DAMAGE AND INTENSITIES IN THE MAGNITUDE 7.8 1929 MURCHISON, NEW ZEALAND, EARTHQUAKE

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SUMMARY

This paper is the result of a study of the M_S = 7.8 Murchison earthquake which occurred in the South Island of New Zealand, on 16(UT) June 1929, a few years prior to the introduction of the first earthquake loadings code in New Zealand. It gives the first description of the damage to buildings in this event in modern earthquake engineering terms, and presents the first Modified Mercalli (MM) intensity map for the event determined from the original felt information. Some definitions of "well-built" pre-code buildings are proposed: these should help in dealing with safety and conservation issues raised when considering the future of such "earthquake risk" buildings. No evidence was found for MM10 intensities, although ground shaking of this strength probably occurred in the unpopulated mountainous countryside close to the fault rupture. Recommendations for improving the criteria for determining MM intensity are made in respect of (1) pre-code buildings and (2) seismically-induced landslides.

INTRODUCTION

The Murchison earthquake occurred at 10.17 am on 17 June 1929 (UT 16 June 22 hrs 47 min). At magnitude M_S = 7.8 [1,2] it was the largest New Zealand earthquake to have occurred since the great 1855 Wairarapa earthquake. From an unpublished study by A J Haines of changes in levels caused by the Murchison earthquake, a moment was estimated from which M_W = 7.6 is obtained. However the model for this study is poorly constrained due to lack of data, and small changes in it could lift the moment magnitude to 7.8 (A J Haines, pers. comm., 1994). As the M_S of 7.8 is a very well determined value with 16 observations and a small standard error [1, 2], M_S is a more reliable indicator of the magnitude of this event than M_W.

Both the epicentre (41.7°S, 172.2°E) and the centre of its fault rupture remain uncertain, but a vertical displacement of about 4.5m occurred on the White Creek Fault [3] where it crosses the highway about 11 km west of Murchison in the mountainous region of the north-west of the South Island of New Zealand (Figure 1). The full extent of the surface trace has not been determined due to the steepness and the heavily forested nature of the terrain. Shortly after the earthquake about 8 km of the surface rupture was mapped [3,4]. No attempts to follow it further have subsequently been made, although a total sub-surface length of 30-50 km is likely for a reverse fault event of M_S = 7.8 (K.R. Berryman and A.J. Haines, IGNS, pers. comms., 1993). It is apparent that it was a predominantly reverse faulting event, with a rupture striking almost north-south [5]. On Figure 1 the likely surface rupture length has been plotted more to the north than to the south of the observed surface trace, so as to relate better to the intensity distribution.

Together with the M_S 7.8 1931 Hawkes Bay earthquake, the Murchison event is the largest New Zealand earthquake to have occurred in the instrumental magnitude era, i.e. since 1901 [1,2]. Because of this size, a modern view of the damage and intensities caused by this earthquake is likely to be instructive and influential in both engineering and seismological terms. The only significant publication on the damage to buildings was a 1929 report [6] by an investigation committee of the New Zealand Institute of Architects, while Henderson [4] included a brief summary of the nature of the damage in his extensive discussion of geological aspects of the event. The remaining major contemporary account of damage was that of Furkert [7], which concentrated on civil engineering aspects, particularly bridges. In addition some useful observations of various aspects have been made in a reconnaissance report by Baird [8].

The only publication on the intensities observed in the earthquake is a brief reference to it in the 1929-30 annual report of the DSIR [9]. This includes an isoseismal map in the Rossi-Forel intensity scale. Eiby prepared a preliminary MM intensity map (which he appropriately did not publish in a scientific paper), using approximate conversions of the RF to the MM scale derived from those for converting MM to RF given by Richter [10]. Intensity maps in the RF scale, or MM conversions from it, are bound to be poor. The RF scale is a poor one and was abandoned by New Zealand in 1945, and Richter's correlation of the two scales is very poor as shown by a comparison of the wording of the two scales, as summarized here in Table 1.

Thus this study is the first modern one of the damage and intensities in this important earthquake. With the recent revision of the New Zealand version of the Modified Mercalli intensity scale [11], and the current need for reliable intensity modelling for earthquake insurance purposes, this present study is also particularly timely.

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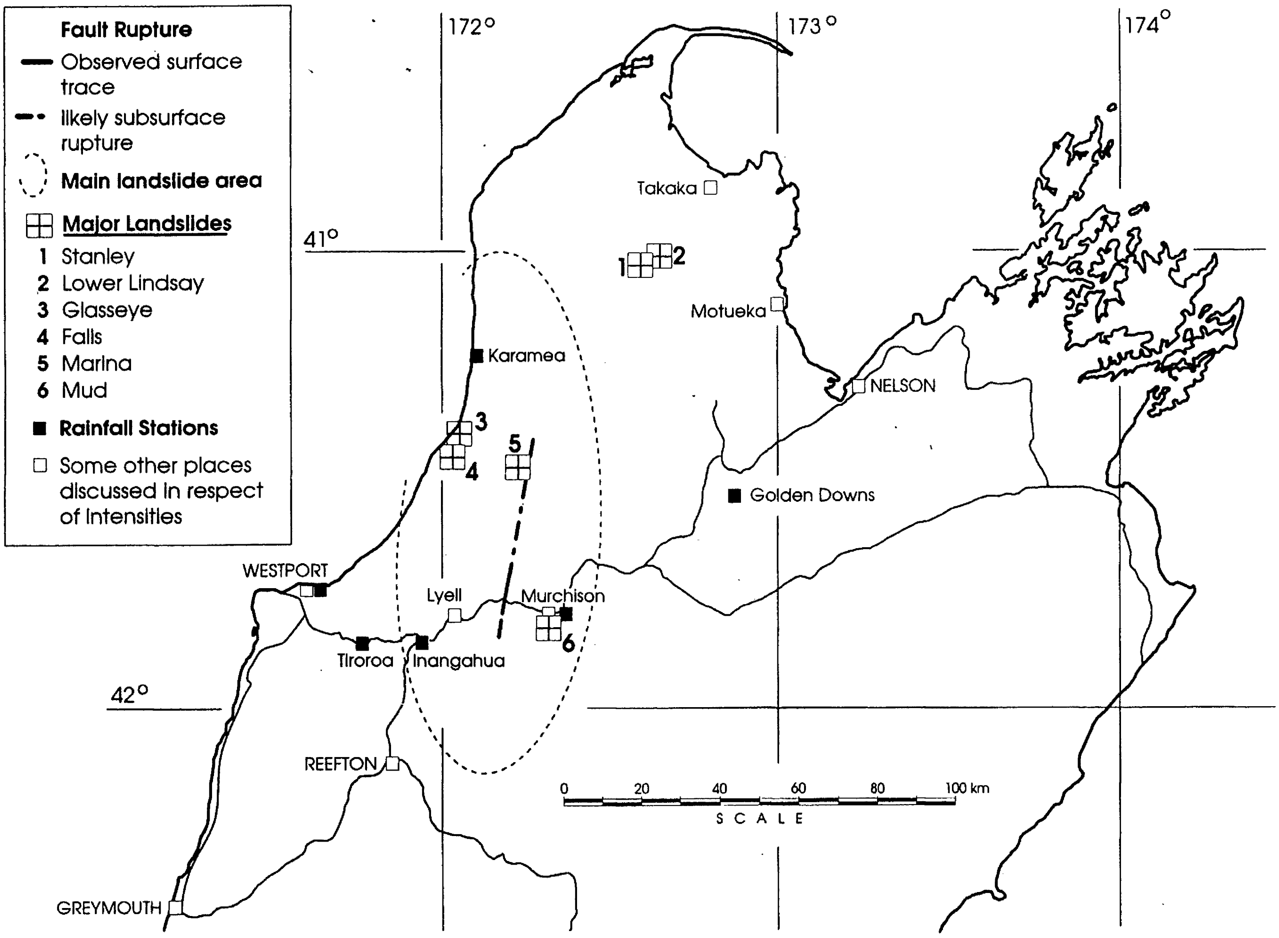


FIGURE 1 *Map of nearer source region of the 1929 Murchison earthquake, showing the probable fault rupture, and some of the features locations discussed in the text.*

TABLE 1: Conversions of Rossi-Forel to Modified Mercalli intensity

RF Intensity	MM Intensity using Richter's conversion [7] inverted*	MM Intensity using equivalent wording
RF3	MM3	MM2,3
RF4	MM3-4	MM5
RF5	MM4-5	MM6
RF6	MM5-6	MM5,6,7
RF7	MM6	MM6,7
RF8	MM7½	MM7
RF9	MM9–	MM8,9
RF10	MM10	MM9,10

* Richter's conversion is actually given for converting from MM to RF, not RF to MM.

