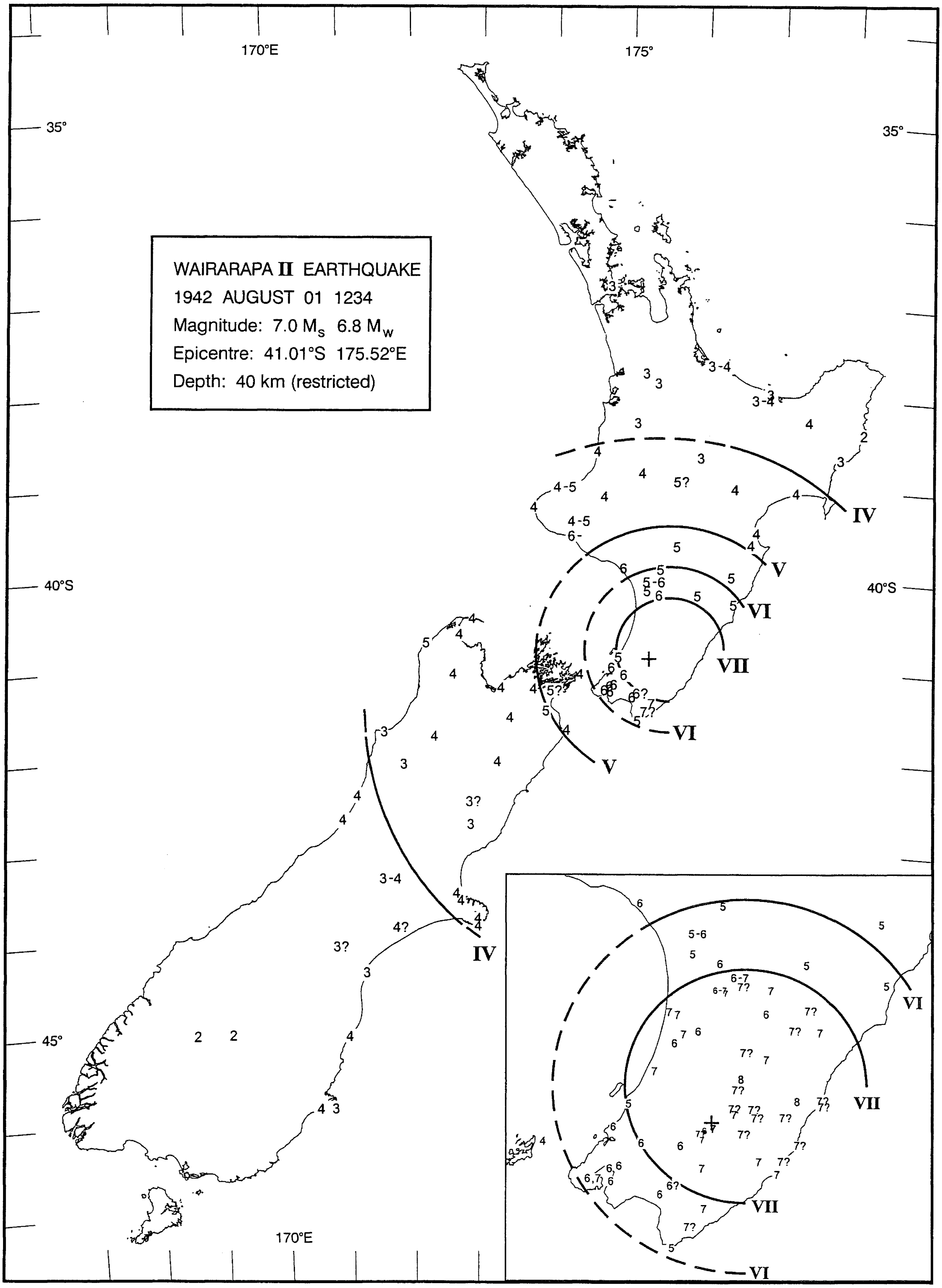

Figure 4: Isoseismal map of the 1942 August 1 (August 2 NZT) M_w6.8 Wairarapa earthquake (Wairarapa II). Inset shows detail within the inner isoseismals. "+" denotes epicentre determined in this paper.

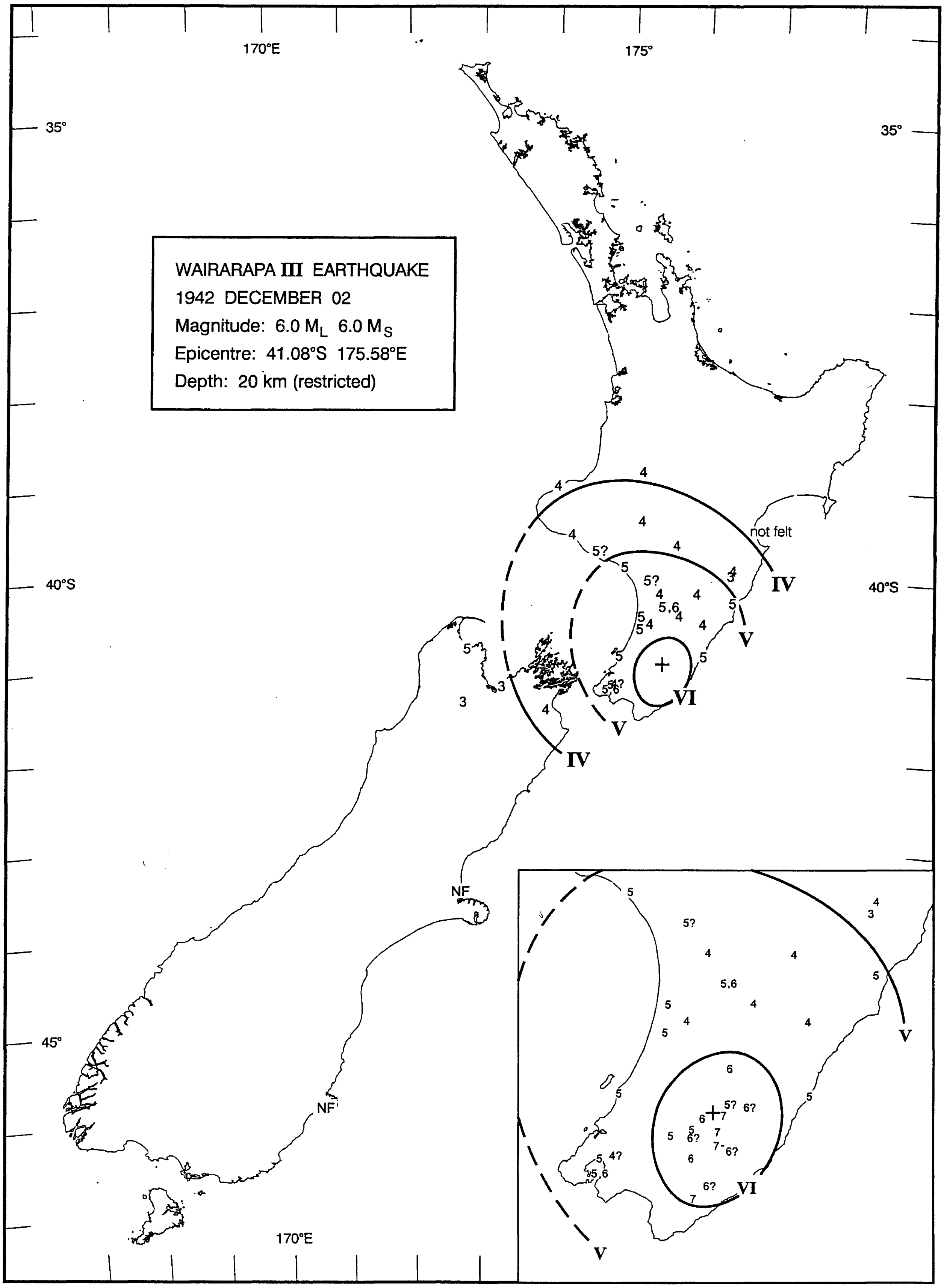

Figure 5: Isoseismal map of the 1942 December 2 M_s6.0 Wairarapa earthquake (Wairarapa III). Inset shows detail within the inner isoseismals. "+" denotes epicentre determined in this paper.

Table 2. Summary of MM intensities for the 1942 June 24 M_w7.2 Wairarapa earthquake. Intensities of MM8 and above are shown in bold.

NORTH ISLAND	Lower Wairarapa Valley - MM6-8	Porangahau - MM6	Whangamomona - MM5
Alfredton - MM8	Maharahara - MM6	**Poroporo - MM8**	Woodville - MM6
Apiti - MM6	Makomako - MM6	Pukekohe - MM2	
Auckland - MM3	**Makuri - MM8**	Rakaunui - MM7	
Awaiti - MM3	Mangamutu - MM7	**Rangitumau - MM9**	*SOUTH ISLAND*
Awakino - MM3-4	Mangapehi - MM5	**Rongomai - MM8**	Akaroa - MM4
Baring Head - MM6	**Martinborough - MM8**	Rotorua - MM4	Akaroa Head Lighthouse - MM4
Buckland - MM2	Marton - MM6	Shannon - MM7	Ashburton - MM3
Bunnythorpe - MM6	**Masterton - MM8**	Taihape - MM5	Blenheim - MM6
Cape Egmont Lighthouse - MM4	**Matahiwi - MM9**	Tarawera - MM5?	Cape Campbell - MM4
Cape Palliser - MM5?	**Mauriceville East - MM9**	Taumarunui - MM5	Cheviot - MM4?
Carterton - MM8	**Mauriceville West - MM8**	Taupo - MM5	Christchurch - MM4
Castlepoint Lighthouse - MM8	Mauriceville County - MM7-8	Tauranga - MM4	Cobb River - MM5?
Dalefield - MM7?	**Mikimiki - MM8**	**Tauweru - MM9?**	Cromwell - MM2
Dannevirke - MM6	Motu - MM3	**Tawaha - MM8**	Culverden - MM4-5
Eastbourne - MM6	Napier - MM4-5	Te Horo - MM7?	Dunedin - MM3
Eketahuna - MM8	Netherton - MM4	Te Kuiti - MM4	Fairlie - MM3
Eltham - MM5	New Plymouth - MM4	**Te Ore Ore - MM9?**	Farewell Spit lighthouse - MM5
Featherston - MM8	Nireaha - MM7	Te Whaiti - MM5	Greymouth - MM5
Feilding - MM7	Norsewood - MM6	**Te Wharau - MM8**	Hanmer Springs - MM4
Foxton - MM7	Ohakea - MM6	**Te Whiti - MM8?**	Hillersden - MM5
Foxton Beach - MM7	Ohakune - MM5	Thames - MM2	Hokitika - MM3
Gisborne - MM4	**Opiki - MM8**	**Tinui - MM8**	Kaikoura - MM4?
Gladstone - MM8	Opotiki - MM4	Titahi Bay - MM7	Karamea - MM4
Greytown - MM8	Opunake - MM5	Tokaanu - MM4	Lake Coleridge - MM3
Hamilton - MM4	Ormondville - MM5	Tolaga Bay - MM4	Middlemarch - MM2
Hastings - MM5	Otaki - MM7	**Tuturumuri - MM8**	Molesworth - MM4
Hawera - MM5	Paeroa - MM4	Upper Hutt - MM7	Murchison - MM4
Hinakura - MM8	Pahiatua - MM7	**Waihakeke - MM8**	Nelson - MM4-5
Hunterville - MM6	Palmerston North - MM7-	Waikanae - MM7	Oamaru - MM3
Hutt Valley - MM6 & MM7	Papatawa - MM6	**Waingawa - MM8?**	Picton - MM6
Kahutara - MM7?	Paraparaumu - MM7	Waipawa - MM5	Queenstown - MM2
Kaiparoro - MM8	Parkvale - MM7-8	Waipukurau - MM5	Reefton - MM4
Kairanga - MM7	Petone - MM7-	Wairoa - MM5	Tadmor - MM4
Kokotau - MM8	Pipiriki - MM6	Wanganui - MM6	Takaka - MM5
Kopuaranga - MM8	**Pirinoa - MM8**	Waverley - MM6?	The Brothers (Cant.) - MM2
Levin - MM7	Plimmerton - MM7	Weber - MM6?	The Brothers lighthouse - MM5
Longbush - MM9	Pohangina - MM7?	Wellington - MM6 & MM7	Timaru - MM4
Lower Hutt - MM7-	Pongaroa - MM6	Whakatane - MM3	Westport - MM4

Somewhat surprisingly, only one serious earthquake-induced fire was reported, despite it being mid-winter and heating by open fires in brick fireplaces being common practice. Again, this may have occurred because of the lateness of the hour. One farm homestead at Waihakeke near Carterton was destroyed by a fire thought to have resulted from earthquake damage to electrical wiring. In Wellington there were two chimney fires, but these and several other minor fires attributed to earthquake damage were extinguished before a major fire developed.

At a distance of over 80 km from the source of both the June 24 and August 1 earthquakes, Wellington was at the threshold of structural damage, experiencing local intensities of MM6 and MM7 in both events (Figures 3, 4, Tables 2, 3). Using the attenuation expression for peak ground accelerations of Zhao *et al.* [32], an expected mean PGA~0.08g is estimated for soil sites in Wellington for both events. Because of the low level of damage of any individual building in Wellington further discussion of damage in Wellington is left to the section on microzoning. Nevertheless, the total loss to the Wellington community was substantial because of the large number of brick buildings and brick chimneys involved and because of the cumulative effect of two earthquakes within a few weeks. Luke [13] estimated the total damage costs for buildings in Wellington City as:

- non-domestic buildings £805,000 ($48.3 million in 1998 New Zealand values)
- dwellings and chimneys £80,000 ($4.8 million in 1998 New Zealand values)

Little of these costs would have been incurred if reinforced brickwork had been used.

Damage to the built environment within the MM8 zone, June 24 1942:

Many parts of the Wairarapa experienced strong ground shaking of Modified Mercalli intensity MM8 or more. While no published works discuss damage in the Wairarapa, fortunately much archival material exists, particularly newspaper accounts, photographs and local authority engineers' files.

Table 3. Summary of MM intensities for the 1942 August 1 (UT; August 2 NZT) M_w6.8 Wairarapa earthquake. Intensities of MM8 and above are shown in bold.

