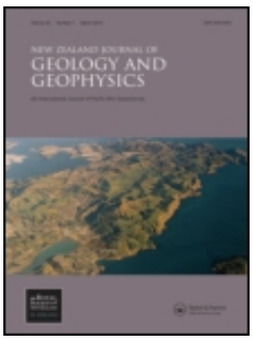

New Zealand Journal of Geology and Geophysics

ISSN: 0028-8306 (Print) 1175-8791 (Online) Journal homepage: http://www.tandfonline.com/loi/tnzg20

Pre-2010 historical seismicity near Christchurch, New Zealand: the 1869 M_W 4.7–4.9 Christchurch and 1870 M_W 5.6–5.8 Lake Ellesmere earthquakes

G Downes & M Yetton

To cite this article: G Downes & M Yetton (2012) Pre-2010 historical seismicity near Christchurch, New Zealand: the 1869 M_W 4.7–4.9 Christchurch and 1870 M_W 5.6–5.8 Lake Ellesmere earthquakes, New Zealand Journal of Geology and Geophysics, 55:3, 199-205, DOI: 10.1080/00288306.2012.690767

To link to this article: http://dx.doi.org/10.1080/00288306.2012.690767

New Zealand Journal of Geology and Geophysics
Vol. 55, No. 3, September 2012, 199–205

Taylor & Francis
Taylor & Francis Group

Pre-2010 historical seismicity near Christchurch, New Zealand: the 1869 M_W 4.7–4.9 Christchurch and 1870 M_W 5.6–5.8 Lake Ellesmere earthquakes

G Downes[a]* and M Yetton[b]

[a]*GNS Science, Lower Hutt, New Zealand;* [b]*Geotech Consulting Ltd, Christchurch, New Zealand*

(*Received 3 December 2011; final version received 8 April 2012*)

The 5 June 1869 (NZMT), 4 June 1869 (UT) Christchurch earthquake has long been known to have caused chimney and structural damage, to Modified Mercalli intensity MM7, in central Christchurch. On 31 August 1870, another strong earthquake shook the city causing widespread contents damage and the cracking and fall of a few chimneys. These two events represent the most significant near-field earthquakes in Christchurch's historical record prior to the 2010 M_W 7.1 Darfield and 2011 M_W 6.2 Christchurch earthquakes. Comprehensive data on the effects of 1869 and 1870 events now provide reasonable constraint on their locations and magnitudes. The 1869 earthquake, known as the New Brighton earthquake prior to 1999, occurred at shallow depth (upper crustal) about 3 kilometres southwest of Christchurch Central Business District, within the aftershock zone of the 2010 and 2011 events. The 1870 Lake Ellesmere earthquake had a larger magnitude, was deeper and was about 30 km south of Christchurch.

Keywords: Christchurch; historical earthquake; isoseismal map; New Zealand

Introduction

Since the start of organised European settlement of Christchurch, New Zealand (inset, Fig. 1) in 1850, and prior to the 2010 M_W 7.1 Darfield and 2011 M_W 6.2 Christchurch earthquake sequence (Bannister & Gledhill 2012), only a small number of earthquakes are known to have shaken Christchurch city strongly enough to cause isolated chimney and minor building damage and/or significant contents damage (i.e. shaking intensities of Modified Mercalli MM6 or more). These include large earthquakes with epicentres more than 50 km from Christchurch, such as the 1888 M_W 7.1–7.3 North Canterbury (Cowan 1991), 1922 M_W 6.4 Motunau (Downes 1995; Dowrick, pers. comm., 1998) and 1929 M_S 7.8 Buller (Dowrick 1994) earthquakes. Only one near-field earthquake is known to have caused pervasive building and chimney damage to intensity MM7 in the Christchurch Central Business District (CBD) and its nearby suburbs, including Avonside, St Albans and Merivale. This event was the 08:00 5 June 1869 (NZMT), 20:30 4 June 1869 (UT) earthquake. Based on limited data, Eiby (1968) assigned MM7 to Christchurch city and located the earthquake off Banks Peninsula, just over 60 km from Christchurch. Eiby assigned a 'C' class to the magnitude, meaning that it was probably between 4.5 and 6. In an unpublished client report for BP (New Zealand) Ltd, based on historical document research carried out at the time Dibble et al. (1980) recognised that the earthquake was close to the city and at a shallow depth. They suggested a magnitude of M 5.75 and a location immediately east of the city in the vicinity of offshore New Brighton. Based on Dibble et al.'s location, the name 'New Brighton' was used by Elder et al. (1991).