DAMAGE

The earthquake caused Modified Mercalli intensities of VIII (MM8) or more at distances of up to c.100 km from Murchison. Major damage was done to the natural environment through landslides, some of which were vast [3,12,13], while substantial damage was done to the built environment by ground shaking, landslides, liquefaction and ground spreading.

For a considerable distance around the source of the earthquake, the countryside consists of steep forested mountains, and is consequently lightly populated and prone to ground damage. Hence the source region was dominated by landslides rather than by damage to buildings. This is reflected in the fact that of the 17 people who died as a result of the earthquake, fourteen were killed by landslides, two were killed by rock falls in mines, and one death was indirect (of a diabetes sufferer from lack of medication caused by disruption to transport).

DAMAGE TO ROADS AND BRIDGES

Landslides caused major damage to roads at several locations within about 30 km of the source, particularly (1) along the main highway following the Buller River west of Murchison, (2) the Matakitaki River Valley and Maruia Saddle south of Murchison and (3) the Corbyvale Pass between Seddonville and Little Wanganui on the West Coast. Subsidence and/or spreading of embankments and bridge approaches occurred at many sites, as far away as Greymouth (c.120 km SW of Murchison) and Takaka and Collingwood counties (c.120 km north or Murchison).

Damage to bridge structures occurred in a few instances only and was caused by substantial displacements of either abutments or piers. As summarized by Henderson [4] "The bridge at Murchison across the Matakitaki, that across Lyell Creek, and that across the Little Wanganui, all approached by embankments, had trusses displaced or distorted. The bridge over Newton River was much damaged and later completely destroyed by flood. A number of small bridges with wooden girders were altogether wrecked".

Further discussion of roads and bridges is given elsewhere [4,7].

DAMAGE TO UTILITIES

The damage to public utilities (namely electricity, water supply, sewerage, gas supply and telephone systems) is not well documented but was evidently mostly modest. The most serious damage was to Murchison's power station at Six Mile, which according to B. Spiers (pers. comm., 1994) was out of commission for months. The water race and fluming were destroyed, the holding dam wrecked and the mechanical plant was damaged. A makeshift motor generator supplied electricity to Murchison for a long time.

Westport (population 4000) lost its electricity supply for 13 hours, its water supply for 9 days and its telephone exchange for about three days. Its gas mains broke in four places. Various of the smaller communities nearer the earthquake source lost telephone and electricity services for lengthy periods because of landslides sweeping poles away.

DAMAGE TO BUILDINGS

On the MM intensity scale [11,14], damage to domestic chimneys starts at MM6 and damage to buildings starts at MM7. The nature of damage to New Zealand buildings is of earthquake engineering interest for intensities of about MM8 and greater. In 1929 in New Zealand no earthquake design code existed, and no buildings were yet being designed formally for calculated horizontal earthquake loads. However some engineers and architects were very aware of earthquake hazard and used intuitive earthquake resistant design features in the structural form and detailing of their buildings, as evidenced by perhaps the first English language book on this subject being published in 1926 by the New Zealand engineer/architect C.R. Ford [15].

A considerable amount of information on damage to buildings has been obtained from a variety of sources, i.e. the splendid report of the NZIA [5], the paper by Henderson [4], a brief report by the Nelson City Engineer [16], hundreds of surprisingly detailed newspaper reports from across the whole country, many photographs held by various bodies (the Alexander Turnbull Library in Wellington, daily and weekly newspapers, and various local museums and libraries). In addition damage information came from personal communications from people (Appendix 1) who were present during the earthquake or who had relevant information from other sources, particularly from involvement with more recent alterations to, or demolition of, local buildings.

To study the performance of non-residential buildings we look of course mainly at the towns which experienced MM8 or more. In this event there were few such towns, the larger ones with their approximate populations being Takaka (400), Motueka (1,700), Nelson (10,600), Murchison (300), Reefton (1,500) and Westport (4,000). The towns of Burnetts Face (c.650), Denniston (c.600), Granity (c.300), Karamea (800), Millerton (c.500), Seddonville (c.400) and Waiuta (600?) each had populations of a few hundreds.

In the zone of higher intensities, MM8 and greater, it is noteworthy that "well-built" buildings resisted the earthquake well, despite the fact that none of them had been designed for horizontal earthquake forces. This fact is evident today, viewed from our current earthquake engineering perspective, and also was remarked upon by professional investigators at the time [4,6,7].

What is meant by "well-built" in the above context? The predominant factors contributing to the classification of "well-built" buildings are set out below:

Timber Buildings

Factors contributing to the classification of "well-built" include:

- Wall openings not too large
- Robust piles (cantilevered or framed), or reinforced concrete strip foundations
- Superstructure tied to piles
- Strong chimneys, or few weak ones (see below)

Masonry Buildings

Factors contributing to the classification of "well-built" include:

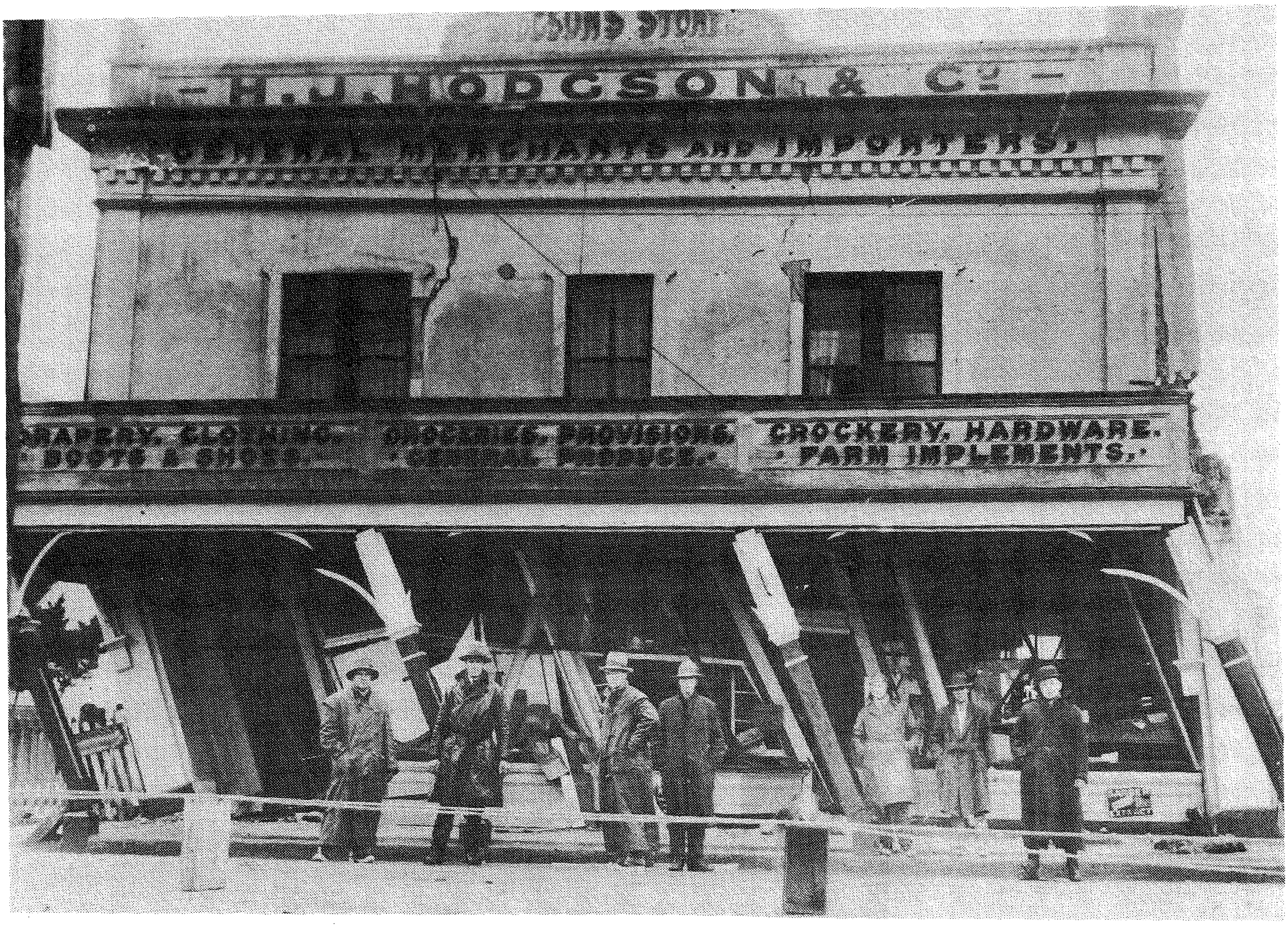


FIGURE 2 *Hodgson's store, Murchison, reinforced concrete, showing soft storey effect due to absence of lateral load resisting frame in shop's frontage. (Reproduced by courtesy of the Alexander Turnbull Library, Wellington, New Zealand).*