NORTH ISLAND	Hunterville - MM5	Tauweru - MM7?	Blenheim - MM5
Alfredton - MM7	Kairanga - MM6-7	Taumarunui - MM4	Cape Campbell - MM4
Auckland - MM3	Kaiwaka - MM7?	Taupo - MM3	Cape Saunders - MM3
Awakino - MM4	Kopuaranga - MM7?	Tauranga - MM3-4	Christchurch - MM4
Blairlogie - MM7?	Levin - MM6	Te Kuiti - MM3	Cobb River - MM4
Bulls - MM5	Lower Hutt - MM6	Te Teko - MM3-4	Collingwood - MM4
Bunnythorpe - MM6-7	Makuri - MM7?	Te Wharau - MM7	Cromwell - MM2
Cambridge - MM3	Martinborough - MM7	**Tinui - MM8**	Culverden - MM3
Cape Egmont - MM4	Marton - MM5-6	Tokaanu - MM5?	Dunedin - MM4
Cape Palliser - MM5	Masterton - MM7	Tolaga Bay - MM2	Fairlie - MM3?
Carterton - MM7	Matarawa - MM7?	Tuhitarata - MM6?	Farewell Spit - MM4
Castlepoint - MM7?	**Mauriceville - MM8**	Tuturumuri - MM7	Greymouth - MM4
Coonoor - MM7?	Motu - MM4	Upper Hutt - MM6	Hanmer Springs - MM3?
Dalefield - MM6	Napier - MM4	Upper Plains district - MM7?	Havelock - MM4
Dannevirke - MM5	New Plymouth - MM4-5	Waipukurau - MM5	Hillersden - MM4
Eastbourne - MM6	Otaki - MM7	Wairoa - MM4	Hokitika - MM3
Eketahuna - MM7?	Pahiatua - MM6	Wanganui - MM6	Kahurangi Point - MM5
Eltham - MM4-5	Paiaka - MM7	Wellington - MM6 & MM7	Lake Coleridge - MM3-4
Featherston - MM6	Palmerston North - MM7	Whakarongo - MM7?	Lyttelton - MM4
Feilding - MM6	Paraparaumu - MM5	Whakataki - MM7?	Molesworth - MM4
Flat Point - MM7	Petone - MM6	Whakatane - MM3	Murchison - MM4
Foxton - MM7	Pirinoa - MM6	Whangaehu - MM7?	Nelson - MM4
Foxton Beach - MM7	Pongaroa - MM7	Whangamomona - MM4	Oamaru - MM4
Gisborne - MM3	Porangahau - MM5	Woodville - MM7	Picton - MM5?
Greytown - MM7	Poroporo - MM7?		Queenstown - MM2
Halcombe - Felt	Pukerua Bay - MM6		Reefton - MM3
Hamilton - MM3	Riversdale - MM7?	*SOUTH ISLAND*	The Brothers lighthouse - MM4
Hastings - MM4	Shannon - MM6	Akaroa - MM4	Timaru - MM3
Hawera - MM6-	Taihape - MM5	Akaroa Head - MM4	Westport - MM3
Homewood - MM7?	Tarawera - MM4	Ashburton - MM4 ?	

Table 4. Summary of MM intensities for the 1942 December 2 M_s6.0 Wairarapa earthquake.

NORTH ISLAND	Masterton - MM5?	Te Whiti - MM7
Admiral Run district - MM6?	Mauriceville East - MM6	Tuturumuri - MM7
Carterton - MM6	Morrison's Bush - MM6?	Waipawa - MM4
Castlepoint - MM5	Napier - Not felt	Waipukurau - MM3
Dannevirke - MM4	New Plymouth - MM4	Wanganui - MM5 & MM6
Featherston - MM5	Pahiatua - MM4	Waverley - MM5?
Feilding - MM4	Palmerston North - MM5 & MM6	Wellington City - MM5 & MM6
Foxton - MM5	Paraparaumu - MM5	Whakapuni - MM6?
Gladstone - MM7	Petone - MM5 & MM6	
Greytown - MM5	Pongaroa - MM4	*SOUTH ISLAND*
Hawera - MM4	Porangahau - MM5	Blenheim - MM4
Hutt Valley - MM4?	Raetihi - MM4	Christchurch - Not Felt
Levin - MM5	Shannon - MM4	Dunedin - Not felt
Longbush - MM7-	Taihape - MM4	Nelson - MM3
Martinborough - MM6	Taumarunui - MM4	Tadmor - MM3
Marton - MM5?	Tauweru - MM6?	Takaka - MM5

Table 5. Summary of MM intensities for the 1942 June 24 M_L5.3 Wairarapa earthquake

NORTH ISLAND	New Plymouth - MM3	Taumarunui - MM4
Baring Head lighthouse - MM3	Norsewood - MM4	Waipawa – MM3
Carterton - MM5	Ohakune - MM2	Waipukurau - MM4
Dannevirke - MM4?	Opunake - MM3	Wanganui - MM4
Eketahuna - MM4?	Ormondville - MM3	Wellington - MM4
Eltham - MM2-3	Otaki - MM4	
Feilding - MM4	Palmerston North - MM4	*SOUTH ISLAND*
Foxton - MM4	Paraparaumu Beach - MM5?	Blenheim - MM3
Hastings - MM3	Pipiriki – MM5	Farewell Spit - MM3
Hawera - MM3	Pongaroa – MM4	Nelson - MM3
Hunterville - MM3	Porangahau - MM4	Picton - MM3
Martinborough - MM5?	Shannon – MM4-5	Takaka - MM3
Masterton - MM5	Taihape - MM3-4	The Brothers lighthouse - MM3

Table 6. Summary of MM intensities for the 1942 August 1 M_w5.6 Makuri earthquake.

NORTH ISLAND	Masterton - ≤MM5	Wanganui - MM4
Bulls - MM4?	Motu - MM3	Wellington - MM4
Cape Palliser - Felt	Napier - MM3-4	*Woodville - MM5-6*
Castlepoint - MM5	New Plymouth - MM3	
Coonoor - MM7?	Otaki - MM5	
Dannevirke - MM5	Pahiatua - MM4-5	*SOUTH ISLAND*
Feilding - MM4	Palmerston North - MM5	Akaroa - MM3
Foxton - MM4?	Pongaroa - MM6	*Havelock - MM3*
Greytown - MM4	Shannon - MM5	Hokitika - MM3
Hastings - MM4	Taihape - MM4	Lyttelton - MM3
Hawera - MM3-4	Tauweru - MM6-	Nelson - MM3
Lower Hutt - MM4	Tuturumuri - MM5	Picton - MM4
Makuri - MM7?	Waipukurau - MM4	The Brothers lighthouse - MM2
Marton - Felt	Wairoa - MM4	

Domestic buildings

Within the MM8 isoseismal (Figure 3) in 1942 there were about 6,000 houses, predominantly of timber-framed construction. While most of these houses sustained earthquake damage, most of the damage occurred to, or was caused by the fall of, unreinforced brick chimneys. According to a report to the Masterton Borough Council made four weeks after the main shock, 13,125 chimneys were "destroyed" in the Wairarapa district. As most houses had two chimneys, it is reasonable to infer that most or all chimneys throughout this region fell, in agreement with press statements.

A few scattered instances of houses within the MM8 isoseismal being structurally damaged by racking, twisting or falling off their piles, suggest local intensities of MM9.

Non-domestic buildings

Most of the non-domestic buildings within the MM8 isoseismal were in the townships of Masterton, Carterton, Greytown, Martinborough, Eketahuna and Featherston. The buildings were of one, two or three storeys and were made of timber, brick or reinforced concrete, with some hybrids. Timber buildings, like the houses, fared well except in relation to damage to unreinforced brick chimneys. Likewise, concrete buildings suffered little damage. Unreinforced brick buildings had damage levels ranging from slight cracking to partial collapse.

Masterton suffered more damage than other Wairarapa towns, mainly because it had the most buildings. Based on the attenuation models of Zhao *et al.* [32] and McVerry *et al* [pers. comm.], and allowing for uncertainties in the location of the source, and the mean peak ground acceleration is estimated to have been in the range 0.3-0.6g in Masterton.

A most valuable source of information on the performance of non-domestic buildings in Masterton is a report prepared by Harris & Burns [33], an engineer and an architect respectively of the Public Works Department. Their report comments on the condition of 131 (initially, and subsequently 9 more) predominantly brick and/or concrete buildings, on a building-by-building basis. The Harris & Burns survey was very thorough, covering over 80 percent of the 95 or so brick buildings that the authors know existed in Masterton at the time. Mabson's summary [34] of the findings of the initial report in relation to brick non-domestic buildings states that:

- 24 brick buildings were seriously damaged, and required partial or complete demolition (for example, Figure 6)
- 43 brick buildings were cracked only, or parapets and gable ends collapsed, and capable of reconstruction to earthquake standards
- 18 brick buildings suffered only minor damage.

Of the 64 or so original reinforced concrete buildings in Masterton, some had brick infill, and only two (State Theatre and Woolworth's shop) had been designed to resist earthquakes. Eight other buildings that had originally been of purely brick construction had been substantially retrofitted after the 1934 M_s7.6 Pahiatua earthquake [24], for example, the Masterton Opera House illustrated in Figure 7. Most concrete buildings were undamaged. Three suffered moderate cracking, and a further ten or so were slightly cracked. Ironically, Woolworth's shop was badly damaged when its roof was destroyed by falling brickwork from a brick building next door. One of the three-storey and one of the two-storey buildings are shown in Figures 8 and 9 respectively.

In Carterton, there were at least 27 unreinforced brick non-domestic buildings, of which at least five had walls or gables collapse, and at least ten others were in a dangerously cracked condition. Of the 14 buildings known to have been of reinforced concrete, most were apparently undamaged, two were slightly cracked and one poorly reinforced one had moderate cracks.

Greytown had at least six non-domestic brick buildings, in three of which the front facades collapsed. The others suffered lesser damage, especially the brick hospital building, which suffered mainly from chimney damage. The four reinforced concrete buildings, notably the 1937 Buchanan Ward at the hospital, appear to have been essentially undamaged.

Eketahuna had at least 21 brick buildings. Four of these buildings were so badly damaged that they were subsequently pulled down, while the remainder required moderate to substantial repairs. Damage to Eketahuna's only concrete building, the County Council Chambers, was restricted to slight cracking of its parapet.

Martinborough had at least 13 brick buildings, all of which required moderate to substantial repairs for cracked walls and parapets. Of the eleven reinforced concrete buildings nine were essentially undamaged and two suffered some cracks, but damage was only moderate.

Figure 6: A view of Queen Street, Masterton on June 25 1942. The debris is from the second storey of Gray's brick building housing Hannah & Co., and Bullick & Blackmore. The undamaged parapet of Woolworth's single storey 1937 reinforced concrete building may be seen just beyond Gray's. (Reference No. G-123912-1/2, "Evening Post" Collection, Alexander Turnbull Library, Wellington, New Zealand).

Figure 7: Present day view of the former Opera House, Masterton, showing reinforced concrete beams and columns attached to brickwalls in retrofitting mostly after 1934. (Photograph by D.J. Dowrick, 1998).

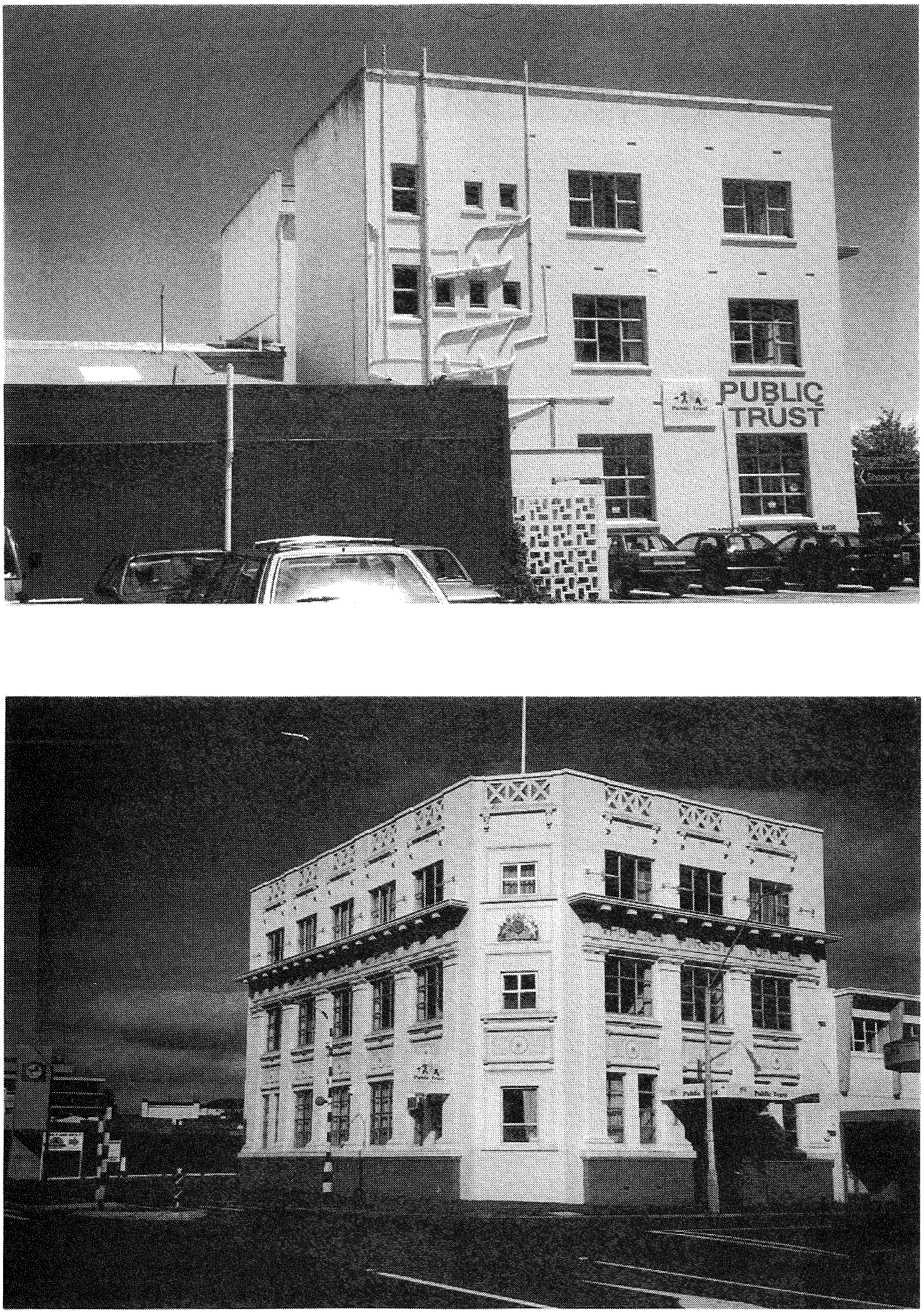

Figure 8: Present day views of 3-storey 1922 wholly reinforced concrete Public Trust building in Masterton, which "suffered no structural damage whatsoever" during the 1942 earthquakes (PGA~0.3-0.6g). (Photograph by D.J. Dowrick, 1998).