Another near-field earthquake that caused damage in Christchurch occurred in 1870, on 31 August at 18:53 (NZMT) or 07:23 (UT). It affected a wider area of Canterbury, generally at lower intensities than the 1869 event. It caused minor building and contents damage, as well as the fall or cracking of isolated chimneys over the eastern parts of mid-Canterbury from Christchurch to Rakaia. Basing his estimates on limited data, Eiby (1968) assigned the same magnitude class and location as the 1869 earthquake, that is, offshore from Banks Peninsula. Dibble et al. (1980) considered that the distribution of intensity was consistent with a magnitude M 6.5 earthquake centred about 60 km east of Christchurch.

Prior to 2010, these two significant (although not major) earthquakes were the only historical events that provided an insight into the occurrence and effects of moderate magnitude earthquakes on faults hidden beneath the alluvial plains upon which Christchurch city is situated. In an Earthquake Hazard and Risk Assessment Study completed for Canterbury Regional Council (now Environment Canterbury) in 1998 (Pettinga et al. 1998), the inadequacy of information about these earthquakes was noted. Recommendations were made to resolve conflicting assessments of intensity and magnitude and to improve locations by in-depth research. This was carried out as part of further work for Canterbury Regional Council in 1999, which was reported on in Stirling et al. (1999, 2001) and Pettinga et al. (2001). As the 2001 papers do not include the historical earthquake studies, we

*Corresponding author. Email: g.downes@gns.cri.nz

ISSN 0028-8306 print/ISSN 1175-8791 online

http://dx.doi.org/10.1080/00288306.2012.690767
http://www.tandfonline.com

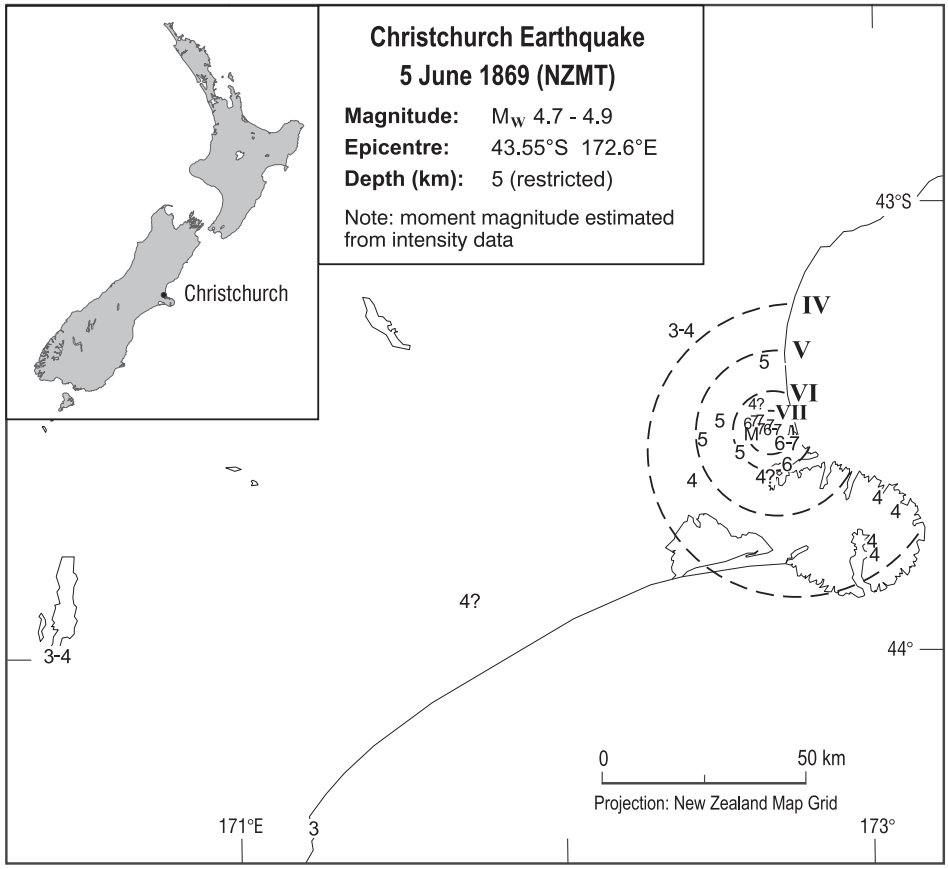

Figure 1 Isoseismal map and macroseismic epicentre (M) of the 1869 Christchurch earthquake. Isoseismal lines, marked with Roman numerals, bound areas judged to have experienced the same MM shaking intensity. The use of M for the macroseismic epicentre on the isoseismal map follows the notation used by Downes & Dowrick (in press) to distinguish these epicentres from those determined instrumentally. Inset: Location of Christchurch, New Zealand.

here review and analyse the data that were found in 1999 and in later investigations.