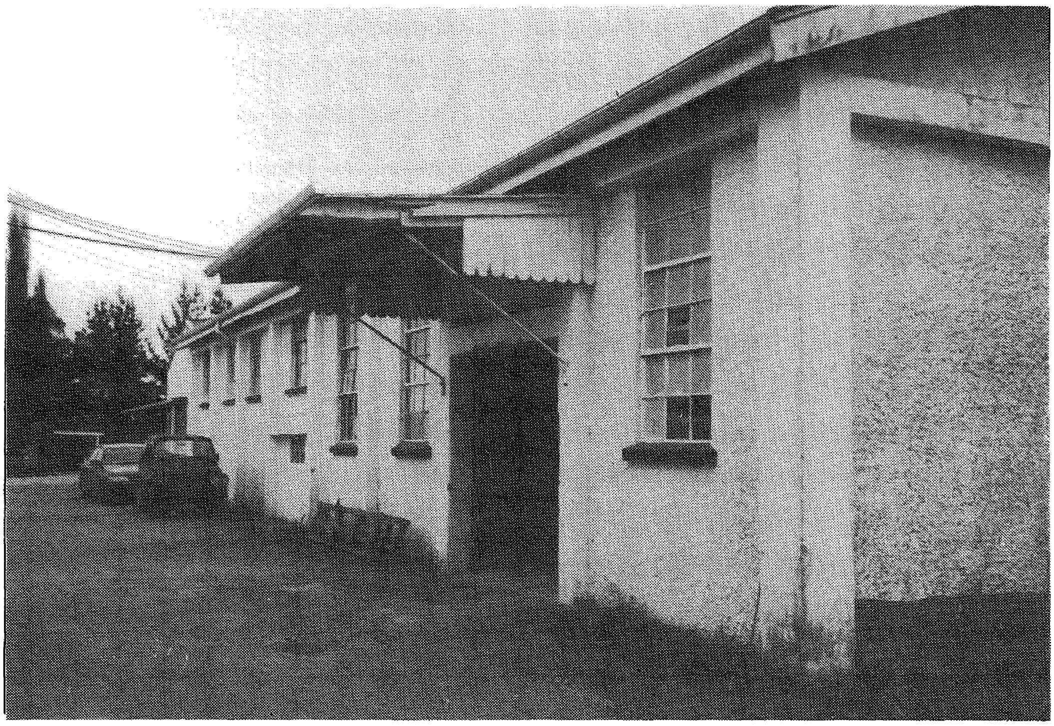


FIGURE 3 *Dairy factory, Murchison, reinforced concrete, undamaged due to having large amounts of structural wall and symmetry in plan.*

- Wall openings not too large, especially no soft-storey effect
- Strong mortar, especially in thin walls
- Brick bonding through corners
- Large buildings to be structurally compartmented
- Gables tied in
- Effective diaphragms, at least at roof level
- No towers or unbraced parapets (see below)

Composite Masonry and Timber Buildings

Many commercial and industrial buildings had some external walls of timber and some of brick, the brick being used either for fire walls or for creating (relatively) imposing front facades. Such buildings were often built well enough in non-seismic terms, but suffered seismically from:

(i) the soft-storey effect of the openings of large shop windows (e.g. Figure 2),
(ii) unrestrained parapets and gables, and
(iii) the inherent difficulty of tying brick and timber together adequately.

Despite these drawbacks, many composite masonry and timber buildings suffered little damage. The criteria for "well-built" composite masonry/timber would be an amalgam of those given above for timber buildings and for masonry buildings.

Concrete Buildings

Few buildings within the MM8 isoseismal were made of concrete. By today's standards, the concrete was low in strength and was under-reinforced. However most of the concrete buildings performed well, apparently because (a) they were low-rise buildings with plenty of structural wall area, and (b) they were reasonably symmetrical in plan. Both these good attributes are illustrated by the dairy factory at Murchison (Figure 3).

Steel Buildings

It seems that the only buildings within the MM8 isoseismal in which steelwork provided the earthquake resistance were at the Onekaka Iron Mills and the Tarakohe Cement Works, both near Takaka. Both these sites were subjected to intensity about MM8, and the steel buildings were undamaged.

Chimneys, Parapets and Towers of Unreinforced Masonry

As in many other earthquakes, otherwise well-built buildings were much more vulnerable to damage if they had brick chimneys, parapets or towers. Not only are such appendages highly vulnerable themselves (primary damage), but they often induce secondary damage in the rest of the building, either through transferred stresses, or through destruction caused if they fall on part of the building below.

When the earthquake performance of a building is *dominated* by such appendages, it is clear that it should not be called "well-built", even if they have the good characteristics listed above for different types of building. This is most dramatically illustrated by brick buildings with heavy towers (usually clock towers). In the zone of higher intensity (≥ MM8) in this earthquake there were four brick buildings with large towers:

- Nelson College Main Block
- Nelson College Scriptorium
- Nelson Central Post Office
- Westport Post Office

Two of these towers fell. At the Westport Post Office the complete tower fell, while at Nelson College Main Block the soft storey top portion of the tower fell (Figures 4 and 5). Also in all four cases the structure below the tower was damaged much more than it would have been if no tower had been present. This raises the question as to what masonry grade such buildings should be classified as, for intensity assignment purposes? These four buildings all conformed fully to the definition of Masonry C, i.e. Buildings Type II* (Appendix 2), as regards materials quality, workmanship and detailing. But the towers made them much more vulnerable to ground shaking than comparable buildings without substantial towers. The two buildings whose towers fell were the most seriously damaged buildings in their respective towns, despite being as well built as any of the other brick buildings. Thus for intensity assignment purposes, such buildings should be regarded effectively as Masonry D, i.e. Buildings Type I.

In addition, the main block of Nelson College was a long building in which the internal cross-walls were timber not brickwork. This was reported [6] to be unsatisfactory, as the internal and external walls were not effectively tied together resulting in a loss of vital out-of-plane stiffening of the longitudinal brick walls.

INTENSITIES

The intensities were assigned generally in accordance with the 1992 revision [11] of the New Zealand version of the Modified Mercalli scale. However because the earthquake under consideration occurred in 1929, before the introduction of formal earthquake resistant design practices in New Zealand, it was appropriate to use the *criteria relating to pre-code buildings* as set out in both the 1992 and the 1965 version [14] of the scale, in order to check that the 1992 version was consistent with the 1965 scale in this respect, as was intended. Some deficiencies in relation to Masonry B, C and D were discovered. The means of dealing with these are proposed in Appendix 2. Manifestations of liquefaction were found to be unhelpful in assigning intensities relating to damage, as discussed by Dowrick and Beetham [17].

The assignment of the higher intensities is illustrated for six key towns, Murchison, Westport, Nelson, Greymouth, Karamea and Motueka (located as shown in Figure 1), as set out below. Numbers in circular brackets after each building, e.g. (2), indicate the number of storeys. An intensity in circular brackets at the end of each individual entry, e.g. (MM7), is the intensity indicated by that entry. An intensity in square brackets at the end of each subheading, e.g. [MM8], is the overall intensity indicated by that subset of entries.

INTENSITY IN MURCHISON

Firstly intensity criteria were applied to data from the NZIA report [6]:

Most chimneys broken (≥MM7). Monument (war memorial) brought down (≥MM8).