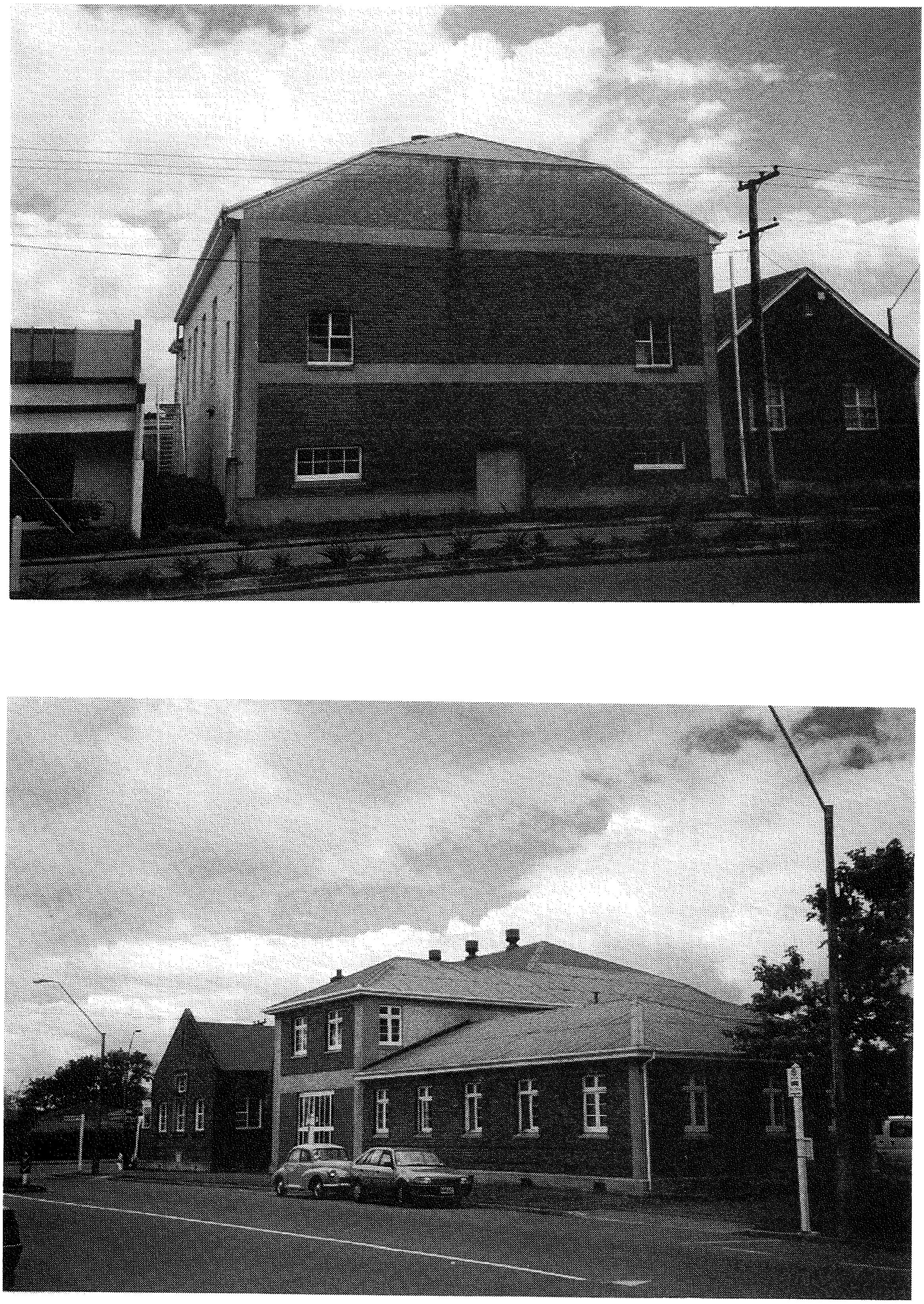

Figure 9: Present day views of 2-storey 1938 Knox Church Hall in Masterton, with a reinforced concrete frame and brick infill, which suffered little or no damage during the 1942 earthquakes. (Photograph by D.J. Dowrick, 1998).

Featherston had four brick non-domestic buildings which had damage ranging from a cracked wall to the fall of the front gable at Wilton's Garage. The eight reinforced concrete buildings suffered little or no damage.

It is evident that very few buildings in the zone of strongest shaking had been designed for earthquake resistance, despite the fact that about 30% of the concrete buildings post-dated the introduction of New Zealand's first earthquake loadings standard in December 1935, and despite the availability of the first draft of that standard from June 1931 [35]. Indeed, at the time of the earthquake in 1942, of the above six towns, only Greytown had adopted the loadings standard as a bylaw, despite urgings to do so by (at least) the Masterton Borough Engineer, C R Mabson [36].

The campaigning for greater earthquake resistance, notably by Mabson in the Wairarapa, is evident in the retrofitting of several brick buildings in Masterton after the 1934 Pahiatua earthquake, and documented in his office's attempts to deal with earthquake risk buildings for at least 20 years after the 1942 earthquakes. This campaign involved leading engineers in Wellington, but it is sobering to note that the campaign did not bear any fruit at the legislative level until 1979 [37].

The good performance of all of the 90+ early brittle reinforced concrete buildings in the Wairarapa in the moderate to strong ground shaking of the main shock, despite almost all of them not being designed for earthquake, is clearly significant, but not exceptional. It is consistent with the similarly good performance of the pre-code concrete buildings in the M_s7.8 1931 Hawke's Bay earthquake, in which such buildings also performed very well, even the 70+ concrete buildings in the near source towns of Napier and Hastings [23, 38]. In these towns the mean PGA's are expected to have been 0.5-0.8g depending on ground class, and the intensity was MM10 [23] as indicated by the heavy damage to brick buildings. The success of all of these concrete buildings appears to be related to the fact that they generally had either concrete walls or brick infill walls in two orthogonal directions even though frequently not symmetrically arranged in plan (Figures 8 and 9).

Damage to Lifelines in the June 24 1942 Earthquake:

Electricity Supply

Loss of electricity was experienced at many locations in the lower North Island from Norsewood (MM6) and Wanganui (MM6) to Wellington (MM6 and MM7). Power was not restored to parts of Greytown (MM8) for 30 hours, but elsewhere it was mostly restored within minutes to a few hours. Nevertheless, moderate costs were incurred by the Wairarapa, Tararua and Horowhenua Electric Power Boards (EPBs). The Wairarapa EPB (within MM8 isoseismal) costs were approximately as follows: reticulation £3,100, inspections £2,500, Kourarau hydro-electric headworks (near Gladstone) £500, and buildings £650 (totalling about $400,000 in 1998 values). Reticulation repairs in the Wairarapa were completed by July 3, nine days after the main shock. Full inspections of all installations were expected to take some months.

The Tararua EPB experienced some broken reticulation lines, but damage to the main distribution was not extensive. Its biggest loss was caused by heavy damage to its two storey brick head-office building in Eketahuna (MM8), which had to be demolished. The Horowhenua Power Board also reported broken reticulation lines, both low tension and several high tension wires. At the Manawatu Heads (MM7, but MM8 probably reached as a microzone effect), many poles in the low lying areas tilted, with consequent damage to wires. One or two poles broke. An explosion and small fire occurred in the switch gear at Pukepapa Road power house near Marton (MM6), and twenty minor service lines were damaged in Wanganui (MM6).

Gas Supply

The town gas supply in Masterton (MM8) was disrupted by the destruction of the brick chimney stack at the Gas Works, but the gas mains were undamaged. A steel chimney was erected within three days, and normal mains pressure was restored on the June 28, less than four days after the earthquake. The main damage was to the Gas Works buildings, of which the brick fronts of the engine room and coal sheds were badly cracked. Carterton (MM8) was the only other town in the Wairarapa to have town gas, and its Gas Works and reticulation were undamaged in the June 24 earthquake. The brick chimney stack was cracked in the August 1 event (suggesting it may have been weakened on June 24), but gas supply was back to normal within 24 hours.

At Petone (MM7), a 9 inch (225 mm) gas main was cracked due to subsidence of 50-150 mm on the west approach to a pipe bridge across the Hutt River.

Water Supply and Drainage

Within the intensity MM8 zone, where the urban areas are all on stiff alluvium, water supply and drainage systems, including private drains, were almost undamaged. The only substantial exception was the collapse of the 40,000 gallon (180 m^3) Masterton water tower, made of bricks, concrete and timber. Water was supplied to this header tank by a 6 inch (150 mm) water main, which was severed when the tank fell. Council staff managed to turn off the control valve on this pipe within a short time and water supply was partially restored the day after the main shock, presumably at reduced pressure.

Fourteen leaks were found in the Waimeha water supply mains at Waikanae Beach (MM7), but the reservoir was not damaged. At Palmerston North in the northern fringe of the MM7 zone, the water supply was interrupted by the fracture of water pipes, as was well documented by the City Engineer [39], as follows:

"One of the filters at the reservoir at Tiritea [7 km southeast of Palmerston North] moved on its foundation blocks both upwards and sideways, breaking both inlet and outlet pipes, and before getting the main under control, a good deal of the surrounding land and the floor of the filter house was flooded. With the telephone out of order, it was not possible for the Caretaker to obtain assistance, but he was ably assisted by Mrs Toms who worked with the Caretaker on the

large valves, and in time had the supply to the filters cut off and the by-pass main to town in operation.

"In the interim the mains to town became partially emptied, the pressure fell and the artesian pumps automatically cut in to take up the supply, but in course of time all reservoirs were emptied and the Public Hospital was dependent on their own storage.

"In the meantime measures for repairs to the filters were put in hand and with the help of the Fire Brigade, the pipe trench was pumped out and new pipes, which fortunately had been kept on hand for this purpose, were placed in position. This work was completed by mid-day on Friday following the earthquake [ie about 36 hours after the main shock]....

"A total of 56 water services had been repaired by 20 July. The west side of the City area seemed to have suffered most in this respect. In many cases the services were completely pulled out of the main. [Twenty five days after the earthquake, reports were still coming in of leaking services.]

"The effect on our stocks of fittings may be serious on account of this unexpected call on supplies. Fortunately we had built up our stocks for E.P.S. [Emergency Precautions Service] work. We will endeavour to procure further supplies as early as possible."

After some earthquakes, damage to underground pipes only becomes apparent months or years later. For example, damage attributed to the 1987 Edgecumbe earthquake was still being discovered in the drains in Edgecumbe in 1999.

In Lower Hutt several burst water mains were reported but just how much damage to underground services in 1942 became apparent later is not known. Aked [12] makes the following valuable remarks about Wellington:

"Little damage was caused to the water mains. The pipes are of cast iron jointed with lead.

"Damage to the sewer and stormwater drains cannot be easily detected unless the damage is of a major character. No damage of this character occurred. Minor damage due to small fractures or subsidence does not usually become evident immediately.

"Where minor fractures occur the liquid waste percolates away leaving the solids behind in the pipe with a resultant blockage. The blockage can be cleared with rods in the usual manner as for normal operational blockages. Repeated blockages at any one position may ultimately reveal a fractured or collapsed pipe, but it is impossible to determine whether the original fracture was due to earthquake or not. A noticeable increase in the number of such blockages during the last eighteen months is suggestive of damage due to the earthquakes a few months previously."

Damage to hot water services throughout the MM6-7 area meant that many homes were without hot water for some weeks. As many rural areas of the Wairarapa depended on tank water, broken joints on tanks and damage to tank stands left many homes without water.

Telephone and Telegraph

Communications were disrupted for some days due to damage to Post (& Telegraph) buildings in the Wairarapa district, and fallen or damaged overhead telephone lines in both the Wairarapa and Manawatu areas. In Masterton, telephone and power lines were brought down by falling facades of brick buildings. Two days after the main shock a number of telephones, mostly country ones, were still out of order, due to line faults. In Palmerston North some 400-600 subscribers reported faults. The total cost of damage to Post Office buildings was estimated at over £100,000 ($6 million, 1998 terms). The brick Post Office building in Eketahuna was so badly damaged that it was condemned, forcing the removal of the telephone exchange equipment to another building.

Railways

The railway line most strongly affected ran from Featherston via Masterton to Woodville, with about 80 km of the track lying within the MM8 isoseismal, including 30-40 km probably directly above the rupture zone (Figure 3). Peak ground accelerations probably ranged from 0.3-0.6g. Following the clearance of a small slip from the line in the Rimutaka Ranges south of Featherston, the train service between Masterton and Wellington operated normally the day after the main shock. North of Masterton, two bridges were damaged and a section of track was out of alignment. This damage was apparently not heavy, but sufficient to keep the line between Masterton and Eketahuna closed for several days.

There was also some damage to the Wellington-Palmerston North line from a slip at Plimmerton (cleared by the next morning) and from subsidence of 29 lengths of rail between Paraparaumu and Te Horo. Temporary repairs and clearance of the slip enabled trains to proceed with care within 12 hours of the earthquake. A large rock also fell in the Manawatu Gorge breaking one rail.