Collecting data involved searching newspapers, published papers, farm records and personal diaries held at the National Library of New Zealand in Wellington and at the Canterbury Museum in Christchurch. The information found is considerably more extensive than that used by previous researchers, and sufficiently comprehensive to provide reasonable constraint on new locations and magnitudes for the 1869 and 1870 earthquakes. We renamed the 1869 earthquake the Christchurch earthquake in Stirling et al. (1999); here, we name the 1870 earthquake the Lake Ellesmere earthquake.

The source information used in the analysis of intensities in this paper has been lodged with the library at GNS Science.

Location, magnitude and effects of the 5 June 1869 Christchurch earthquake

Intensities of shaking, assigned using the Dowrick (1996) version of the Modified Mercalli Intensity Scale (MM) for New Zealand, are given in Table 1 and shown on the isoseismal map (Fig. 1).

The highest intensity of shaking was clearly confined to within a few kilometres of Christchurch city. In 1869, Christchurch city (Fig. 2) was largely confined within the four avenues of Deans, Bealey, Fitzgerald and Moorhouse, which now constitute the CBD. Contents damage occurred in many shops and homes and many chimneys and chimney tops fell or were cracked. The side of a brick house in Manchester Street collapsed. The stone spire of St John's Church in Latimer Square was cracked from top to bottom, reportedly the worst damage in the city. At the Government buildings, the tops of two chimneys fell, plaster was cracked and several stone blocks were displaced. Similar damage occurred in other brick and stone buildings, including the NZ Trust & Loan building, the NZ Insurance building and the nearby 'Matson' building. Some brick and stone buildings were not damaged. The relatively low level of masonry damage in the city is consistent with MM7 rather than the MM 7–8 assigned by Dibble et al. (1980).

The suburb of Avonside and, more generally, the area north of the Avon River and east of and along Papanui

Table 1 MM intensities caused by the 1869 Christchurch earthquake. Also given for comparison are the mode or range of most commonly reported intensities, as appropriate, as well as the full range of reported intensities in the 26 December 2010 M_W 4.7 earthquake at the locations for which there are intensities for the 1869 earthquake.

	1869 Christchurch earthquake	26 December 2010 M_W 4.7 earthquake	
Place name	Intensity	Mode or range of most commonly reported intensities	Full intensity range
Akaroa	MM4	MM4	MM4
Ashburton	MM4?	MM4	MM4
Avonside	MM7	MM5–6	MM5–6
Christchurch CBD	MM7	MM4–6	MM4–8
Cust	MM3–4?	MM4	MM4
Fendalton	MM6	MM5	MM4–8
Halswell	MM5	MM4	MM4–6
Heathcote	MM6–7?	–	–
Kaiapoi	MM5	MM4	MM4–6
Little Akaloa	MM4	MM4	MM4
Linwood	MM6–7	MM5	MM4–6
Lyttelton	MM6	MM4	MM4–8
Merivale	MM7	MM5–6	MM4–8
Ohinetahi	MM4?	–	–
Okains Bay	MM4	–	–
Redwood	MM4?	MM4	MM4–7
Springston	MM4	–	–
St Albans	MM7	MM5	MM4–8
Takamatua	MM4	–	–
Tekapo	MM3–4?	–	–
Templeton	MM5	MM4	MM4–5
Timaru	MM3	MM4	MM3–4
Yaldhurst	MM5	MM4–5	MM4–5

Road were also badly affected with extensive contents damage and many damaged or fallen chimneys.

The impression recorded by observers in Christchurch city was that the earthquake waves came from directly below or from the southwest. In Fendalton, c. 2–3 km northwest of the city, an observer heard a noise and then noticed the shaking of trees advancing from the south or southwest a few seconds before reaching him and passing on towards Kaiapoi. Evidence from the same observer recorded that at the same time as the earthquake reached him, a noise was heard from the city. This noise probably represents the passage of earthquake waves rather than a result of damage occurring in the city (as implied by the observer). No reports of damage to the southwest of the city, specifically at Riccarton or Addington, have been found. Riccarton was probably part of the Deans family farm at the time, but no Deans family records covering this period have been found.

Outside the city and its nearby suburbs, intensities decreased rapidly reaching MM5 at Kaiapoi and Halswell. A few chimneys and household contents were however damaged at Lyttelton.