Bldgs Type III*, damaged in some cases [MM8]

Partial Collapse: None. *Damaged:* Bank of NZ housed in the Commercial Hotel (1), concrete haphazardly reinforced; ill-restrained gable fell. Spier's garage (1), reinforced Concrete

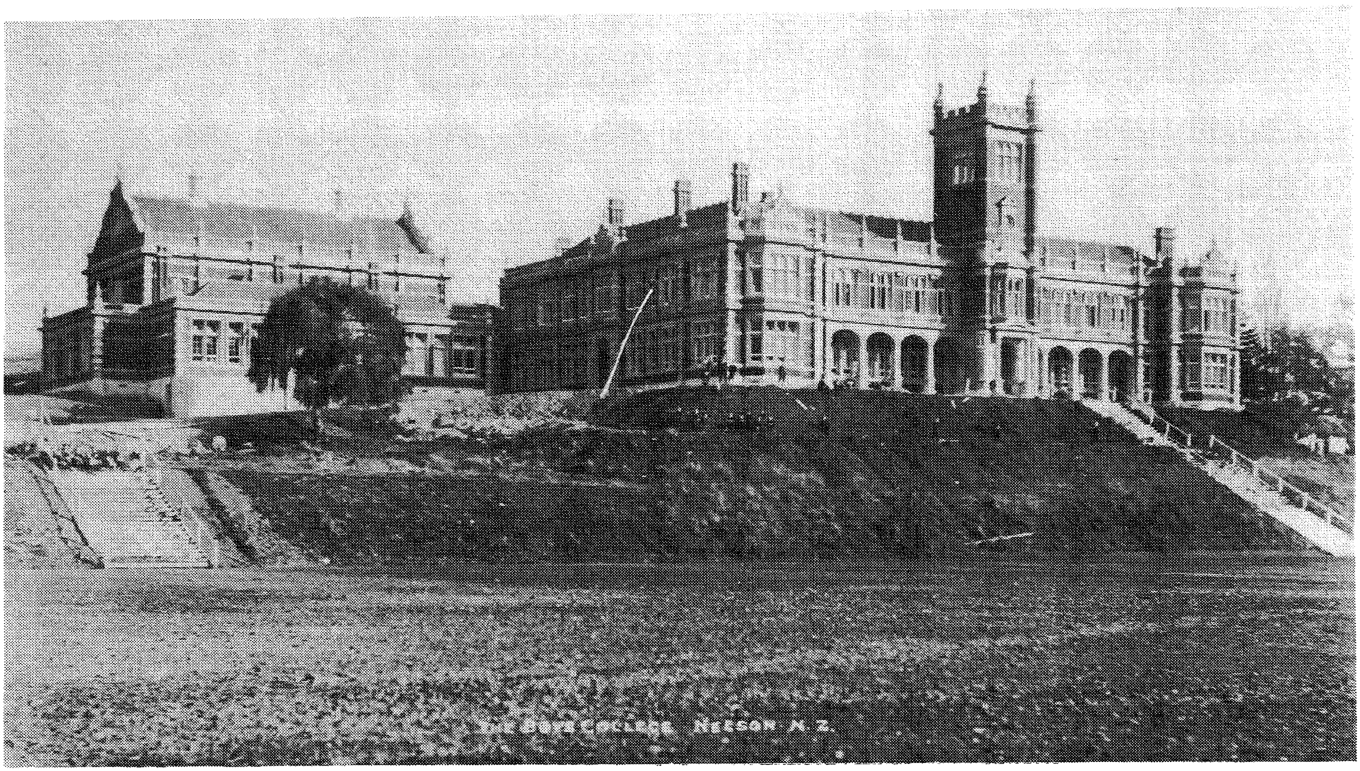


FIGURE 4 *Nelson College Main Block before the earthquake. (Reproduced by courtesy of the Alexander Turnbull Library, Wellington, New Zealand).*

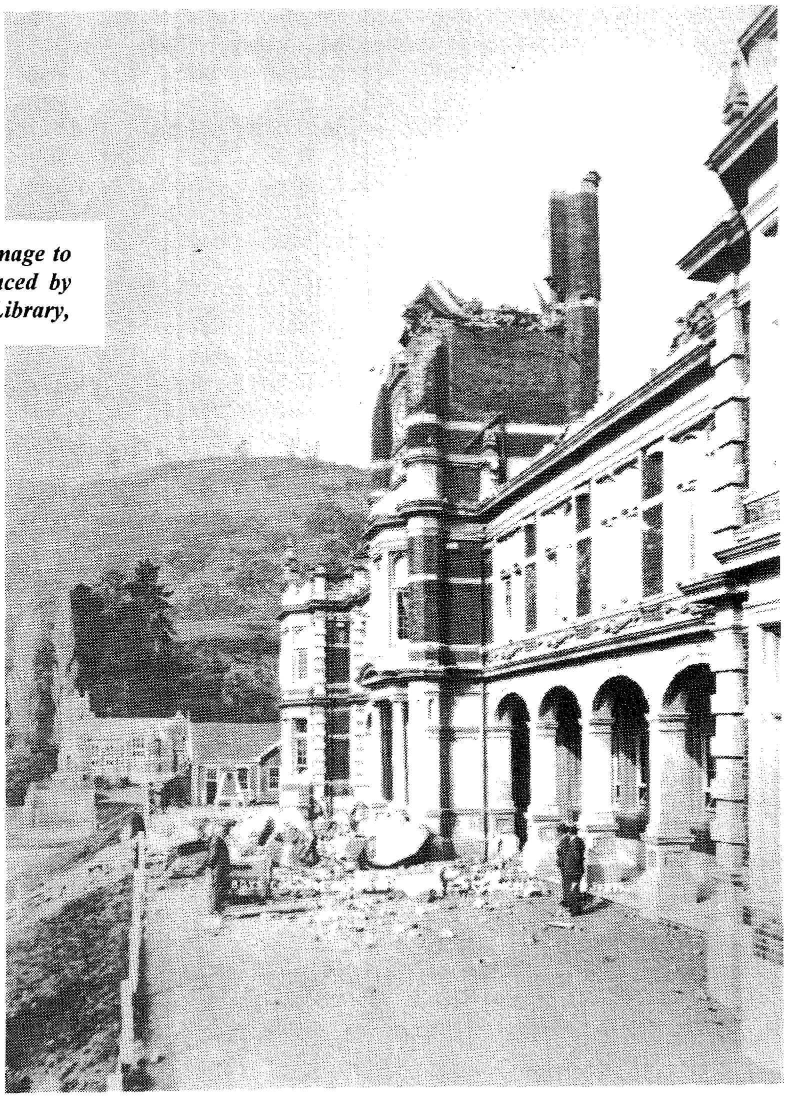


FIGURE 5 *Nelson College Main Block showing damage to tower and unbraced parapets. (Reproduced by courtesy of the Alexander Turnbull Library, Wellington, New Zealand).*

crack in floor and i) pediment over doorway. *Undamaged:* Dairy factory (1), reinforced concrete (Figure 3); McNee's store (1), reinforced concrete.

Bldgs Type II* None in Murchison.

Bldgs Type I [≥MM8]

Near collapse: Hodgson's store (1 and 2). Concrete, no reinforcing bars, a few bed ends acting as haphazard reinforcement. The two storey portion was beyond repair due to large sway deflection of the soft storey front wall (c. 1m drift) (Figure 3). The rear single storey portion was essentially undamaged and was still in use in 1993. This part of the building on its own would be classified Bldg Type III*. There were no other Type I buildings in Murchison.

Timber Buildings [MM9]

Evidently some houses fell off their piles, implying an intensity of MM9. This is confirmed by a local historian who was in Murchison at the time (T.Monahan, pers. comm. 1993). Another Murchison resident (B. Spiers, pers. comm. 1993) knew of only two houses that fell off their piles, both of which had relatively tall piles (> c.600mm) for that vicinity. The NZIA [6] shows a photo of one of these two houses. Henderson [4] notes that "some buildings shifted from their piles; others were warped and twisted", but "on the whole the injury to reasonably well-built homes was relatively slight". According to the NZIA report [6], "The main damage to buildings, with the exception of Hodgson's store and the Bank of New Zealand was practically confined to chimneys". The NZIA discusses three timber buildings as summarized below:

- Council Chambers (1). Timber, on piles. Little damage, except chimneys.
- Young Men's Institute (1). Timber on piles. Little damage, billiard tables moved.
- Public school (1). Timber, on piles. Little damage except from falling (weak) chimneys.