Roads

For several days after the main shock the newspapers reported many instances of damage to roads within the MM8 isoseismal (Figures 3, 10). This damage took the form of subsidence of fills, cracking and blockage or undermining by landslides. Landsliding was widespread in the steep hillcountry that dominates much of the MM8 zone (see following section). The larger landslides were documented by Ongley [6], but many more small slides occurred that were sufficient to block some country roads for many days. Subsidences of about a metre occurred on approach fills to two bridges, one on the Tauweru River (Masterton-Stronvar Road) and one on the Ruamahanga River near Kahutara. Just north of Greytown on the main road to Masterton, the approach to the bridge over the Waiohine River subsided about half a metre forcing a temporary road closure. On a side road nearby, the timber structure of the Matarawa bridge was reported to have developed waves, suggesting differential settlement of its piers. About 15 km east of Greytown ground damage was reported to be heavy with cracks in roads.

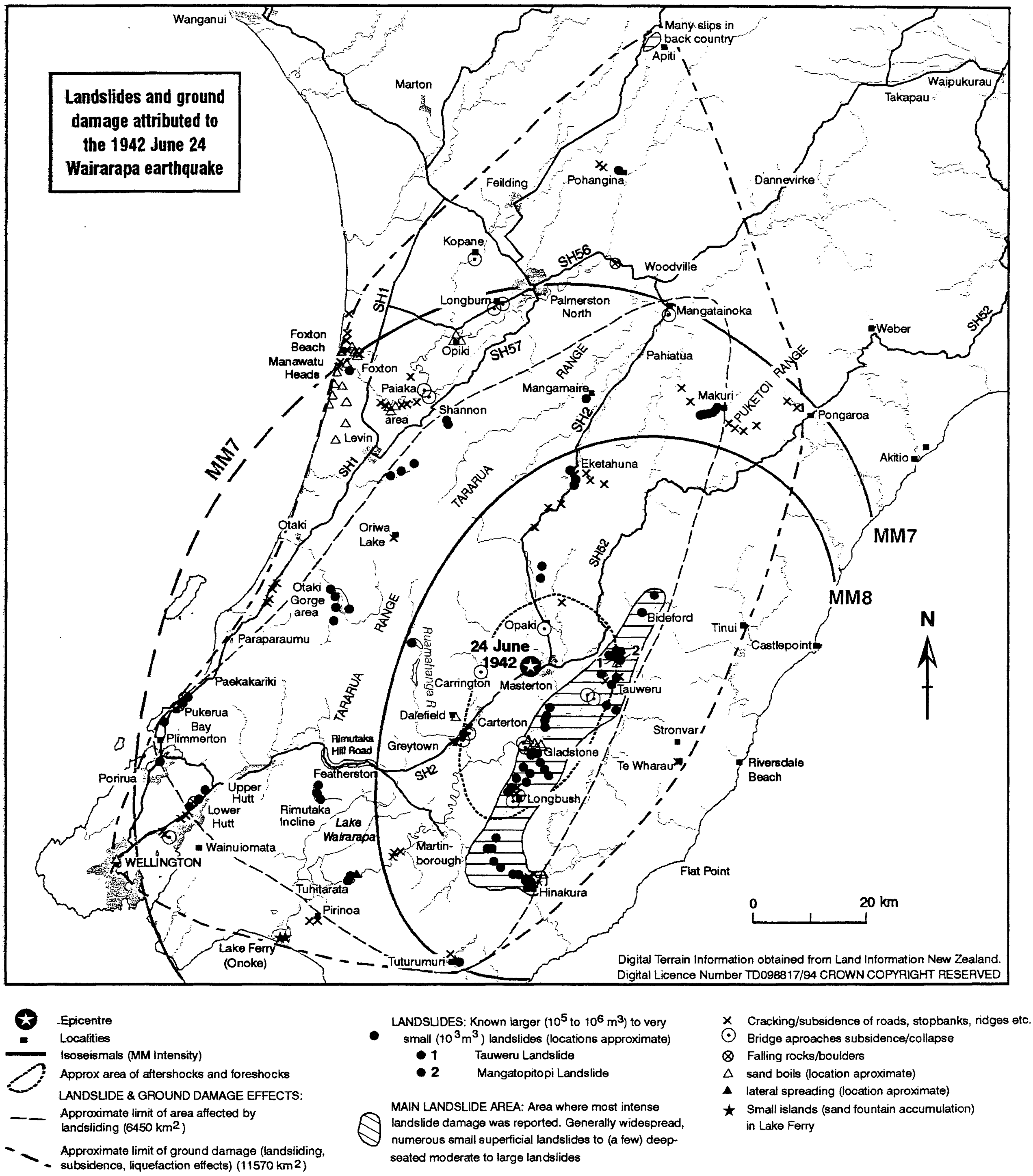

Figure 10: Geographic distribution of landslides and ground damage attributed to the June 24 1942 Wairarapa earthquake. Isoseismal lines are from Figure 3.

According to a report in *The Dominion* newspaper (20 August 1942) the Main Highways Board estimated costs of road repairs in the Wairarapa to be £20-25,000 ($1.2-1.5 million in 1998 values).

In the Manawatu, road damage was mainly confined to subsidence of bridge approaches and the cracking and subsidence of several roads, mainly to the west of Shannon and near Foxton Beach, where there were also extensive liquefaction effects (see following section). Several moderate to large slides occurred on the Shannon-Mangahao and Otaki Gorge roads.

As mentioned in the section on gas reticulation, there was slight subsidence of the approaches to two bridges in the lower Hutt Valley area, the pipe bridge over the Hutt River (50-150 mm) and the Seaview Road bridge over the Waiwhetu Stream ("very slight"). In Wellington, minor cracking of the bitumen at the Chaffers Street/Herd Road intersection and at the approach to the Kelburn viaduct caused no problems for traffic.

Landslides, Ground Damage and Liquefaction Effects, June 24 1942:

The June 24 earthquake caused significant, widespread landsliding and liquefaction-induced ground damage throughout an area of about 11,500 km^2 in the lower North Island centred near Masterton (Figure 10). This map shows the approximate locations and distribution of landslides, rock falls, liquefaction effects (sand and water ejections, lateral spreading), cracking and subsidence of roads, railway lines, and bridge approaches that were reported in newspapers, other archival sources or in [6].

The total area in which landsliding was reported was about 6,500 km^2. Strong shaking caused slope and road cut failures, embankment cracking, and subsidence at considerable distance from the epicentre. The most distant slope failures reported were in the Pohangina and Apiti areas (about 85 to 105 km north of the epicentre), and at Plimmerton and along the Hutt Road (about 70 km southwest of the epicentre).

The most extensive landsliding occurred in low-strength Tertiary rocks in a relatively narrow belt of Wairarapa hill country east of Masterton, extending about 60 km from Hinakura in the south to Bideford in the north, with areas about Tauweru, Gladstone to Longbush, and Martinborough to Hinakura particularly badly affected. Most of the landslides were of small to moderate size (10^3-10^5 m^3), with many smaller rock and debris falls scattered throughout the hills. Only one or two large to very large landslides (10^5-10^6 m^3 *or greater*) were reported (for example, at Spooners, ca. 200,000 m^3). Most roads to the east and south of Masterton (to Tauweru, Gladstone, Longbush, Stronvar, Bideford) were blocked by landslides.

According to the County Overseer (Mr Wallace) the worst landslide damage in the Carterton area was at Gladstone where there were numerous landslides, as well as sand ejections, and fissures formed parallel to the Tauweru River [6]. Between Gladstone and Longbush, slides were mainly shallow slips down dip-slopes in soft mudstone, falling into the Whangaehu River from both sides.

In the Masterton area, the landslide damage was worst near Tauweru. Here, hills were reported as being 'blown apart', with major slumping in mudstone and lateral spreading on the bank of the Tauweru River [6]. A scarp feature formed on the side of a hill about 3 km north-northeast of Tauweru, on the southern side of the Mangatopitopi Stream, was identified by Ongley [6] as the surface fault trace associated with the June earthquake. However, recent examination by two of the authors has shown that this feature is actually the head scarp of a very large (10^6 m^3 *or greater*) incipient landslide (Tauweru Landslide, "1" in Figure 10). This and another nearby incipient landslide feature are described more fully in the next section. Nearby, the lower Mangatopitopi Stream was dammed by a moderately large (ca. 450,000 m^3) landslide (Mangatopitopi Landslide, "2" in Figure 10). This small landslide-dammed lake was the only such feature reported following the earthquake, but there were probably others that could now be identified on 1943-44 aerial photos.

Many landslides were also reported from around the Eketahuna area and also along the Makuri Gorge road. Larger landslides affected the railway line between Mangamahoe and Mangatainoka north of Eketahuna.

In the Wellington region, some moderate to large slides occurred in greywacke in the southern Tararua Range southeast of Otaki, and very small to small debris slides and rockfalls occurred in the Wellington City and Kapiti coast areas. A landslide at Goat Point south of Plimmerton blocked both lines of the North Island Main Trunk railway line, and smaller rockfalls were reported on the line between Plimmerton and Paekakariki. On State Highway 2 (SH2), rock falls were reported along the Western Hutt road and there were small rock and soil falls from cut slopes on Mangaroa Hill. Rock falls, cracking and subsidence (fill failures near summit) occurred on the Rimutaka Hill road, but it remained negotiable with care. A small failure was reported on the Rimutaka railway incline (Cross Creek), and there were also slides in the Waiohine River gorge west of Masterton. In the upper Otaki River area Lake Orewa (a ridge-rent tarn) was reported after the earthquake to have been drained, probably due to ridge-top cracking. Further to the north, boulders fell on to the road in the Manawatu Gorge.

Liquefaction effects were evident in many places, with sand and water ejections (sand boils), cracking and minor lateral spreading widely reported (Figure 10). These were far more extensive than reported by Fairless and Berrill [40] in 1984. In the Wairarapa, liquefaction-related cracking badly affected riverbanks and stopbanks, particularly around Gladstone and Greytown, and sand ejections were reported from as far away as Lake Ferry (70 km southwest of the epicentre).

In the Manawatu, the Foxton Beach area and Manawatu River stopbanks (50-65 km northwest of the mainshock epicentre) were badly affected with widespread cracking and sand ejections (Figure 11). At the Manawatu Heads and Foxton Beach practically all power poles in swampy, low-lying areas were tilted, and one fell over, due to liquefaction-induced ground failure. Although at 60 km or so from the earthquake source, the alluvial and flax swamp deposits present in these areas are highly susceptible to liquefaction effects, as demonstrated by other historical earthquakes such as the 1855 Wairarapa [41, 42] and the 1934 Pahiatua [24, 41] earthquakes.

Sand boils also occurred near Aotea Quay in Wellington (over 80 km southwest of the mainshock epicentre).

Figure 11: ***Sand boils at Paiaka, near the Manawatu River, caused by the 1942 June 24 Wairarapa earthquake. Note patches in the background that also appear to be affected.***

Relationships between ground damage and MM intensity

The isoseismals shown in Figures 3 and 10, generally assigned on the basis of building and contents damage, are consistent with incidence of landsliding and ground damage. The heaviest ground damage, where landsliding and blockage of roads was common, occurred within the MM8 isoseismal. Within the MM7 isoseismal area, landslides were sparser, and rare on natural slopes, but many cut slopes and fills failed. In the MM6 isoseismal area, minor rockfalls or falling rocks occurred. These were mainly of little more significance than nuisance value, except at Pohangina and Apiti , about 90 and 110 km north of the epicentre, where two significant failure areas were reported. The moderately large landslide at Goat Point near Plimmerton, (MM7) occurred on a cut slope that had a prior history of instability. The same area failed again during rain in the late 1970s, requiring remedial works to protect State Highway 1.

Liquefaction in the Gladstone and Dalefield area is consistent with MM8 shaking. The extensive liquefaction effects in the more distant Shannon and Foxton areas (within the MM7 isoseismal) are also consistent with MM8 shaking, but this is probably a microzone effect caused by highly susceptible ground conditions in these areas.

Relationship of landsliding to epicentre and aftershocks

A recent study of historical earthquake-induced landsliding in New Zealand [42] showed a good correlation between the areas most affected by landsliding during earthquakes and the (subsurface) fault rupture zone, as indicated by the zone of aftershocks. Convincing close relationships were demonstrated for the 1929 Murchison, 1968 Inangahua, 1990 Weber, and 1994 Arthur's Pass earthquakes. This association suggested that, for a given earthquake and allowing for topographic and terrain effects, landslide distribution could provide a reliable indication of the epicentre location, and also the extent of the fault rupture zone at depth. The same association is supported by this study of the June 24 1942 earthquake. The area of most intense landslide damage caused by the earthquake also shows a close correlation with the zone of aftershocks, and to the epicentre (Figure 10). Topographic influence is also apparent, with most landsliding occurring in steeper hill country on the eastern side of the aftershock zone. Few landslides were reported on the western side of this zone, which extends across the Ruamahanga River plains, where ground damage was mainly limited to sparse ground cracking, embankment subsidences, and minor liquefaction effects.

Tectonic setting of the 1942 Earthquakes and surface rupture in the June 24 1942 earthquake:

Compared to much of the rest of the country, central New Zealand, which includes the location of the 1942 Wairarapa earthquakes, has a high rate of occurrence of large magnitude earthquakes, and consequently has a high seismic hazard (for example, [43-45]). The tectonic setting of central New Zealand, that is, the driving mechanism behind most of the larger earthquakes, is dominated by the oblique westward subduction of the Pacific Plate beneath the Australian Plate. In the southern North Island, the subduction margin between the two plates, and the overall structural grain of the deformed overriding Australian plate, has a general northeast-southwest trend. The relative motion of the Pacific Plate, with respect to the Australian Plate, is approximately due westwards (azimuth of ca 260°) at a rate of about 40 mm per year.