No liquefaction or ground damage was reported, nor was there any damage to the Lyttelton rail tunnel. No rockfalls were reported. However, minor settlement may have occurred in the Heathcote estuary, where it was reported that 'the tide runs higher up the Heathcote River than formerly' (Weekly News 26 June 1869). An intensity of at least MM6, and more probably MM7, is implied.

Interestingly, the well-known early New Zealand geologist Julius von Haast commented on the earthquake's effects in an article in the Weekly Press (11 June 1869) that: 'It is almost needless for me to observe that, according to the nature of the ground, great changes in the nature and intensity of an earthquake usually take place, and that in this instance amongst other secondary causes the direction of the bed of or vicinity to the River Avon may here have had a material influence in different parts of Christchurch .... That the earthquake was not so severely felt in Lyttelton as in the plains may be accounted for by the fact that the former town is built upon volcanic rocks, which have a far greater elasticity than sand and gravels on which Christchurch stands.'

The duration of shaking in the city–which was generally reported to be of the order 5–10 s (there were some estimates of 30 s)–the small areal extent of MM7 and the rapid attenuation of shaking intensity are consistent with an earthquake at shallow depth within a few kilometres of the present-day CBD. Unless there is strong evidence for a different location, (macroseismic) epicentres for small–moderate pre-instrumental earthquakes are conventionally located near the centre of the isoseismal pattern with as few decimal places in latitude and longitude as are warranted by the data. Taking this into account as well as the eye-witness report of an origin south or southwest of the city, we assign a macroseismic epicentre (M in Fig. 1) at 43.55°S 172.60°E and standard (default) upper crustal depth of 5 km. The nominal error in the location is 5 km. Given the location, we considered it appropriate in 1999 to assign the name 'Christchurch' rather than 'New Brighton' used by Dibble et al. (1980) and Elder et al. (1991).

Comparison of the isoseismal map with Dowrick & Rhoades' (1998) attenuation models for the main seismic region with unspecified mechanism suggests a magnitude of M_W 4.7–4.9, although the observed attenuation is more rapid than the model. The occurrence of about ten distinct but slight aftershocks and several other slight vibrations in the four days following the earthquake is consistent with this magnitude.

Earthquakes were also felt in Christchurch on 11 February and on 24 June 1869, but these were unrelated to the 5 June earthquake. A brief analysis of newspaper accounts suggests that the February event had a distant source (possibly the Kermadec area) while the 24 June earthquake, which was widely felt throughout the southern half of the South Island and the West Coast, probably had a source in Fiordland.

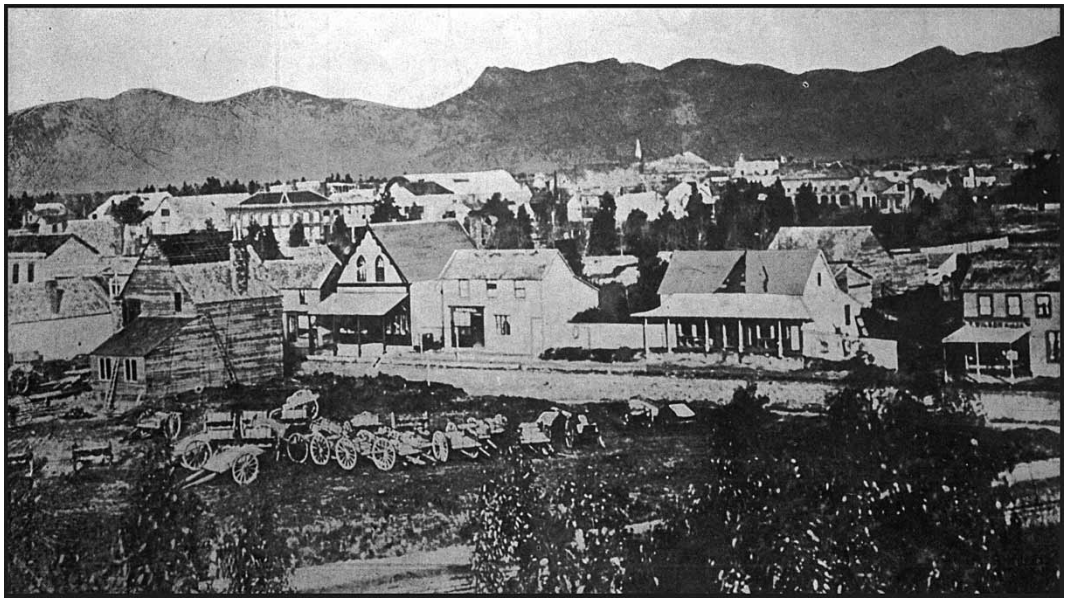

Figure 2 View of Gloucester Street looking towards Christchurch city. The photo was taken in 1869. While wooden buildings dominate the foreground, brick and stone were more common in the central city area. Image from Christchurch City Libraries, File reference: CCL-KPCD05-IMG0036. Source: The Weekly Press, 17 Dec. 1925, p. 1.