The above discussion summarizes the available information relating to intensity criteria, from which it is seen that the intensity in Murchison reached MM9. The evidence for this is not especially strong, resting solely on houses shifting off their piles. The small amount of damage to the four Type III* buildings suggest that the intensity is unlikely to exceed MM9.

INTENSITY IN WESTPORT

According to C Turton, a Westport structural engineer and contractor, (pers. comm., 1993) in Westport in 1929 no brick buildings had reinforcing bands, and the brick facades on shops were not bonded to the side walls. Information relating to intensity is as follows:

Reinforced Concrete, Bldgs Type III*, little damage [<MM9]
Bank of NZ (2), St Joseph's School (1).

Bldgs Type II*, various levels of damage [MM8 max.]

Partial collapse: Taylor & Enright's shop (2). *Minor brick falls:* Albion Hotel (2), Customs House (1), Hospital (1 and 2), State School (1), Te Aro House (shop) (2). *Cracked:* Racing Club grandstand, Technical School (1). *Little Damaged:* O'Conor Home (1). *Unbraced parapet fell:* Fair's shop (1 + mezzanine). *Undamaged:* There were about 13 other one and two storey non-domestic Type II* buildings that were structurally undamaged.

Bldgs Type I, various levels of damage [MM8 max]

Partial Collapse, Masonry: Post Office (2 + tower), Railway Workshops (1). *Partial Collapse, Composite masonry and timber with soft storey:* Bett's garage (2), Fire Brigade (2), Lawson's (Wood's) boot shop/Westport Times (1). *Undamaged:* A few further composite buildings existed, which suffered little or no damage.

Timber Buildings [MM8]

Most timber buildings suffered only from chimney damage. Of the 20 or so two storey timber framed commercial buildings only one was damaged. Some houses moved on their piles, but none fell off.

Monuments at cemetery, many fell. [≥MM8]

Bridge across Buller River, undamaged. [<MM9]

Summarizing the above Westport data, it is seen that the following criteria for the intensity reaching at least MM8 were fulfilled:

- Bldgs Type II* (Masonry C) damaged with partial collapse (less than half were damaged).
- Some houses moved on their piles.
- Monuments brought down.

There is no evidence for MM9 in Westport because: Bldgs Type III* (Masonry B) was not seriously damaged, Bldgs Type II* (Masonry C) did not completely collapse, Bldgs Type I were not destroyed, houses did not fall off their piles, the Buller Bridge was undamaged, and none of the other MM9 criteria was reported. Hence the intensity in Westport is assigned as MM8.

INTENSITY IN NELSON

Information relating to intensity is as follows:

Bldgs Type III*, damaged in some cases [MM8]

Partial collapse: None. *Damaged:* F & D Edwards offices (3), Kerr's shop (2), Majestic Theatre (2), Newman's Garage (1 + Mezzanine). *Undamaged:* Anstices' Building (3), Baird's Bldg (1 and 2), Bennett's Workshop (1), Auckland Point School (2) (minor cracks), Nelson Institute and Library (2), Nelson Electric Power House (2), Gibbs Garage (2), Grand Cafe (2), Wyber's Garage (2), YMCA (1).

Bldgs Type II*, damaged in some cases [MM8]

Partial collapse: None. *Damaged:* Auckland Clothing Co (2), Boon's shop (2), Public Hospital (3-4), Bank of NZ (1), School of Music (1), Union Bank (2), Commercial Hotel (3), Loan and Mercantile (2), Evening Mail (2), AMP offices/Hurst's shop (2), National Bank (2), Louisson's/Hannah's shops(2), Hallenstein's shop (2), Milner & Neale's offices (2), Pitt & Moore (2), Salvation Army Citadel (1), Trathen's shop (3).

Undamaged: In addition there were at least 55 further one and two storey unreinforced brick non-domestic buildings in Nelson which suffered little or no damage to structure (i.e. excepting falling chimneys). This number of undamaged buildings is in accord with Henderson's statement [4] that "a large number of important buildings escaped with but trifling injury or with no damage at all".

Bldgs Type I (all external walls masonry), cracked and damaged [MM7]

Damaged: Central Post Office (2 + tower), Masonic Hotel (2), Nelson College Scriptorium (1 + tower), Nelson College Main Block (2 + tower).

Bldgs Type I (Composite brick and timber), a few damaged [MM7]

Moderately damaged: Dee's shop. *Undamaged:* In addition there were at least 32 commercial buildings of composite construction that suffered little or no structural damage.

Timber Buildings [<MM9]

Most houses were of timber, and there were scores of substantial non-domestic timber buildings up to four storeys in height. Damage to timber buildings was light, generally being restricted to that associated with chimneys, and a few cases of plaster falling from ceilings. Houses generally did not shift much on their piles (one known exception).

Industrial Brick Chimney Stacks [MM8]

Public Hospital Boiler House stack fell; Griffin's 60 ft high factory stack, top 20 ft fell; Dodson's Brewery stacks cracked; Nelson Boys College boiler stack, top fell.

Monuments undamaged [<MM8]

Neither of the two public monuments (Soldiers Memorial and Troopers Memorial) were brought down.

Bridges undamaged [<MM9]

There were three road bridges in Nelson, none of which was damaged.

Summarizing the above Nelson data, it is seen that the following criteria for the intensity reaching at least MM8 were fulfilled:

- Bldgs Type III* (Masonry B) damaged in some cases: (3 damaged, 5 undamaged).
- Bldgs Type II* (Masonry C) damaged, with partial collapse: (18 damaged, none with partial collapse, 30+ undamaged).
- Industrial chimney stacks brought down: (one fell, 3 damaged).

There is no evidence for MM9 in Nelson for the same reasons as those given above for Westport. Hence the intensity in Nelson is assigned as MM8.

INTENSITY IN GREYMOUTH

Many unreinforced domestic chimneys broken, usually at roof-line [≥MM7]

Unbraced parapets and architectural ornaments may fall [MM7]

Kim William's shop (2), Town Hall (2 + tower).

Unreinforced stone and brick walls cracked [MM7]

Baty's garage (1), Convent chapel, Grey County Offices (1), Methodist Church, Presbyterian Manse (2), St Patrick's Church, St Patrick's Presbytery (2).

Bldgs Type III*, undamaged [<MM9, possibly <MM8]

Only four masonry or concrete buildings are known to have contained some reinforcing; three of brick together with the Westland Hospital of reinforced concrete. All four of these buildings were undamaged.

Bldgs Type II*, a few damaged [MM7]

Evening Star offices (2), Hallenstein's shop (2), Phoenix Assurance (1), Post Office (2 + tower), Presbyterian Church. (A few of the buildings listed under the previous two subheadings could alternatively be included here, but the intensity inference is the same).

Bldgs Types I and II*, undamaged

The great majority of brick buildings were structurally undamaged (about 95 non-domestic buildings and about 12 houses), as compared to the 15 (modestly) damaged buildings listed above. Nearly all the brick buildings were unreinforced and were mostly Bldgs Type II* (Masonry C) with a few probably being Bldgs Type I (Masonry D).

Industrial Brick Chimney Stacks [MM7]

One undamaged, two damaged but not brought down.

The above analysis of damage establishes that the intensity in Greymouth was MM7. In addition there is evidence that the intensity did not reach MM8, because (1) partial collapse of Bldgs Type II* (Masonry C) did not occur, and (2) none of the three industrial chimney stacks fell.

INTENSITY IN KARAMEA

All the buildings in the Karamea area were built of timber. Many chimneys fell implying that the intensities was at least MM7. In addition there appears to have been two zones of different damage level, as discussed below.

(1) *On soft ground near the river and streams:* Piles of some buildings tilted towards the waterways, and some buildings racked (MM9). Some houses, built in stages broke apart at the vertical construction joints (MM8-9). Most domestic water tanks fell (MM8). Piles to the wharf tilted badly, probably due to liquefaction (MM8-9). Road embankments cracked badly and subsided (MM8 could have caused this). The three bridges (Karamea, Quinlan's and Oparara) were all usable after the earthquake, despite subsidence of the abutments to Quinlan's bridge. After the

1931 flood the wooden piles of the Karamea bridge were found to have been fractured. (Bridges suggest MM8-9).

Overall the intensity on the Karamea soft ground was MM9.