To a first approximation, the oblique motion between the two plates is partitioned into margin-parallel and margin-normal displacement in a manner first described by Fitch [46], and in the New Zealand setting by Walcott in 1978 [47]. The margin-parallel motion appears to be largely accommodated by slip on a northeast-trending zone of active right-lateral strike-slip faults at the rear, northwestern boundary, of the subduction margin. At the latitude of the 1942 Wairarapa earthquakes, this zone of strike-slip faulting comprises, from east to west, the Wairarapa, Wellington, Ohariu, Pukerua and offshore Wairau faults (for example, [48]) (see Figure 2). The margin-normal motion, that is, contraction perpendicular to the margin, appears to be expressed as thrusting, reverse faulting, and folding east of the strike-slip faults, and as slip on the subduction interface (for example, [49-52], and references cited therein). There are, however, complications and exceptions to this simple model. For example, there is a group of active faults that extend east-northeast across the subduction margin from the Wairarapa fault near Carterton and Masterton (for example, Lensen [53]), the best expressed of these faults being the Carterton and Masterton faults (Figure 2). Recent work by Zachariasen et al [pers. comm.] suggests that the Carterton Fault is primarily right-lateral strike-slip with a lateral slip rate of at least 2 mm/yr. The rate of movement and sense of slip on the Masterton fault is still, however, not known. Also, there are no doubt elements of margin-normal contraction accommodated within the zone of strike-slip faulting, as well as margin-parallel motion accommodated in the "contractional" zone to the east. Two good historical examples of the latter are the 1934 Pahiatua earthquake, and the June 24 1942 Wairarapa earthquake. Both these earthquakes appear to be large, M >7, strike-slip earthquakes with a preferred focal plane that is steep-dipping, right-lateral, and north-northeast to northeast striking.

Surface fault rupture in the June 1942 earthquake

Immediately following the 1942 June 24 Wairarapa earthquake, a group of New Zealand Geological Survey geologists visited the epicentral region. Their observations regarding earthquake-triggered ground damage are reported in Ongley [6]. Near the township of Tauweru, they report scarp-like ground damage features that they ascribe to primary surface fault rupture. These scarp-like features, with a combined length of about 1 km, are located west of the Tauweru River on both sides of Mangatopitopi Stream about 2.5 km north of the Carterton fault, and about 3.5 km north-northeast from Tauweru township (approximate grid references, NZMS 260 S27 465265 to 474268). Air photos (904/27, 28 and 29), taken only 14 months after the June 1942 earthquake, clearly show these scarp-like features, as well as quite a few pre-existing deep-seated landslides, some of which appear to have been freshly re-activated. The photos also show numerous shallow seated slides that were presumably the result of the heavy rains that followed the earthquake.

On June 8 1999, Gaye Downes and Russ Van Dissen visited and photographed (Figures 12, 13) the scarp-like ground damage features located southwest of Mangatopitopi Stream (Ongley's Figures 4-7; Ongley's Figures 4, 6 are reproduced here in Figures 12, 13). The authors could also look northeast across Mangatopitopi Stream to the scarp-like features depicted in Ongley's Figures 8 and 9. (Figure 9 of Ongley [6] is also reproduced as Figure 169A of Cotton [54]). The scarp-like features located southwest of Mangatopitopi Stream generally face south, have a strike of ca N80°E, and are on trend with and continuous with the head scarp of a large south-flowing pre-existing landslide. South of the scarp-like features, i. e. downslope of the features, the hill slope comprises classic hummocky landslide topography.

The scarp-like features located on the northeast side of Mangatopitopi Stream, as depicted in Figures 8 and 9 of Ongley [6] and seen in the background of Figure 13, have largely been destroyed as they now define the lateral margin of a narrow landslide. Originally these features had an overall northeast-trend, and faced northwest. It is interesting to note that the en-echelon pattern of surface cracking defined by the scarp-like features, shown in Figure 9 of Ongley [6], is consistent with the differential lateral movement expected across the lateral margin of a landslide.

Another important observation relevant to the genesis of the scarp-like ground damage features is that there is very little, if any, offset of relatively pronounced strike ridges of resistant lithology on either side of, and oriented approximately normal to, the western and eastern extent of the scarp-like features. That is, the scarp-like features are contained within the zone between these two parallel strike ridges, and these north-south trending strike-ridges are not displaced by the scarp-like features. In map view, the two strike ridges form the two vertical lines of the capital letter "H", and the scarp-like features form the horizontal line between.

It is our consideration that the scarp-like ground damage features reported by Ongley [6] as surface fault rupture associated with the June 1942 are in all likelihood landslide related. The scarp-like features are invariably associated with, and in most cases, coincident with, pre-existing or subsequent landslides, and there appears to be no offset of pronounced geological units along strike of, but at a high angle to, the scarp-like features. The authors consider that the best explanation for the formation of these scarp-like features, at least those located southwest of Mangatopitopi Stream, during the 1942 earthquake is not tectonic fault rupture of the ground surface, but rather minor re-activation of a pre-existing landslide. The re-activation of the landslide was no doubt triggered by the strong ground shaking generated from the 1942 earthquake. Ongley [6] describes the maximum vertical displacement across the freshly formed scarp as approximately 3 feet, and notes that the freshly formed scarp comprises only a part of a larger scarp of about 10 feet. Ongley proposed that the larger scarp height was the result of additional, older, fault movements. The authors agree with Ongley that the larger scarp height documents repeated, older, movement, but the authors ascribe the movement not to tectonic fault rupture, but rather to landslide failure.

***Figure 12:** Photographs of the scarp near Tauweru (Landslide 1 in Figure 10) that Ongley attributed to surface fault rupture, now recognised as the western side of the head scarp of a large landslide. The upper photograph was taken in June 1999 at approximately the same location as Ongley's [6] Figure 4 shown below.*

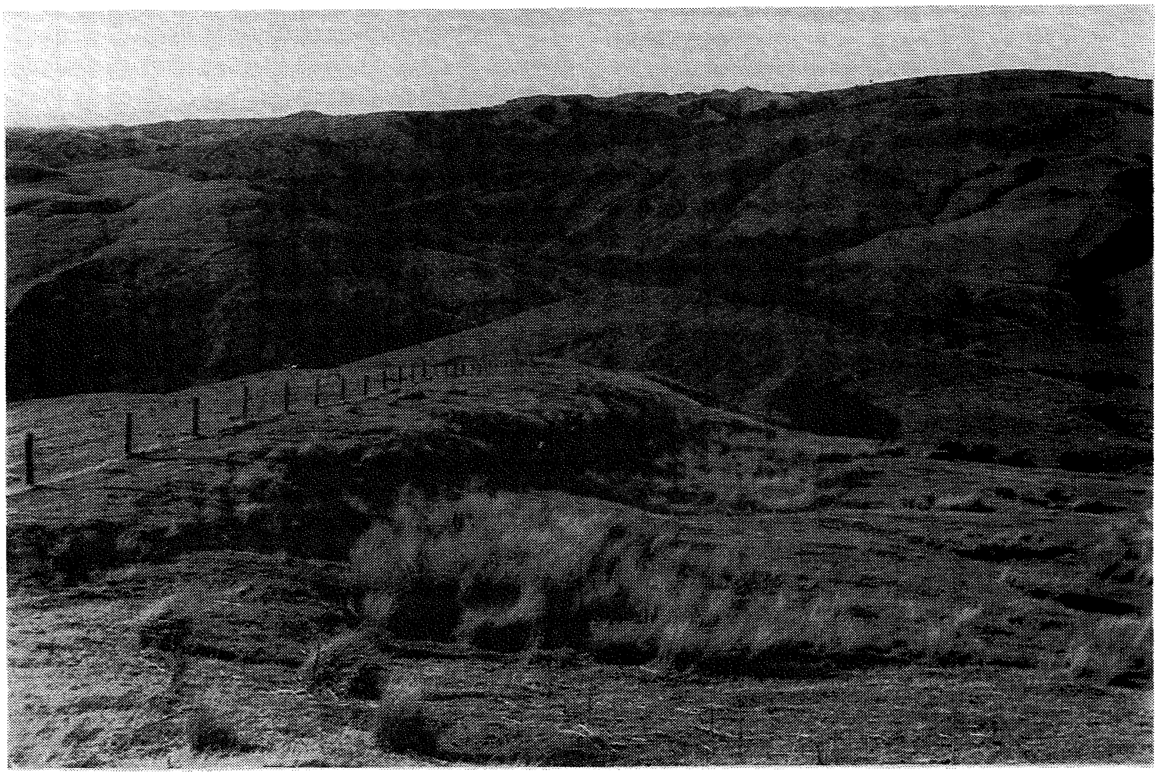

Figure 13. Photographs of the scarp near Tauweru that Ongley attributed to surface fault rupture, now recognised as the eastern side of the head scarp of a large landslide. The upper photograph was taken in June 1999 at approximately the same location as Ongley's [6] Figure 6 shown below.

The authors are not the first to question the tectonic origin of the scarp-like features described by Ongley. For example, Lensen in 1968 [53] states:

"... *those traces that were definite surface breakages formed during the Wairarapa Earthquake of 24 June 1942 (Ongley, 1943) [6] have not been shown [on the Late Quaternary Tectonic Map of New Zealand]. These have been examined in the field and also on air photographs flown in November 1943 shortly after the earthquake. The traces illustrated by Ongley in figs. 4, 5, 6, 7, 8, and 9 cut across a large low angle mud slide and do not extend on to "solid" ground on either side. Other traces run parallel to and near river banks. All can be explained without requiring a fault origin and none is aligned with a positive fault trace.*"

And Schermer et al. [55] state:

"... *we examined airphotos from 1943-44 in the northern part of the area of 1942 ground disturbance and rupture reported by Ongley [6]. The ruptures occur only on steep slopes and ridgelines in areas where no continuous, active, or long-lived fault trace can be seen on the airphotos. Although ground shaking features are described north to Bideford, no other ruptures are reported by Ongley, and are not evident on the photos between Bideford and the Dryers Rock fault zone.... Thus we suggest that the 1942 rupture described by Ongley (1943) instead represents the effects of ground shaking rather than fault slip.*"

The lack of damage to water and sewerage systems in Masterton, through which the Masterton Fault passes, suggests that this fault did not rupture to the surface. The lack of a report of significant ground displacement across the Masterton-Tauweru Road, which would have been sighted by Ongley and others, and which crosses the Carterton Fault, suggests that this fault also did not rupture to the surface. In addition, the fact that intensities greater than MM9 occurred only at isolated locations, and were not widespread near the epicentre, is consistent with rupture failing to reach the surface.

No explanation can be found for reported faulting in the Aorangi Ranges [9] some 60-70 km south-south-west of the epicentres of the June and August earthquakes. A scarp was apparently noticed by a resident of the Pararaki Valley after a large earthquake in 1942, and reported in Berryman [9] and Stevens [56]. Berryman [9] investigated the site, reporting that, although near the headscarp of a large pre-existing slip, the scarp suggested faulting rather than landsliding or ridge renting, as the observed throw was contrary to that of the headscarp of the landslide. Further, the trace extended over the spur of a ridge and is continuous for ca. 400 m. Dendrochronological evidence suggested disturbance of growth rings in the trees that was consistent with its having occurred in 1942-43 [9]. The site is too distant from the 1942 June, August or December mainshocks to be primary or even secondary faulting, and no other large earthquakes occurred nearby within the June-December 1942 period. However, it is within the MM7 isoseismal of the June earthquake and hence ground damage in susceptible terrain would not be unexpected.

THE M_W6.8 AUGUST 1 1942 EARTHQUAKE

While the August 1 earthquake (M_w6.8, h_c 40 km) was almost as large as the June 24 event (M_w7.2, h_c 12 km) and its epicentre was within a few kilometres, it was far less damaging overall because of its greater depth (Table 3). The strongest isoseismal is MM7 compared to MM8 in the June event (Figures 3, 4). Hence the damage to domestic and non-domestic buildings is insufficient to warrant describing it in as much detail as the June event.

A significant feature of the earthquake was the extensive additional damage caused to previously damaged structures and to freshly rebuilt (and hence, very weak) structures, particularly chimneys. This was more noticeable in areas only moderately damaged in the June earthquake, for example, in Wellington. Here, the collapse of buildings, and parapets in the central city area and the repeated destruction of many chimneys made the August earthquake seem much more severe than that in June.

In the Wairarapa, there was considerable further damage to unreinforced brick chimneys and some extra damage caused to some of the brick buildings in the townships, particularly Masterton, Carterton and Eketahuna. Some timber houses in rural areas were also reported as being damaged, e.g. "badly wrenched" (the meaning of which is unclear).

There were no casualties reported. As with the June earthquake, the lack of casualties can be attributed to the time of the earthquake (00.34am local time), when few people were on the streets and most people were asleep in their timber houses.

The assignment of intensities of MM6 and greater are less certain than for the June earthquake because of the presence of previously damaged, or nearly repaired, structures. At locations where this effect is significant, intensities that might superficially be assigned as MM7 or MM8 are assigned as "MM7?" (Table 3; Figure 4).

Lifelines Damage in the 1942 August 1 Earthquake:

Electricity

Loss of electrical supply affected fewer locations over a smaller area and for a shorter time than in the June earthquake. The longest period of power loss (18 hours) was in Eketahuna (MM7), while elsewhere power was generally restored in less than an hour. In Wellington, the electricity supply was interrupted for about 20 minutes, the failure being attributed to the tripping of a switch at Mangahao and the failure of an earth clamp on a transformer at Pauatahanui. The collapse of parapets and facades in Wellington (MM6 and MM7) also brought down power lines in several places. There was further damage to poles and service lines at Foxton Beach (MM7, possibly MM8 in places), where liquefaction effects were again evident. Several hundred service lines and several feeder lines required attention in the Manawatu and Horowhenua areas (MM7).

Gas Supply

Two instances of damage to gas supply were recorded. At the Carterton Gas Works (MM7), not damaged in June, there was minor damage to retort doors, the brick chimney stack and the engine room roof. The supply was back to normal within 24 hours. Some gas installations were damaged in Wellington's Manners Street.

Water Supply

Eketahuna (MM7) reported the most serious damage to water mains. The subsidence of a road in the town caused the water main to break in three places, and the town was without water for most of the day following the earthquake. Several connections to houses at Otaki (MM7) were damaged and one water main was broken near the reservoir servicing Palmerston North (MM7). In Wellington (MM6 and MM7), one or two water mains were damaged, and three joints in the water pipe from Wainuiomata sprang leaks.

Telephone and Telegraph

Telegraph services were not disrupted and the incidence of damage to telephone services was considerably less than in June. For example, in Palmerston North only 170 faults were reported, compared with over 600 in June.

Railways

Locations in the Wairarapa that caused problems for railway services in June were again troublesome, with landslides, and subsidence of bridge approaches and parts of the line. However, service along the section of the line between Eketahuna and the Rimutaka Incline (MM7), where the most serious delays were caused, was restored within 12-15 hours. Minor damage between Waikanae and Levin (MM7) meant that trains could travel only at reduced speed, as they could at Kakariki (MM6), near Halcombe, where the railway bridge was reported out of alignment.