Location, magnitude and effects of the 31 August 1870 Lake Ellesmere earthquake

Intensities of shaking, assigned using the Dowrick (1996) version of the Modified Mercalli Intensity Scale (MM) for New Zealand, are given in Table 2 and shown on the isoseismal map (Fig. 3).

This earthquake was more widely felt than the 1869 earthquake with the highest intensities around Christchurch, on Banks Peninsula and in South Canterbury. It was felt at least as far south as Dunedin, on the West Coast and in North Canterbury.

In Christchurch city and nearby suburbs, there was damage to household and shop contents as well as isolated chimney damage (e.g. one or two chimneys fell in Avonside, one in Chester Street, another in Papanui Road and the upper parts of several chimneys were rotated near the railway station). There was also isolated minor structural damage. At St John's Church in Latimer Square, the stone cross fell and caused damage to several roof slates and some old cracks opened in the stonework. Old cracks in the Town Hall also moved. The damage is consistent with MM6 at most. Isolated chimneys and household goods (intensity MM6) were damaged at Lyttelton, about Banks Peninsula and in South Canterbury as far south as Temuka, although the intensity at the latter location is somewhat higher than at nearby towns.

Table 2 MM intensities caused by the 1870 Lake Ellesmere earthquake.

Place name	Intensity	Place name	Intensity	Place name	Intensity	Place name	Intensity
Akaroa	MM6	Eyreton	MM5	Little Akaloa	MM6	Rangiora	MM5
Arowhenua	MM5	Flaxton	MM5	Little Port Cooper	MM6	Riccarton	MM6
Ashburton	MM5	Four Peaks Stn	MM4	Lyttelton	MM6	Saltwater Creek	MM5
Avonside	MM6	Geraldine	MM5	Merivale	MM6	Selwyn	MM5
Awaroa/Godley Head	MM5	Greymouth	MM4	Milton	MM3–4	Southbridge	MM6
Bealey	MM4?	Hokitika	MM4	Mount Peel	MM5	Takamatua	MM6
Bill Hill Range	MM4	Homebrook, Southbridge	MM6	Mount Torlesse	MM5	Tekapo	MM5?
Brooklands	MM4	Horsley Down	MM5	Ōamaru	MM4	Temuka	MM6
Burkes Pass	Not felt	Hurunui	MM5	Okains Bay	MM5	The Point, Rakaia	MM4
Cass	MM4?	Irwell	MM6	Ōpawa	MM6	Timaru	MM5
Castlehill	MM5	Kaiapoi	MM6	Orari	MM5	Waiau	MM3
Christchurch CBD	MM6	Kawhaka	MM4?	Ōtira	MM3	Waimate	MM4
Courtenay	MM5	Kirwee	MM5	Oxford	MM5	Waipara	MM5
Cust	MM5	Le Bons Bay	MM4	Pigeon Bay	MM6	Wellington	Not felt
Darfield	MM5–6	Leeston	MM6	Pūrau	MM7?	Woodend	MM5
Dunedin	MM4	Leithfield	MM5	Rakaia	MM6		