(2) *On firm/stiff ground:* The damage to buildings was much less here than on the soft ground. No houses fell off piles (<MM9). Occupants of houses on the soft ground went to stay in houses in firm ground. Some domestic water tanks fell (MM8).

Overall the intensity on the Karamea firm ground was MM8.

INTENSITY IN MOTUEKA

Many chimneys brought down, usually at roof-line [≥MM7]

Approximately 700 chimneys fell [8]. In 1926 there were 341 houses in Motueka [20] and most houses had two chimneys, occasionally more, so most chimneys must have broken.

Unbraced parapets and architectural ornaments may fall [MM7]

Motueka Star (1) parapet fell. (No ornaments fell from churches, and the War Memorial did not fall.)

Bldgs Type III* (Reinforced Concrete) structurally undamaged [<MM9, possibly <MM8]

McGregor's Cash Wholesaler (1), Bank of NZ (2), Majestic Theatre (2), Catholic Church, Methodist Church, Presbyterian Church, Pratt's hop kiln, Hart's Bakery (2).

Bldgs Type II*, a few damaged [MM7]

Lightly damaged (cracked): Post Office (1), Rankin's store (1). *Undamaged:* Goodman's Bakery ovens, High School (now Motueka Museum) (1), (some reinforcement in rear wall, so this building is partly Type III*, Masonry B).

Timber Buildings

Timber buildings suffered only from chimney damage. The town's c.350 houses were all timber-framed, on wooden piles. Few if any moved significantly off their piles (<MM8).

Summarizing for Motueka, firstly none of the potentially available criteria for MM9 were reached, i.e. Bldgs Type III* (Masonry B) were not seriously damaged, and houses did not shift off their piles. Secondly, the intensity certainly reached MM7. There is no positive evidence of MM8 within the borough. This may be simply because there were only four unreinforced masonry structures there, and because there were few domestic water tanks on stands. However there were no known instances of houses shifting on their piles. Overall, on the face of the evidence the intensity for Motueka is MM7, but because Nelson, Takaka and Collingwood were all MM8, it is likely that Motueka actually experienced MM8.

INTENSITIES INFERRED FROM LANDSLIDES

The main uses of the results of this study are in helping to define and mitigate seismic hazard to the built environment, notably at high intensities. Because of the lack of buildings near the fault rupture, it has not been possible to identify a MM10 zone. Nor is the MM9 zone well defined, only Murchison and (probably) Lyell reaching that intensity. Hence consideration of the landslides in the central region has been of more concern in this study than it would have been if more intensity data from building damage had been available.

The revised New Zealand MM intensity scale [11] assumes that small slides start at MM7 and that at MM9 landsliding is general on steep slopes. These present criteria may be broadly correct, but are insufficiently detailed to be of much use as they stand because they do not allow for the various factors which combine to make landsliding easier or harder to initiate. For example, much landsliding occurs on New Zealand's steep terrain in wet weather *without* earthquakes, particularly if it is unforested. In the epicentral region (of MM9 and greater) of the Murchison earthquake the land was forested, but was very steep and wet, and along the highways many slopes were undermined by road cuttings. Rainfall statistics for places near the main 1929 landslide area (Table 2), indicate the general wetness of the area, and show that there was substantial rainfall both in the fortnight before and the fortnight after the main shock. Not only was June 1929 a wet month, but it was much wetter than the average June for all six stations in Table 2.

Allowance should be made for ground water retention capabilities of different landslide sites; for example steep rocky sites obviously drain quickly. However it is evident that rock strength, discontinuities, topography and ground water conditions combined to enable some of the 1929 landsliding to be caused by ground shaking of intensity MM7 or MM8. For example, rockfall/avalanches from very steep slopes such as that at Lake Elmer, are estimated to require only c.MM7 to trigger them. In consultation with N.D. Perrin, MM9 was assigned only to those landslides which are estimated to have required strong excitation to initiate failure, i.e. first-time landslides either very large ($\geq 10^7 m^3$) or large (c.$10^6 m^3$) and well-drained enough not to be triggered by heavy rainfall. In this earthquake many landslides occurred [4], 16 of them causing lakes to form [12,13]. Only six of the landslides were considered (N.D. Perrin, IGNS, pers. comm., 1993) to be certainly of the MM9 category, namely, Stanley, Lower Lindsay, Glasseye, Falls, Marina and Mud. The two northernmost of these "MM9" landslides, Stanley and Lower Lindsay, lie 20 km outside the main landslide region and are about 60 km north of the next most northerly of the remaining MM9 landslides, which are close to the northern end of the probable fault rupture zone (Figure 1). The main landslide region is remarkably symmetrical about the probable fault rupture. In the northern part of the main landslide region (Figure 1), the landslides are generally of the MM7 category, such as Lake Elmer noted above. The present author and N.D. Perrin consider that the Stanley and Lower Lindsay landslides are likely to have been caused by specially strong local shaking from the topographical effect of focusing of waves within the two adjacent steep mountain ridges from which they came. This likelihood, plus their distance from the main landslide area, suggest that these two slides constitute a microzoning effect (consistent with placing them outside the MM9 isoseismal as discussed in the next section).

A further barrier to the use of the landslides for assigning intensities in this event is the complicating effect of aftershocks. Because of the absence of people in much of the main landslide area (particularly the northern part), for many of the slides the relative influence of the main shock and the

TABLE 2: Rainfall statistics for stations in or near the main landsliding area of the 1929 Murchison earthquake. (For station locations refer to Figure 1.)

Station	Rainfall (mm)					
	June 1-16, 1929	June 17-30, 1929	June min	June mean	June max	Years recorded
Westport	115	307	75	189	363	1944-80
Karamea	114	307		169		1910-87
Tiroroa	312	579		360		1929-41
Inangahua	*	*		186		1948-92
Murchison	*	*	81	136	239	1969-80
Golden Downs	119	311	11	114	311	1929-80

* Not available

aftershocks was not observed. In particular the largest aftershock ($M_S = 6.3$) is likely to have caused MM9 over an area of nearly 10 km radius. The centre of this event is not known, but it seems likely to have been within 10-15 km of Murchison as it caused the final collapse of Hodgson's store. Although it is reasonably certain that the six large slides on Figure 1 were caused by the main shock, there is a tradition that the Lake Lindsay slide occurred about a week after the main shock, in which case it may have been finally triggered by an aftershock.

It is concluded that the criteria for MM intensity inferred from landslides should be expanded to give guidance on the conditions in which landslides may be occur at MM7, MM8 and MM9, i.e. combinations of rock strength, stratigraphy, topography and ground water that form different categories of vulnerability (parallel to the categories of buildings already used in the intensity scale). Such criteria should be inferred from studies of actual landslides, especially those that can be correlated to intensities inferred from building damage criteria.

ISOSEISMALS

The local intensities assigned in this study (Table 3) and the isoseismals derived therefrom are plotted on Figures 6 and 7. The isoseismal lines were produced as a collaborative effort by a team of four people, namely M.A. Lowry, G.L. Downes, W.J. Cousins and the author. Each of us independently produced our own initial isoseismal maps, then we discussed and resolved the differences.

A key feature of Figures 6 and 7 is the absence of any observations of intensity MM10. It is reasonable to suppose that the intensity could have reached MM10 close to the fault rupture, (if MM10 can be achieved in New Zealand). But there were no buildings in that area, so that no damage criteria arose that would be suitable for assigning MM10. There is room on Figures 6 and 7 for a narrow MM10 zone close to the fault. This is consistent with Freeman's observations [18] that in large earthquakes the high damage zone is confined to an area very close to the fault rupture (major microzoning effects excepted). Housner [19] also gives a narrow zone of maximum intensity.

Likewise the MM9 isoseismal is fairly narrow, and it is nearly symmetrical about the likely *maximum* fault rupture. In addition the MM9 isoseismal is nearly symmetrical with respect to the main landslide area (Figure 8).

CONCLUDING REMARKS

As a result of this study of this large pre-code 1929 earthquake, the following observations may be made:

1. Press reporting in this era was remarkably complete, and with some substantiation and enhancement from other sources has permitted the assembly of a good picture of the damage and intensity of this important New Zealand earthquake.

2. In the stronger shaken region (intensities MM8 or more), "well-built" buildings performed surprisingly well. In particular in Murchison (MM9, PGA $\approx$ 0.5 - 0.9g) concrete buildings with plenty of walls were virtually undamaged. Some of the characteristics of "well-built" pre-code buildings have been described. These criteria may help in preserving "earthquake risk" buildings from unnecessary demolition or excessive strengthening.