Roads

Damage from landslides, subsidence of road edges and bridge approaches (described in greater detail in the next section) was widespread in the Wairarapa, new slips and subsidences occurring at many of the locations that were badly affected in the June earthquake and also in several new locations within the highest intensity isoseismal, MM7. At Tinui and Mauriceville (both MM7), roads were cracked and bridges damaged whereas this had not been reported in June. At Eketahuna (MM7), subsidence of one road, unaffected in June, was serious enough to break the water main. Considerable damage was done to four bridges in the Wairarapa, with minor damage to a fifth, all within 10-15 km east to southeast of Masterton. The principal damage was to abutments, with no damage to the superstructure. The culvert at Devil's Elbow, near Tauweru, was shattered. Heavy rain and floods two weeks before the earthquake may have contributed to the landsliding and subsidence.

In the Wellington area (MM6 and MM7), there were superficial cracks in Upland Road and Glenmore Street, while in the Manawatu and Horowhenua area, there was further cracking of the roads about Foxton (MM7) and a small landslide and superficial cracks east of Otaki (MM7).

Landslides, Ground Damage and Liquefaction Effects, August 1st 1942:

Earthquake-induced landsliding, ground cracking, subsidence and liquefaction effects caused by the August earthquake were less severe than those in the June earthquake and occurred over a significantly smaller area (5,600 km^2; Figure 14). Landslide damage occurred in a few localised, widely separated areas in the Wairarapa hillcountry to the south, east and north of the epicentre, but also to the west as far away as Pukerua Bay, Paekakariki, and Otaki. Many of the slope failures occurred in the same general areas as in the June earthquake, but the slides were generally far less numerous and damaging.

There was only moderate landslide damage in the Wairarapa, and minor subsidence of bridge approaches. The most intensive damage occurred in the Martinborough area, with all roads to the coast again blocked by slips, cracks, and subsidence. Slips again blocked the Stronvar road southeast of Masterton. In the north, slips fell on to the road south of Eketahuna, where there was also road cracking and subsidence. Again, there were numerous slips in Makuri Gorge. A slip occurred on the Rimutaka Incline between Cross Creek and the summit, and small landslides were reported in the Otaki Gorge area. The Paekakariki Hill road was closed by a "big slip" while at Pukerua Bay there was a "slight fall of earth" near the railway line. On the railway line south of Plimmerton there was no further trouble from the June slip area at Goat Point. There was little landsliding in Wellington City with only minor, very small regolith slides and falling rocks reported in a few places.

Soil liquefaction effects were also evident during this earthquake, particularly in the far field. Significant localised liquefaction effects were again reported in the Foxton to Levin area (Figure 14). Sand fountaining occurred along the river front at Foxton Beach, and bridge approaches in the area subsided. In the swampy ground in the Horowhenua area, power poles were tilted over, probably by liquefaction-induced ground failure. On the Paiaka Road to the Manawatu River (west of Shannon) widespread "sand geysers" again occurred over about 5 acres (2 ha), with sand piled up 400-500 mm and spread out over 2-4 m from some vents. Similar effects also occurred in about the same location during the June earthquake, although possibly more widespread. The widespread liquefaction effects in the Foxton-Horowhenua area indicate local shaking bordering on MM8 in an otherwise MM7 area, emphasising the high susceptibility of ground in the area to soil liquefaction and hence, microzone effects.

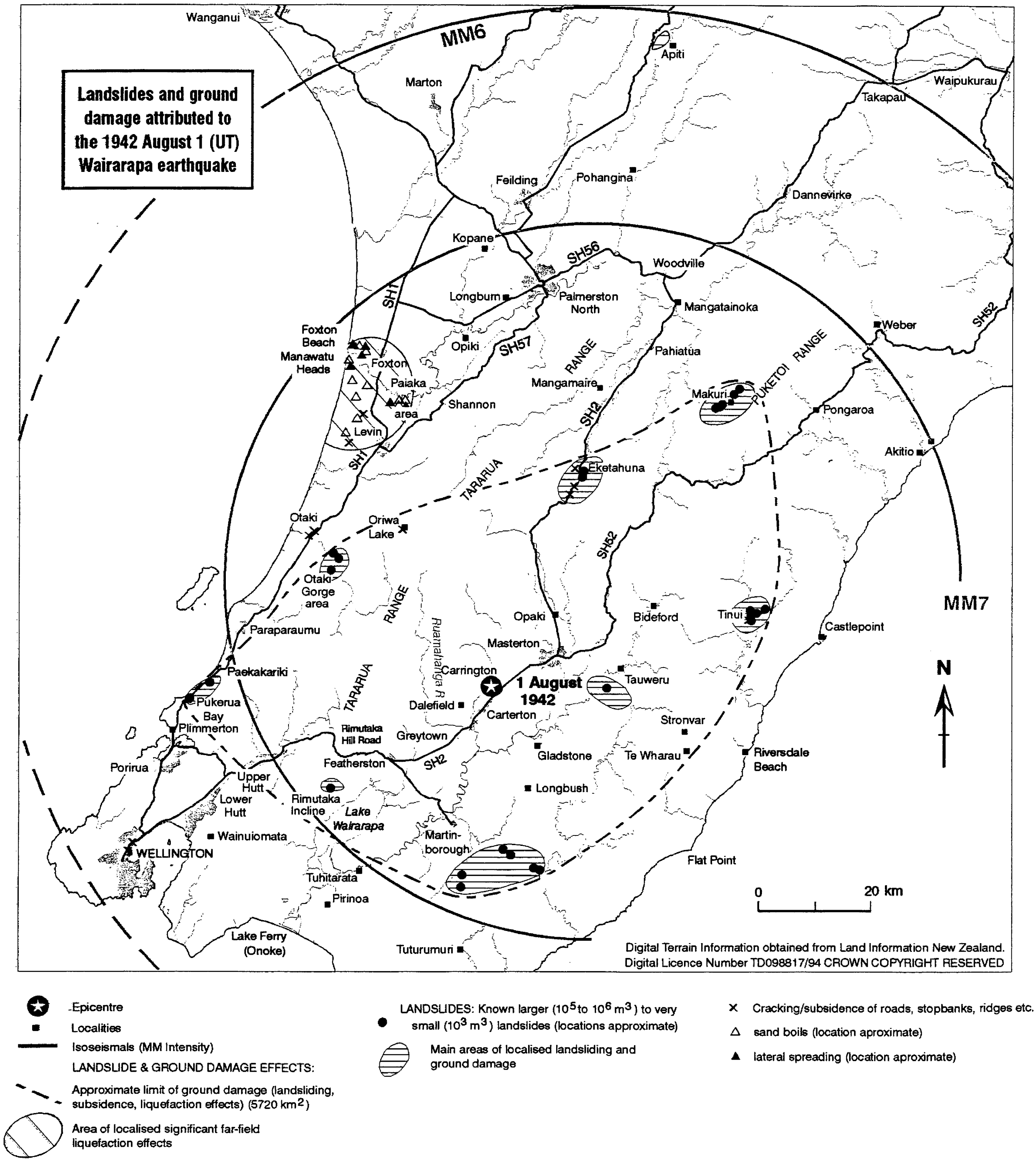

Figure 14: Geographic distribution of landslides and ground damage attributed to the August 1 1942 Wairarapa earthquake. Isoseismal lines are from Figure 4.

Surface Fault Rupture in the 1942 August 1 Earthquake?

Given the depth of the 1942 August earthquake (about 40 km) surface fault rupture would not be expected, and indeed, Hayes [3] in his annual report for the Dominion Observatory notes that "no fresh surface faulting was found on 2nd August". However, Neef [8] suggests that a 2 km long bedding plane parallel fault scarp to the east of the Alfredton Fault, which he noted as fresh-looking on 1944 aerial photographs, ruptured in the August 1942 earthquake (the mistakenly identified fault trace for the June earthquake [6] having been located elsewhere). Based on their observations, on the same 1944 aerial photographs, and on photographs taken in 1935 and 1947 of the main Alfredton fault, Schermer et al [55] observe that: "the main Alfredton fault trace is at least as fresh [as Neef's bedding plane fault], and probably moved at the same time", and that the most likely date of the most recent rupture along it was in 1855, not 1942 or 1934 (in the 1934 Pahiatua earthquake).

THE M_S6.0 DECEMBER 2 1942 EARTHQUAKE

The calculated epicentre of the December earthquake correlates reasonably well with the highest intensity area (Figure 5, Table 4), where each of the small communities yet again experienced the destruction of crockery and glassware, and the fall of at least a few chimneys. Some of the chimneys were still "green" from recent reconstruction after the previous earthquakes. The earthquake exacerbated previous damage elsewhere, particularly in Wellington, but none was serious. Some areas of the Wairarapa on alluvial flats (for example, at Tuturumuri) and in Wellington appear to have been shaken more strongly than others nearby, probably indicating a microzone effect.

FORESHOCK ON JUNE 24 1942 AND EARTHQUAKE ON AUGUST 1 1942 (THE MAKURI EARTHQUAKE)

With a magnitude of M_L5.3, the earthquake on the evening of June 24 (3 hours before the M_w7.2 earthquake) was insufficient to cause any damage other than the fall of a few items from shelves in Masterton (Table 5).

The M_w5.6 Makuri earthquake on August 1 was widely felt in the southern half of the North Island (Table 6). As this earthquake could not be located instrumentally an epicentre has been adopted that is consistent with the intensity data. The only significant damage was the fall of many chimneys at Makuri (MM7?) and Coonoor (MM7?) and the fall of a few at Pongaroa (MM6). As noted earlier, intensities have been assigned "?" where the effect of cumulative damage from the June earthquake is uncertain.

DAMAGE IN WELLINGTON IN THE JUNE 24 AND AUGUST 1 1942 MAINSHOCKS AND MICROZONING EFFECTS

The variability of damage from one location to another nearby has been recorded in the media in many New Zealand earthquakes. In the 1942 earthquakes clear variations in ground shaking were evident in Wellington City and in the Manawatu. Wellington City has the best dataset for examining the microzoning effects in these events. Some damage information also exists for the Hutt Valley, but the distribution of houses damaged is not well determined. Other than newspaper accounts, the only major sources of information found were State Housing Corporation files (held at National Archives) detailing damage to State Houses in Lower Hutt. These indicate that a great many houses suffered chimney damage, some damage to plumbing and some minor cracking but the distribution of damage shows little more than the distribution of State housing in the Hutt Valley, i.e. Waterloo/Woburn, Avalon and Naenae/Taita.

In Wellington, depending on location, intensities of MM6 and MM7 were experienced in the June and in the August earthquake. The August earthquake appeared to do more damage, especially to commercial buildings. With only six weeks between the two large earthquakes repairs from the June event had not begun, were still in progress, or were recently completed with mortar or concrete still weak. Reports of the damage prepared by engineers of the time do not attempt to separate out the effects of June and August earthquakes, which they well recognised as cumulative.

The Wellington data can be divided into residential and commercial damage. The residential damage was primarily to chimneys, although several houses in Webb Street and Barker Street were so badly damaged from falling chimneys and cracked and fallen brick walls that they were evacuated. Luke [13] prepared a map of the percentage of damaged domestic chimneys in each of 32 building districts (reprinted in [15]). Chimney damage per district varied from 0 to 84%. While there is a minor correlation with age of housing, probably due to improved building practices in the newer houses, there is a far better correlation with areas of soft sediment [15].

The overall pattern of damage is consistent with the 1992 ground shaking hazard map [16, 57], except for Kelburn and Northland, which had 63% and 54% chimney damage respectively. Both suburbs are almost entirely in the lowest hazard zone on the 1992 map. As the original data used by Luke is not available, it is not possible to examine this discrepancy nor to recalculate the percentage damage in each of the 1992 zones.

Of the commercial buildings, 36 required major structural repairs and a few hundred others required minor repairs, according to the newspapers published a week or two after the June earthquake. While some parapets collapsed, many more were only cracked and the most obvious damage to the Central Business District (CBD) was the breakage of many hundreds of windows (over 300 in one building alone), the extensive stock damage, and the extensive cracking and tilting of brick walls. The Te Aro area was reported to be badly affected as were the areas about Cambridge Terrace, Webb and Buckle Streets. In the wharf area, there was subsidence of fill at several locations and liquefaction was reported near the Social Security building in Aotea Quay.

The damage to the CBD from the August earthquake was extensive and more obvious than in June, with many parapets, masonry walls and brick walls cracked and dangerous, or collapsed into the city streets. Although some instances of damage were reported to be in buildings not previously damaged, most were seen by the media and the building/engineering community to be the result of the weakening caused by the June earthquake.

Some new interpretation of the distribution of damage within the CBD is possible with new information on the damage to non-Government commercial structures. A map of unknown authorship (Figure 15a) was photocopied in about 1992 from the original held by the Wellington City Council (and now apparently lost). The map may have been drawn up by Johnson, who surveyed 900 buildings in the CBD for the Earthquake & War Damage Commission and briefly reported his observations at the Second World Conference on Earthquake Engineering [14]. Alternatively the map may have been drawn by Aked or Luke (previously mentioned Wellington engineers). It identifies the damaged non-Government (NZ) buildings in the CBD, classifying them by age of construction, i.e. pre-1914, 1914-1935 and 1935-1942 (Figure 15a). Neither the construction type nor the extent of damage is specified. No text other than the map legend is available for the map so it has only been interpreted in broad terms and only in the areas where there are few residential structures, as damage to residential structures does not appear to be included on the map.

The authors have limited their analysis to the pre-1914 buildings, as the map clearly shows that these older buildings suffered the greatest percentage of damage. There is broad agreement between the distribution of buildings damaged and the 1992 earthquake shaking hazard zoning map previously referred to (Figure 15b), but there are two areas where the 1942 damage is higher than predicted by the zoning on the 1992 hazard zoning map. The concentration of damage around Manners Street falls in Zone 2 and a small concentration near the northern end of Lambton Quay is in Zone 1. The sediments in the Manners Street area may be deeper than estimated in the 1992 sediment thickness map [58] as the subsurface control there is limited (Perrin, pers comm). The buildings at the north end of Lambton Quay are on bedrock (the basis for the Zone 1 classification) and are the only buildings listed on the map in Zone 1 that were damaged.