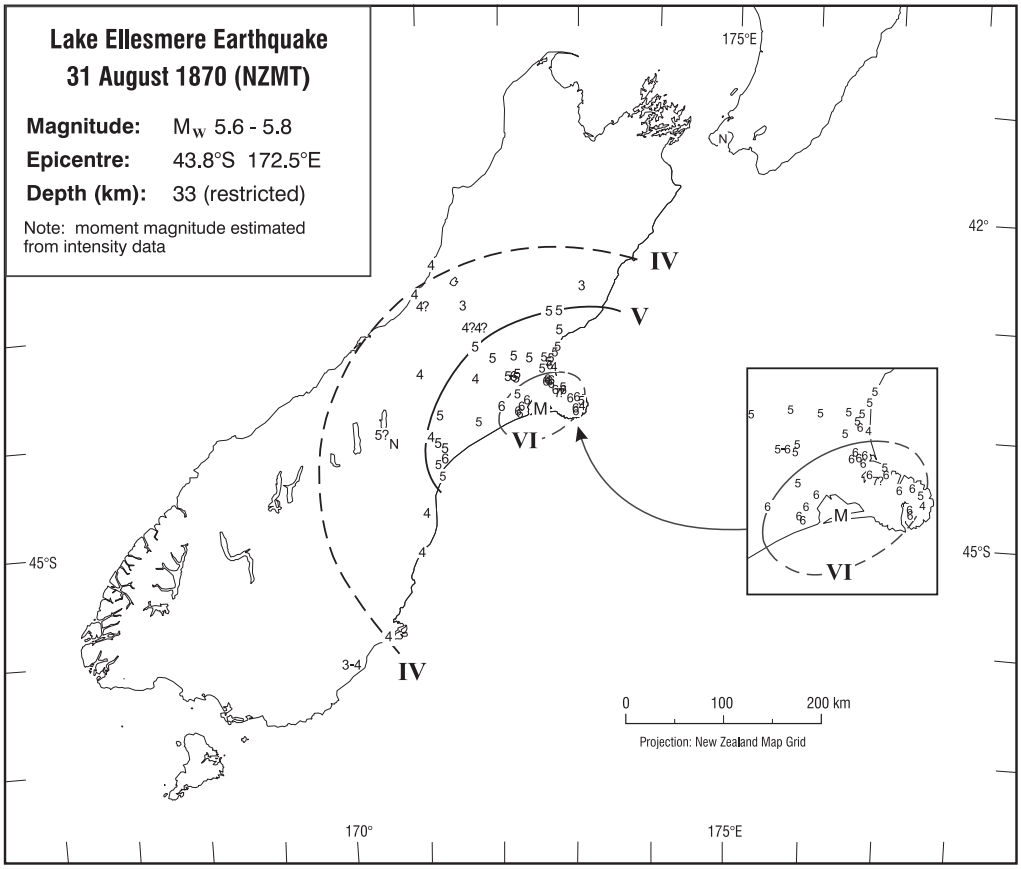

Figure 3 Isoseismal map and macroseismic epicentre (M) of the 1870 Lake Ellesmere earthquake. Isoseismal lines, marked with Roman numerals, bound areas judged to have experienced the same MM shaking intensity. The use of M for the macroseismic epicentre on the isoseismal map follows the notation used by Downes & Dowrick (in press) to distinguish these epicentres from those determined instrumentally. N indicates 'not felt'.

The MM7? assigned to Pūrau, based solely on the description 'considerable damage' to one house, may be too high. However, the fall of several tons (tonnes) of overhanging rock into the bay opposite the Pilot Station (Little Port Cooper) suggests an intensity of at least MM6, possibly MM7.

The earthquake was also felt strongly in a boat approaching Lyttelton, the occupants reporting that 'the sea jumped up and boiled as it were all around the boat' and that 'they thought it was a huge landslip and sheered off into deeper water'. However, no changes in water levels were noted along the shores of the harbour or nearby bays as would be expected had a significant submarine landslide occurred and consequent small tsunami generated.

No liquefaction or sand fountains were reported, although muddying of a creek occurred near Lake Ellesmere.

The wide areal distribution of intensities (Fig. 3) indicates an earthquake at greater depth than the 1869 earthquake. This is consistent with the reported longer duration of strong shaking than the 1869 event, a distinct interval between two shocks which were almost certainly P and S wave arrivals, and the occurrence of only one or two slight aftershocks.

We assign a macroseismic epicentre (M in Fig. 3) for the earthquake at 43.8°S 172.5°E near Lake Ellesmere. The nominal error in this location is 20 km. The depth is assigned the standard (default) lower crust depth of 33 km, nominal error ±10 km. Comparison of the isoseismal map with the Dowrick & Rhoades' (1998) attenuation models suggests a magnitude of M_W 5.6–5.8.

Discussion

As noted earlier, the 1869 Christchurch and 1870 Lake Ellesmere earthquakes represent the most significant near-field earthquakes in Christchurch's historical record prior to the 2010 M_W 7.1 Darfield and 2011 M_W 6.2 Christchurch earthquakes. Their locations in relation to the 2010–2011 events are clearly of interest.

The 1869 Christchurch earthquake epicentre lies within the diffuse distribution of aftershocks following the 2010 Darfield earthquake and within the field of Bannister et al.'s (2011) relocated aftershocks of the 2011 Christchurch earthquake, in an area where aftershocks were sparse, about 2–4 km west of a dense area at the western end of the main aftershock zone (Fig. 4). The assigned depth of the earthquake is consistent with the relocated aftershock depth distribution given in Bannister et al. (2011).