3. No building collapsed completely due to ground shaking (excepting a few primitive sheds), although there were many masonry and poorly structured composite material buildings in the region of intensity $\geq$MM8.

4. In the 1992 revision of the New Zealand version of the MM9 intensity scale, the criteria relating to pre-code buildings have been over-simplified to the detriment of the scale, and corrections have been proposed.

5. Criteria for assigning intensity based on landslides need to be described in more detail in order to be reliable at intensities MM8 and MM9. A range of categories of landslide vulnerability, similar to those already used for buildings, would be appropriate.

6. The sparse settlement of the epicentral region made reliable assessment of the size of the MM9 region difficult.

TABLE 3: MM intensities assigned at various locations

Location	MMI	Location (con't)	MMI	Location (con't)	MMI	Location (con't)	MMI
Buller and West Coast		**N E South Island**		**S W North Island**		**Central North Island**	
Murchison	9	Blenheim Town	7	Wellington	6	Taumaranui	6?
Owen River	8?	Blenheim District	6	Petone	6	Te Kuiti	5
Gowanbridge	8?	Seddon	5-6	Lower Hutt	6	Whakatane	0
Lyell	9?	Havelock	6	Otaki	6	White Island	0
Inangahua	8?	Picton	6	Levin	5	Opotiki	3
Reefton	8	Kaikoura	6-7	Shannon	5	Tauranga	3
Maruia (Frog Flat)	7-8	Christchurch	5	Foxton	5	Rotorua	3
Springs Junction	7	Lyttelton	5	Palmerston North	5	Ngongotaha	4
Waiuta	7-8	Sumner	4	Sanson	5-6	Taupo	4?
Karamea	8&9	Akaroa	4	Marton	5	Arapuni	3
Seddonville	8	Waikari	6	Hunterville	5	Te Awamutu	5
Hector	8	Rangiora	5	Taihape	5?	Cambridge	5
Granity	8	Kaiapoi	6	Wanganui	6	Hamilton	5
Millerton	8	**S E South Island**		Patea	6	Raglan	5
Burnetts Face	8	Ashburton	5	Hawera	7	Kawhia	3
Westport	8	Mt Somers	5	Stratford	6	Matamata	5
Greymouth	7	Staveley	4	Eltham	6	Morrinsville	4
Cobden	7	Timaru	5	Inglewood	6	**Northern North Is**	
Blackball	7	Waimate	5	New Plymouth	6	Paeroa	3
Runanga	7	Temuka	5	Waitara	5-6	Thames	4
Hokitika	7	Oamaru	4	**Eastern North Island**		Te Aroha	3
Kokotahi	6	Queenstown	4	Carterton	5	Waihi	2
Ross	6	Dunedin	4	Masterton	6	Waiuku	4
Moana	7	Milton	4	Eketahuna	5	Pukekohe	3
Otira	6	Gore	5?	Pahiatua	5-6	Auckland	3
N W South Island		Winton	4	Woodville	5	Helensville	2
Nelson	8	Invercargill	4?	Dannevirke	5	Dargaville	4
Mahana	6	Franz Joseph	≥4	Waipukurau	5	Whangarei	3
Orinoco	8	Springfield	5-6	Hastings	5	Kaitaia	2
Motueka	7			Napier	5		
Takaka	8			Wairoa	3		
Tarakohe	8			Gisborne	3		
Collingwood	8						
Puponga	6						
Farewell Spit	6-7						
Bainham	7-8						

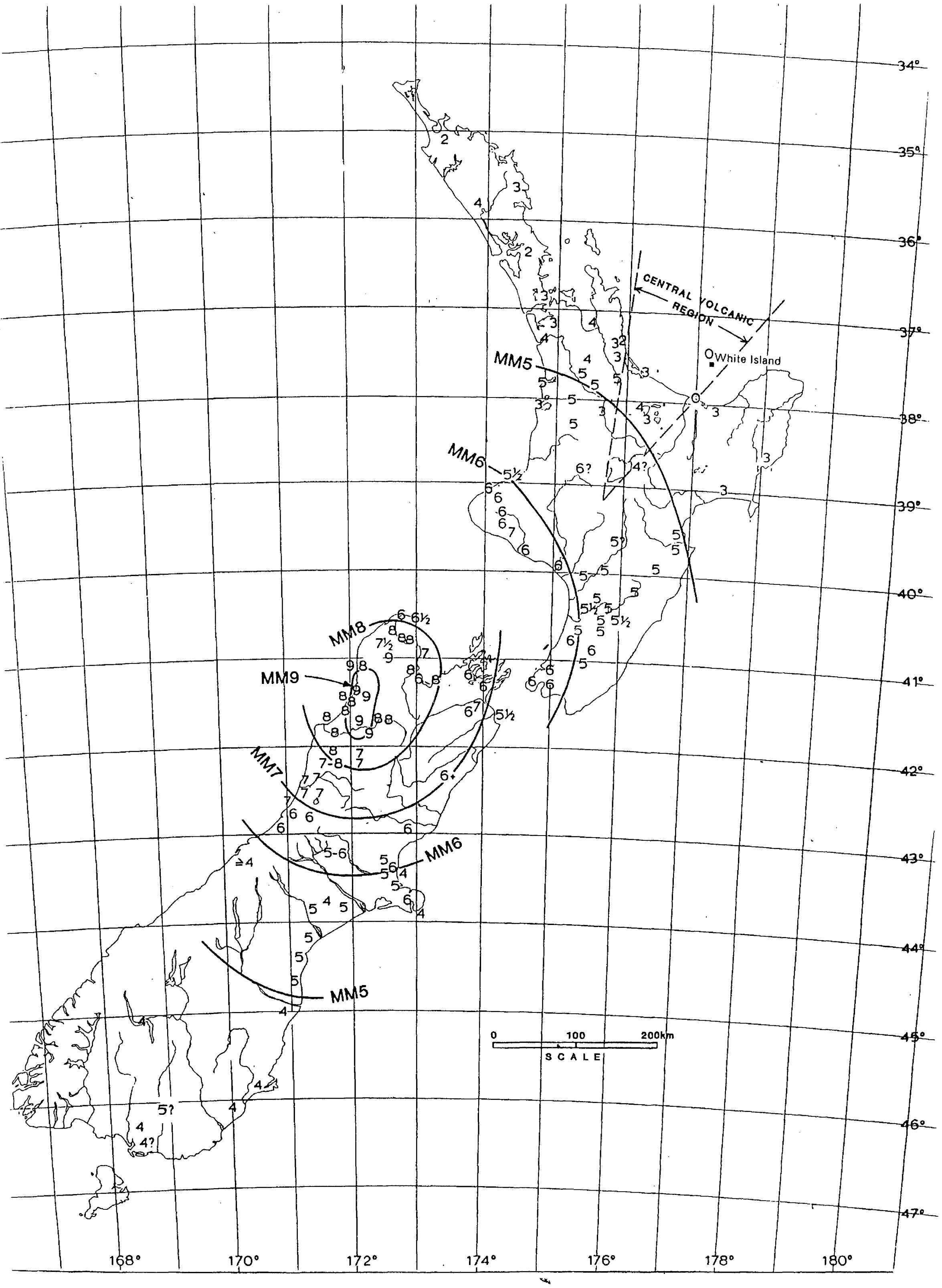
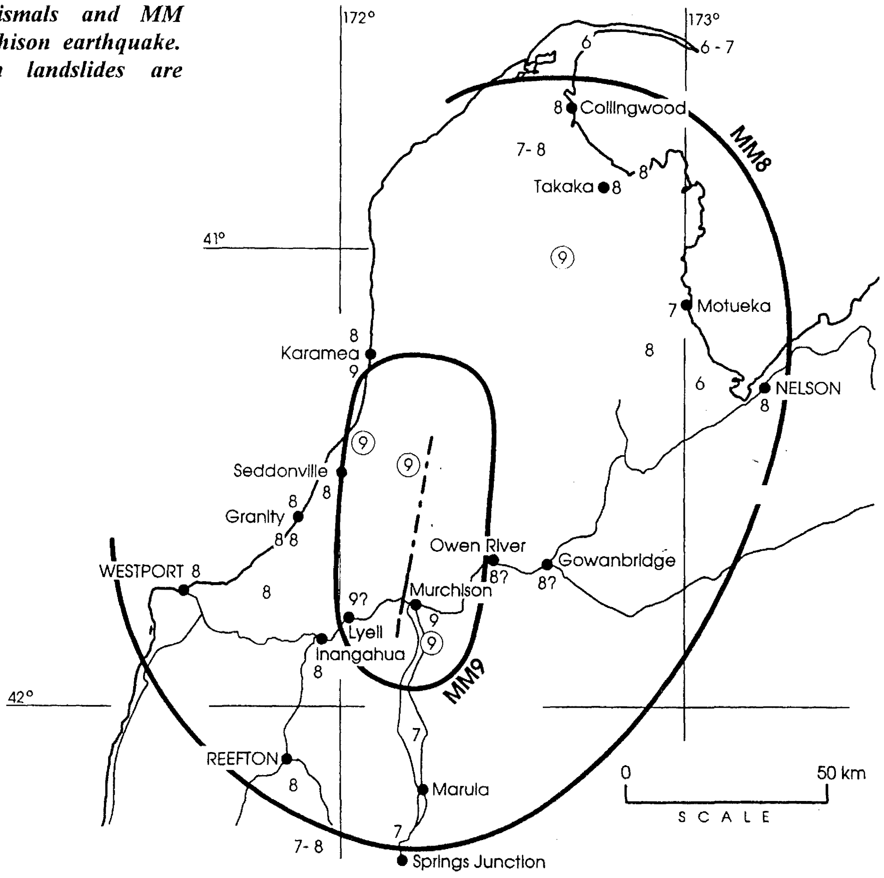