Many of the buildings damaged in 1942 were sited on areas of fill seaward of the pre-1855 shoreline, the first such reclamation occurring in 1852 and the last major reclamation being completed in 1914. The boundaries of the 1992 shaking hazard map were based largely on the depth of soft sediment and did not differentiate between different units of fill. However, the newly found building damage map shows a strong correlation of damage to particular units of fill (Figure 15c). Damage incidence in individual units varies from zero to over 50% of the buildings. The difference may be due to a number of causes, including the type of fill and whether it had been compacted, perhaps the similarity of construction or use, or to the construction technique in vogue immediately following reclamation. Nevertheless, the effect merits further investigation.

The Wellington City Archives holds original building inspection records of over 420 buildings dating from the June 24 earthquake onwards, in which there are details of the type of building (though not the age), the damage to the structure and recommended repairs. A useful, separate study could be conducted to interpret the damage descriptions from these and the newspaper accounts, and to prepare a detailed microzoning report on the damage to commercial structures. Such a study could address the effect of building height, and type of structure as well as the microzoning effects.

IMMEDIATE RESPONSE AND RECOVERY

Without doubt, recovery and reconstruction after the 1942 earthquakes were impeded by the scarcity of labour and materials created by the Second World War. Repairs to chimneys after the June earthquake proceeded more slowly than many householders and local authorities wished. Heavy rain (and flooding) throughout the southern North Island on July 13-14 heightened awareness of inadequate progress. Despite the restriction that one essential chimney only was repaired for each household and despite repairs being organised by local authorities rather than individuals, repairs proceeded slowly and many complained about overcharging and unnecessary demolition of chimneys by the Emergency Precautions Service (EPS) and the army.

On the other hand, the usefulness of having EPS personnel, which had been formed to manage and respond to war emergencies, was more than evident. An unknown writer in the Wairarapa Times-Age June 26 1942 writes: "The necessity of an EPS organised to function in peace time as well as war time has been brought home by the incidents of the last few days". The EPS personnel were mobilised and immediately available for managing public safety, demolishing dangerous buildings and chimneys and setting up canteens and shelters for labourers, and for small numbers of evacuees in Wellington and the Wairarapa, just as the regional and local authority Civil Defence units are today. The military in the Wairarapa also provided labour for patrolling streets and for demolition work. Soldiers with building skills were relieved temporarily of their duties, primarily to help rebuild chimneys.

The 1942 earthquakes also provided the impetus to the Government to establish a national insurance scheme. The Earthquake and War Damage Commission was established in 1944.

DISCUSSION

The study has provided valuable information on the locations and effects of the 1942 earthquakes, all of which are relevant to seismic hazard assessment. However, several results have significant implications for seismic hazard assessment that takes into account the variability of hazard with time.

Although the June 1942 earthquake was shallow enough (~12 km) and large enough (M_w7.2) for surface rupture to have occurred, evidence suggests that it did not. Thus, there is a strong likelihood of other similar strike-slip earthquakes having occurred in the past without leaving a clear surface manifestation of their occurrence in the geological record. Hence, attempts to define the long-term rate of occurrence of similar or lesser magnitude earthquakes based on paleoseismic studies of the geological record are likely to underestimate the frequency with which large damaging earthquakes have occurred, leading to a potential underestimation of seismic hazard.

Also significant for seismic hazard assessment is the closeness in time and space of the 1942 Wairarapa earthquakes and the 1934 M_s7.6 Pahiatua earthquake. The June and August 1942 mainshocks are almost along strike and within 10-15 km of the assumed sub-surface rupture zone of the predominantly right-lateral strike-slip 1934 Pahiatua earthquake [24], suggesting that stress changes caused by the 1934 event may have induced the 1942 events. Studies of stress triggering of the 1942 events (using the models of King et al [61], for example) will be possible when source mechanisms of Doser & Webb are finalised, and will follow on from studies of other New Zealand earthquakes, such as those of Robinson & McGinty [62] and McGinty *et al* [63].

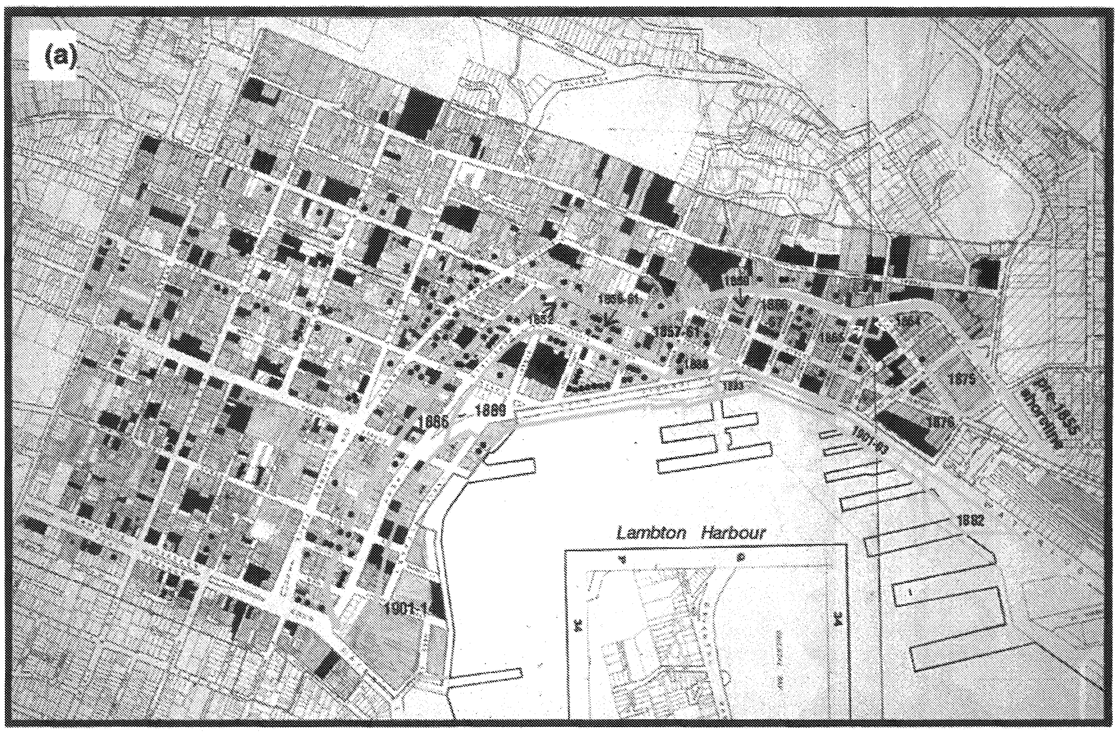

Figure 15. (a) Map (of unknown origin) of damage to commercial structures in the Wellington CBD. Black circles show damaged structures. Structures are separated into three categories: pre-1914 (red), 1914-1934 (blue), and post 1934 (black). Non-commercial structures are shown on map but are not classified as to damage

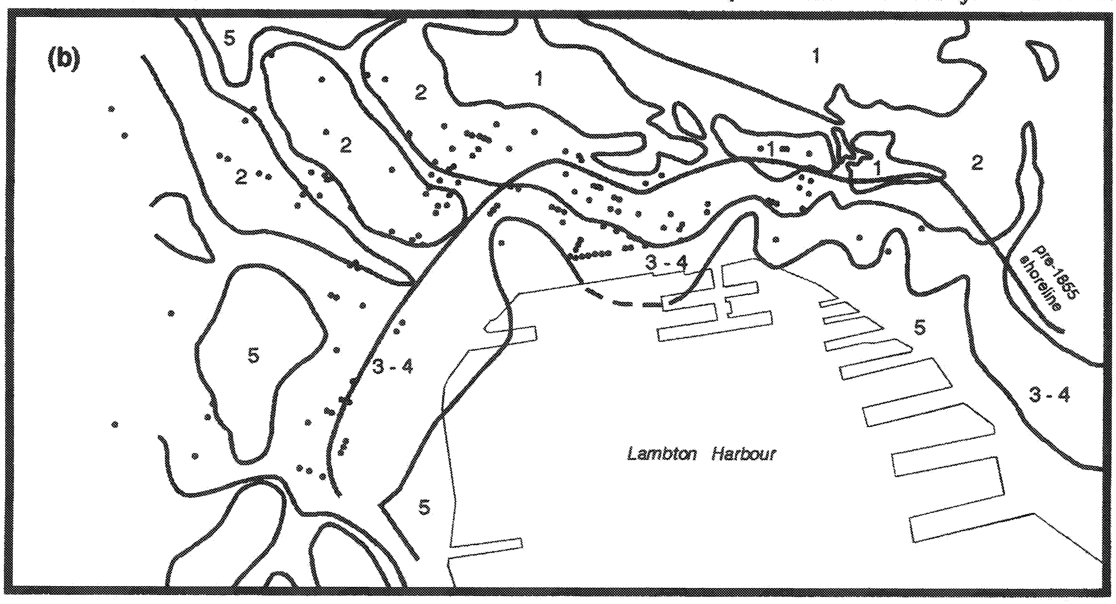

Figure 15 (b): Wellington ground shaking hazard map, based on strong motion, weak motion, and subsurface geology [57, 58]. Zone 1 (least shaking) corresponds to bedrock and Zone 5 (greatest shaking) corresponds to regions with greater than 10 m of soft sediment.

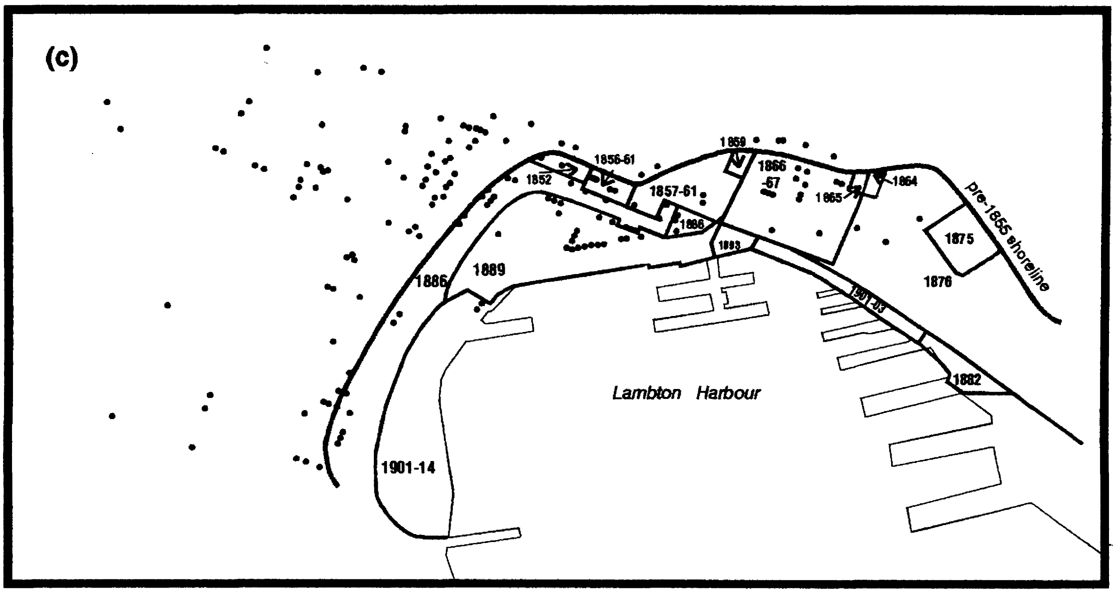

Figure 15 (c): Map of individual units of fill and dates of creation. Compiled using a 1936 Wellington Harbour Board map [59] and Baillie [60].

The closeness in time and space of the earthquakes within the June-December 1942 sequence also suggests some causal relationship and possible stress triggering. The occurrence of a sequence of moderate to large earthquakes like the June–December 1942 sequence is not unique in the Wairarapa-Hawke's Bay area. In February 1990, a M_w6.2 earthquake in the subducted plate under Weber was followed by a M_w6.4 earthquake in the upper plate in May 1990 [64]. Two subsequent events, both M_L5.5, occurred in the subducted plate in August 1990 and March 1992. All were within 15 km of each other. The new epicentre and depth of the June 1942 mainshock show that it occurred in the upper plate while the source of the August 1942 earthquake was 15 km to the southwest in the subducted plate, although it should be recognised that epicentres may be mislocated by up to 20 km. Nevertheless, the 1942 earthquakes seem to be paired in a similar manner to the 1990 Weber earthquakes, although in 1990 the first event was the deeper event and in the upper part of the subducted plate [64], somewhat shallower than the August 1942 event. This coupling of earthquakes (and possibly the occurrence of a third earthquake in 1942, and a third and fourth earthquake near Weber in 1990-1992) shows that such sequences are probably not isolated occurrences and the probability of such sequences should should be taken into account in hazard modelling.

CONCLUSIONS

This study has achieved its goal of providing more reliable and extensive data on the locations and the effects of the June 24 M_w7.2, August 1 M_w6.8 and December 2 M_s6.0 1942 Wairarapa earthquakes, their major aftershocks, and other associated shocks. In particular, damage data provide valuable insight on the performance of lifelines, and domestic and non-domestic buildings in urban and small town environments at intensity MM8, and on the effect of strong shaking on previously damaged, and newly repaired, and hence weakened, structures. The good performance of reinforced concrete and retrofitted brick buildings in the Wairarapa at high intensities is of particular relevance for hazard assessment.

Discrepancies between the distribution of damaged buildings shown on a newly uncovered map of damage in Wellington CBD and the shaking zones delineated on the 1992 Wellington shaking hazard map (microzoning), and a strong correlation of damage with reclamation units, suggest the need for an intensive study of 400+ files held at the Wellington City Council Archives in conjunction with the map and newspaper accounts.

Our results show the 1942 June earthquake to be one of the more significant historical ground damaging earthquakes in New Zealand. The area in which landsliding and liquefaction ground damage occurred (about 6,500 to 11,500 km^2) was far more extensive than previously recognised (3,700 km^2) in a national reconnaissance study completed in 1997 [39]. This suggests that relationships given in the 1997 study for areas affected by historical earthquakes in New Zealand are likely to be minimum values. Further studies of specific earthquakes are likely to reveal similar differences between the reconnaissance-level data and what can be learned from more in-depth research.