It would clearly be valuable to compare the isoseismal maps and/or intensity distributions of $M_W \sim 5$ aftershocks of the 2010–2011 earthquakes within a few kilometres of the 1869 earthquake epicentre with those of the 1869 earthquake. One key problem with doing this is that aftershock intensities may be skewed by previous damage, which could result in artificially low intensities (little left to damage) or high intensities (further damage to previously damaged structures). A greater problem is that the relatively new internet-based questionnaire, which is submitted by the general public and analysed using a computer algorithm (described in Coppola et al. 2010), frequently results in a range of intensities at a location (e.g. a suburb or town). There has been no published discussion on how to interpret these for the purposes of assigning intensities and drawing isoseismal maps comparable to those for historical earthquakes. In some cases, the distribution is dominated by one value i.e. the mode. In other cases, several intensities are equally represented and the mode may not characterise the intensity comparable with that determined from historical data, especially as key elements of the intensity scale depend on numbers of items or structures damaged.

For example, in the 10:30 26 December 2010 (NZDT), 21:30 25 December (UT) M_W 4.7 earthquake, which was within a few kilometres of the 1869 epicentre at c. 5 km depth (GeoNet earthquake hypocentre database 2012; GeoNet moment tensor solution database 2012; Bannister & Gledhill 2012), reported intensities for Lyttelton (GeoNet Shaking Map 2012) span MM4–8 with 11 MM4s, 2 MM5s and one MM8, giving a mode of MM4. Christchurch city intensities also span MM4–8, but MM4, MM5 and MM6 are almost equally represented with 35, 42 and 38 reports, respectively, 1 MM7 and 3 MM8s.

Given the difficulties, comparison of historical data with recent data presents problems that need more discussion than can be given here. Nevertheless, Table 1 – which gives the mode or range of most commonly reported intensities as appropriate and the full range of intensities experienced in the 26 December 2010 M_W 4.7 earthquake at the locations for which there are intensities for the 1869 earthquake – shows sufficient similarity to indicate that the location and magnitude range for the 1869 earthquake are not unreasonable.

No earthquakes comparable in location and magnitude with the 1870 Lake Ellesmere earthquake occurred following the 2010 Darfield and 2011 Christchurch earthquakes (as of September 2011). However, in the 10 years prior to the 2010 Darfield earthquake, the depth distribution of seismicity relocated by Reyners et al. (2010) using the new nationwide