FIGURE 6 Map showing Modified Mercalli intensity observations and isoseismals of the 1929 Murchison earthquake, as assigned in this study (6½ indicates MM6-7).

FIGURE 7 *Map showing inner isoseismals and MM intensities of the 1929 Murchison earthquake. Intensities based only on landslides are enclosed in circles.*



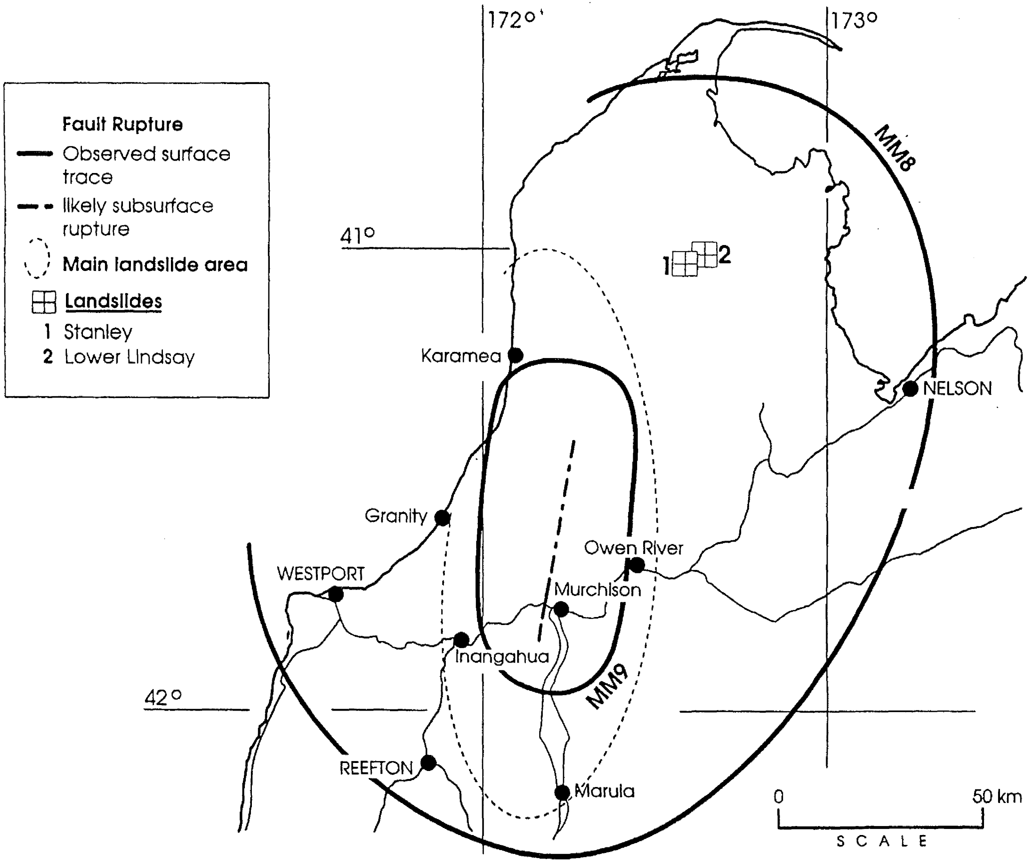


FIGURE 8 *Map showing relationship of the MM8 and MM9 isoseismals to the main landslide area of the 1929 Murchison earthquake.*

Similarly the data on ground damage effects, particularly landslides, and their relationship to the intensity scale, were of limited use in determining local intensities within the MM8 isoseismal.

7. No observations for MM10 were available. Ground shaking which could have caused this intensity almost certainly occurred close to the fault rupture, but there were no buildings in this vicinity.

ACKNOWLEDGEMENTS

The author wishes to acknowledge the many people who helped to bring this study to fruition. Firstly many residents of the more strongly shaken area provided data which helped in defining the 1929 building stock and the intensities. These people are listed in Appendix 1. In preparing the isoseismal map the collaboration of my colleagues J. Cousins, G. Downes and M. Lowry was much appreciated, as were my discussions of landslides with N. Perrin. Thanks are also due for the constructive in-house reviews of the manuscript by my colleagues G. Downes and G. McVerry.

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APPENDIX 1: List of people who provided information on buildings in key towns.

Murchison: T. Monahan, B. Oxnam, B Spiers

Owen River: T. Monahan, B Spiers

Greymouth: K. Brown, B. Dowrick, G. Hopkinson, H. Hutchinson, A. Keown, G. Williams

Westport: J. Dellaca, D. Drummond, C. Robertson, C. Turton

Reefton: A. Cleaver

Maruia (Frog Flat): D. Spiers

Springs Junction: W. Blackadder

Nelson: R. Davies, B. McLean, P. Thornton, D. Smith

Motueka: R. Askew, W. Drummond, W. Hartshorn, F. Holyoake

Takaka, Collingwood and hinterland: Jane Baird, Jim Baird, W. Drummond

Karamea: D. Harman, K. Jones, S. Lineham, W. Simpson

Seddonville: D. Dawson, J. Dawson

Lyell: N. Mangos, J. O'Regan, G. Welch

Burnetts Face: W. Andrews

Granity: W. Crawford, D. Smith

Millerton: F. Plummer

Waiuta: S. Stephens

APPENDIX 2: Criteria for intensities MM7-MM10 relating to pre-code buildings.

This study has made the author aware of some over-simplification (that he was party to) in the recent revision of the MM scale [11] in respect of pre-code buildings, i.e. Masonry B and C in the earlier scale [14] were compressed into a single new category, Buildings Type II. This results in an important loss of intensity defining power in the scale, and needs to be corrected by dividing Buildings Type II into two categories. Thus the revised scale would have five building categories I - V, instead of four, as set out below (revised categories marked with an asterisk):

Buildings Type I (Masonry D in other MM scales)

> Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick or rammed earth. Soft storey structures (e.g. shops) made of masonry, weak reinforced concrete or composite materials. Masonry buildings generally conforming to Types I - III, but also having heavy unreinforced masonry towers.

Buildings Type II (Masonry C in other MM scales)*

> Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Buildings Type III (Masonry B in other MM scales)*

> Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

Buildings Type IV:* same as Buildings Type III in Ref [10].

Buildings and Bridges Type V:* same as Buildings Type IV in Ref [10].

For intensities MM7 - MM10 in the 1992 scale [11], those criteria relating to pre-code buildings need to be replaced with the following:

MM7 Buildings Type I cracked and damaged.
A few instances of damage to Buildings Type II*.

MM8 Buildings Type I heavily damaged, some collapsing.
Buildings Type II* damaged, with partial collapse.
Buildings Type III* damaged in some cases.

MM9 Buildings Type I destroyed.
Buildings Type II* heavily damaged, some collapsing.
Buildings Type III* seriously damaged.

MM10 Many Buildings Type III* destroyed.