The distributions of landsliding and other ground damage in the June and August mainshocks are consistent with their respective isoseismal maps, for which intensities were assigned on the basis of building and contents damage rather than ground damage. The 1942 Wairarapa earthquakes provide further evidence that, after allowing for topographic and terrain effects, a zone of intense earthquake-generated landsliding can place reliable constraints on the epicentral location of an historical, or pre-historical, earthquake, the extent of fault rupture at depth, and hence, magnitude.

Although the locations of the June mainshock and distribution of its aftershocks do not define the rupture zone, they are compatible with Doser & Webb's preliminary source mechanism of a predominantly right-lateral strike-slip earthquake. Despite being shallow enough and large enough for surface rupture to have occurred, apparently it did not and the scarp-like features described by Ongley [6] in 1943 as surface fault rupture are now considered to be landslide-related, and not tectonic in origin. This has significant implications for modelling the seismic hazard of this part of New Zealand, in that a large (M_w7.2), shallow (~12 km), strike-slip earthquake can occur without leaving a clear geological signal. This may lead to underestimation of the frequency of similar large damaging events.

The closeness in time and space of the earthquakes both within the sequence and with the 1934 Pahiatua earthquake, and the similarity of the sequence with the 1990 Weber earthquakes suggest that seismic hazard assessment in this part of New Zealand should take into account the possibility of similar short time-scale (within a few months) and longer time-scale (within a few years) sequences of large earthquakes in the future, together with their implications for time-variable hazard and cumulative damage.

ACKNOWLEDGEMENTS

This research was jointly funded by the Earthquake Commission and the Foundation for Research, Science and Technology. The authors would like to thank Dr M. E. Reyners, Dr W. R. Stephenson, N. Perrin and P. Davenport for helpful comments that led to improvements in the content and text. Diagrams have been expertly drafted by Carolyn Hume and Biljana Lukovic.

REFERENCES

1. Dowrick, D. J., Rhoades, D. A., (1998). "Magnitudes of New Zealand earthquakes, 1901-1993". *Bulletin of the New Zealand National Society for Earthquake Engineering* 31: 260-280.

2. Gibowicz, 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.

3. Hayes, R. C., (1942). "The Wairarapa earthquake of 24th June 1942". *DSIR Dominion Observatory [New Zealand] Bulletin S-66.*

4. Hayes, R. C., (1943b). "Earthquakes in New Zealand during the year 1942". *New Zealand journal of science and technology* 24: 191-194.

5. Hayes, R. C., (1942). (Unpublished) "Report on the reconnaissance of Wairarapa earthquake area 1942 June 26th-30th". *DSIR Dominion Observatory [New Zealand] internal report.*

6. 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.

7. Hayes, R. C., (1943a). "Extract from the Annual Report of the Department of Scientific and Industrial Research, 1942-43". *DSIR Dominion Observatory Bulletin R28.*

8. Neef, G., (1976). (Note.) "Probable faulting on a minor, reverse bedding fault adjacent to the Alfredton Fault, north Wairarapa, during the 1 August 1942 earthquake". *New Zealand journal for geology and geophysics* 19: 737-742.

9. Berryman, K., (1977). "Dating recent tectonic events in parts of New Zealand with dendrochronology". *Unpublished BSc (Hons) paper.* Victoria University of Wellington, Wellington, New Zealand.

10. *New Zealand journal of science and technology* 15: 3-115 contains six papers on various aspects of the 1931 Hawke's Bay earthquake.

11. *New Zealand journal of science and technology* 18: 845-865 contains four papers on the 1932 Wairoa earthquake.

12. Aked, W. E., (1945). "Damage to buildings in the City of Wellington by earthquake, 1942". *Proceedings of the New Zealand Institution of Engineers* 31: 132-183.

13. Luke, K. E., (1943). "City of Wellington, NZ. Report on damage by earthquakes, 1942". (Unpublished) *City Engineers' report to Wellington City Council.* Wellington City Council Archives and GNS files.

14. Johnston, J. A. R., (1960). "A brief history of damaging earthquakes in Wellington City and developments in multi-storey building construction in New Zealand". *Proceedings of the Second World Conference on Earthquake Engineering, Tokyo and Kyoto* 1: 457-471.

15. Grant-Taylor, T. L.; Adams, R. D.; Hatherton, T.; Milne, J. D. G.; Northey, R. D.; Stephenson, W. R., (1974): "Microzoning for earthquake effects in Wellington, N. Z." *New Zealand Department of Scientific and Industrial Research Bulletin 213.*

16. Van Dissen, R. J., Taber, J. J., Stephenson, W. R., Sritharan, S., Perrin, N. D., McVerry, G.H., Campbell, H. J., Barker, P. R., (1992). "Earthquake ground shaking hazard assessment for Wellington City and suburbs, New Zealand". *DSIR Geology & Geophysics Contract report 1992/23, prepared for the Wellington Regional Council.*

17. Van Dissen, R. J., Taber, J. J., Stephenson, W. R., Sritharan, S., Perrin, N. D., McVerry, G.H., Campbell, H. J., Barker, P. R., (1993). "Ground shaking hazard zonation for Wellington City and suburbs, New

Zealand". Conference technical papers. *New Zealand National Society for Earthquake Engineering, Technical Conference and AGM, Wairakei Hotel, Taupo, 26-28 March 1993*: 134-141.

18. 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.

19. Downes, G. L., (1995). "Atlas of isoseismal maps of New Zealand earthquakes". *Institute of Geological & Nuclear Sciences monograph 11.* Institute of Geological & Nuclear Sciences Ltd., Lower Hutt, New Zealand.

20. Smith, W. D., (1995). "A development in the modelling of far-field intensities for New Zealand earthquakes". *Bulletin of the New Zealand National Society for Earthquake Engineering* 28: 196-217.

21. 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.

22. 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.

23. Dowrick, D. J., (1998). "Damage and intensities in the magnitude M_s7.8 1931 Hawke's Bay, New Zealand, earthquake". *Bulletin of the New Zealand National Society for Earthquake Engineering* 31: 139-163.

24. Downes, G., Dowrick, D., Smith, E., Berryman, K., (1999). "The 1934 Pahiatua earthquake sequence: analysis of observational and instrumental data". *Bulletin of the New Zealand Society for Earthquake Engineering* 32: 221-245.

25. Dowrick, D. J., Rhoades, D. A., (1999). "Attenuation of Modified Mercalli intensity in New Zealand earthquakes". *Bulletin of the New Zealand National Society for Earthquake Engineering* 32: 55-89.

26. Webb, T. H., (1989). "The 1942 Wairarapa earthquakes". *Bulletin of the New Zealand Society for Earthquake Engineering* 22: 33.

27. Webb, T. H., Doser, D. I., (1998). "Historic seismicity of the North Island, New Zealand, and its relation to oblique subduction along the Hikurangi Margin". *EOS, Transactions, American Geophysical Union, 1998 Fall meeting, 79 Supplement:* F904.

28. Dowrick, D. J., Rhoades, D. A., Babor, J., Beetham, R. D., (1995). "Damage ratios for houses and microzoning effects in Napier in the magnitude 7.8 Hawke's Bay, New Zealand, earthquake of 1931". *Bulletin of the New Zealand National Society for Earthquake Engineering* 28: 135-151.

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

30. Maunder, D. E. (ed.) (1999). "New Zealand seismological report 1997. Seismological Observatory Bulletin E0180". *Institute of Geological & Nuclear Sciences science report* 99/20. 167p.

31. Ansell, J. H., Bannister, S. C., (1996). "Shallow morphology of the subducted Pacific plate along the Hikurangi margin, New Zealand". *Physics of the Earth and Planetary Interiors 93*: 3-20.

32. Zhao, J. X., Dowrick, D. J., McVerry, G. H., (1997). "Attenuation of peak ground accelerations in New Zealand earthquakes". *Bulletin of the New Zealand National Society for Earthquake Engineering* 30: 133-157.

33. Harris, A. G., Burns, D. J., (1942). "Earthquake damage. Borough Surveyors' [unpublished] Reports". Prepared for C.R. Mabson, Borough Engineer, on non-domestic buildings in the Borough of Masterton, 2 July & 17 July, plus addenda dated 22 August 1942. *Held at Wairarapa Archives, Masterton, New Zealand.*

34. Mabson, C.R., (1942). Letter written by the Borough Engineer to the Mayor and Councillors of Masterton regarding the effects of the earthquake of June 24. Undated, but between 17 July and 24 August. *Held at Wairarapa Archives, Masterton, New Zealand.*

35. Building Regulations Committee, (1931). *Report of the Building Regulations Committee, to the House of Representatives, Wellington, 23 June 1931.*

36. Mabson, C. R. (ca. 1939). Memo from C R Mabson to the Mayor of Masterton. *Held at Wairarapa Archives, Masterton, New Zealand.*

37. Local Government Amendment Act, 1979. New Zealand Government, Wellington.

38. Dowrick, D. J., (1998). "Earthquake risk for property and people in New Zealand". *New Zealand National Society for Earthquake Engineering technical conference and AGM, Wairakei Hotel, Taupo, 1998: 43-50.*

39. Hughes, J. R., (1942). Letter on "Earthquake Damage" from the City Engineer to Town Clerk, Palmerston North, 8 July 1942.

40. 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.

41. Grapes, R., Downes, G., (1997). "The 1855 Wairarapa, New Zealand, earthquake – analysis of historical data". *Bulletin of the New Zealand National Society for earthquake Engineering 30*: 271-368.

42. Hancox, G. T., Perrin, N. D., Dellow, G. D., (1997). "Earthquake-induced landslides in New Zealand and implications for MM intensity and seismic hazard assessment". *GNS Client Report 43601B prepared for the Earthquake Commission, 10 December 1997.*

43. Smith, W. D., Berryman, K. R., (1986). "Earthquake hazard in New Zealand: inferences from seismology and geology". *Royal Society of New Zealand Bulletin 24*: 223-243.

44. Stirling, M. W., Wesnousky, S. G., Berryman, K .R., (1998). "Probabilistic seismic hazard analysis of New Zealand". *New Zealand Journal of geology and geophysics 41*: 355-375.

45. Stirling, M., McVerry, G., Berryman, K., McGinty, P., Villamor, P., Van Dissen, R., Dowrick, D., Cousins, J., Sutherland, R., (2000). "Probabilistic Seismic Hazard Assessment of New Zealand: New Active Fault Data, Seismicity Data, Attenuation Relationships and Methods". Prepared for the Earthquake Commission Research Foundation. *Institute of Geological & Nuclear Sciences client report 2000/53.*

46. Fitch, T. J., (1972). "Plate convergence, transcurrent faults and internal deformation adjacent to southeast Asia and the western Pacific". *Journal of Geophysical Research 77*: 4432-4460.

47. Walcott, R. I., (1978). "Present tectonic and late Cenozoic evolution of New Zealand". *Geophysical Journal of the Royal Astronomical Society 52*: 137-164.40.

48. Van Dissen, R. J., Berryman, K. R., (1996). "Surface rupture earthquakes over the last ca 1000 years in the Wellington region, New Zealand, and implications for ground shaking hazard". *Journal of Geophysical Research 101*: 5999-6019.

49. Barnes, P. M., Mercier de Lepinay, B., (1997). "Rates and mechanics of rapid frontal accretion along the very oblique convergent southern Hikurangi margin, New Zealand". *Journal of Geophysical Research 102*: 24,931-24,952.

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

51. Nicol, N., Van Dissen, R. J., (1997). "Late Miocene to recent fault and fold deformation east of Martinborough, Wairarapa". *Geological Society of New Zealand Miscellaneous Publication 95B*, Geological Society of New Zealand Annual Conference field trip guide FT 3, November 1997, 17 p.

52. Reyners, M., (1998). "Plate coupling and the hazard of large subduction thrust earthquake at the Hikurangi subduction zone, New Zealand". *New Zealand journal of geology and geophysics 41*: 343-354.

53. Lensen, G. J., (1968). Sheet N158 Masterton (1st Ed.) "Late Quaternary Tectonic Map of New Zealand 1:63360". *Department of Scientific and Industrial research, Wellington, New Zealand.*

54. Cotton, C.A., (1958). *Geomorphology: An introduction to the study of landforms.* Whitcombe & Tombs Limited, 7th Edition, 505 pages.

55. Schermer, E., Van Dissen, R., Berryman, K., (1998). "In search of the source of the 1934 Pahiatua Earthquake". *Final report on EQC Research Project 97/320.*

56. Stevens, G. R., (1974). *Rugged landscape.* A. W. & A. H. Reed, Wellington.

57. Kingsbury, P. A., Hastie, W. J., (1992). "Seismic hazard map series: Ground shaking hazard, Map Sheet 1 Wellington 1:20000". *Wellington Regional Council Publication No. WRC/PP-T-92/45.*

58. Perrin, N. D., Campbell, H. J., (1992). "Compilation of geological data, Wellington area". *DSIR Geology and Geophysics Contract Report 1992/24* prepared for the Wellington Regional Council.

59. Wellington Harbour Board, (1936). "Historical Plan of reclamations in the Port of Wellington (Port Nicholson)". Compiled and drawn at the Head Office of the Wellington Harbour Board. Original held at the Maritime Museum, Queen's Wharf, Wellington.

60. Baillie, H., (1924). "The early reclamations and harbour works of Wellington". *Transactions of the New Zealand Institute* 55: 700-720.

61. 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.

62. Robinson, R., McGinty, P., (2000). "The enigma of the Arthur's Pass, New Zealand, Earthquake, 2: The Aftershock Distribution and its relation to Regional and Induced Stress". *Journal of Geophysical Research* 105: 16,139-16,150.

63. McGinty, P., Darby, D., Haines, J., (2000). "Earthquake Triggering in the Hawke's Bay, New Zealand, region from 1931 to 1934 as inferred from elastic dislocation and static stress modelling". Submitted to *Journal of Geophysical Research.*

64. Robinson, R., (1994). "Shallow subduction tectonics and fault interaction: The Weber, New Zealand, earthquake sequence of 1990-1992". *Journal of Geophysical Research 99*: 9663-9679.