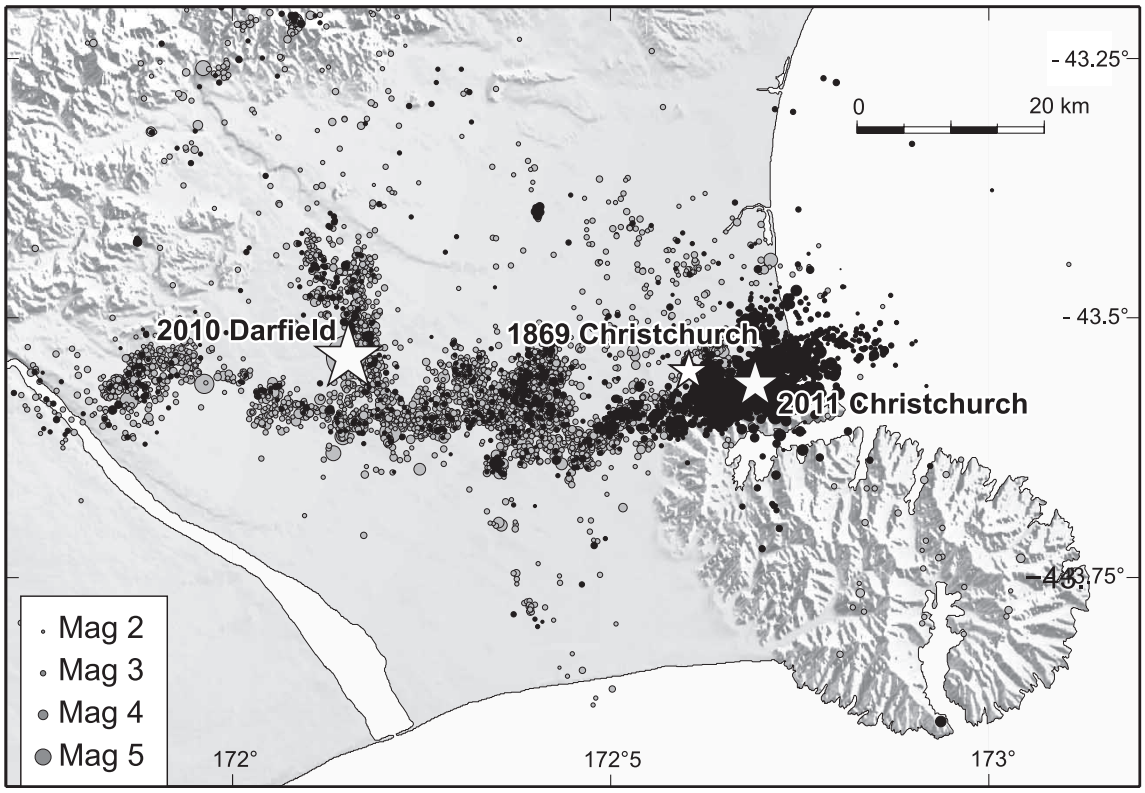

Figure 4 Location of the 1869 Christchurch earthquake (smallest star) overlaid on Bannister et al.'s (2011) figure showing the locations of the 2010 M_W 7.1 Darfield and 2011 M_W 6.2 Christchurch earthquakes (marked by stars) and the distribution of seismicity following these events until 30 April 2011. Earthquakes occurring after the 2011 Christchurch earthquake are shown as filled black circles, while earlier events are grey. Circle size is scaled with magnitude.

3D seismic velocity model indicates earthquakes at lower crustal depths within a broad area encompassing the Darfield earthquake fault and Lake Ellesmere; this suggests that assigning a lower crustal depth to the 1870 Lake Ellesmere earthquake is reasonable.

A search of the National Earthquake Information Catalogue for events with $M \geq 4.7$ within 30 km of Christchurch CBD identifies only one earthquake in the period 1964–2009: a M_L 5.0 event at 33 km depth in 1968 26 km southwest of the city. The only other events recorded prior to this are the 1869 and 1870 earthquakes and an earthquake on 4 August 1895, for which the catalogue has a location 20 km east of Christchurch city and a class 'C' magnitude.

The 1895 earthquake has not been studied in detail, but a brief perusal of newspapers of the day indicate that it was felt from Õamaru to Amberley and caused isolated minor chimney and contents damage around Akaroa and in some parts of Christchurch. However, it should be recognised that not all such small events that cause little damage have been recognised or recorded in the catalogue, which is variously incomplete for small–moderate magnitude earthquakes prior to 1964 and dependent on the quality and distribution of the seismic network of the time and the extent of known felt intensity information. It can however be said that, although small–moderate magnitude earthquakes have not been common in the last 140 years, they are not exceptional or unexpected as far as seismic hazard assessment for Christchurch is concerned. Such events, which provide no geological surface expression of their occurrence and cannot be assigned to a known fault, have been incorporated into the Stirling et al. (2008) seismic hazard model for Canterbury as distributed seismicity within a series of cells.

Acknowledgements

This research was made possible through studies commissioned by the Canterbury Regional Council (now Environment Canterbury) and through funding from the Foundation for Research, Science and Technology. The authors thank Martin Reyners and Mark Stirling (GNS Science) for their helpful reviews.

References

Bannister S, Gledhill K 2012. Evolution of the 2010–2012 Canterbury earthquake sequence. New Zealand Journal Geology and Geophysics 55. doi: 10.1080/00288306.2012.680475.

Bannister S, Fry B, Reyners M, Ristau J, Zhang H 2011. Fine-scale relocation of aftershocks of the MW6.3 February 22nd Christchurch earthquake. Seismological Research Letters 82: 839–845.

Coppola JM, Cowan LX, Downes GL, Fenaughty KF, Grimwood PD, Leach P, Robertson E de J 2010. Felt earthquake reporting via the Internet in New Zealand. Seismological Research Letters 81: 984–991.

Cowan HA 1991. The North Canterbury earthquake of September 1, 1888. Journal of the Royal Society of New Zealand 21: 1–12.

Dibble, RR, Ansell, JH, Berrill, JB 1980. (Unpublished) Report on the study of seismic risk for BP New Zealand sites at Woolston and Lyttelton.

Downes G 1995. Atlas of isoseismal maps of New Zealand earthquakes. Institute of Geological and Nuclear Sciences monograph 11. Lower Hutt, GNS Science. 300p.

Downes GL, Dowrick DJ In press. Atlas of isoseismal maps of New Zealand earthquakes 1843–2003. Second edition (revised). Institute of Geological and Nuclear Sciences monograph 25. Lower Hutt, GNS Science.

Dowrick DJ 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.

Dowrick DJ 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.

Dowrick DJ, Rhoades DA 1998. Attenuation of Modified Mercalli intensity in New Zealand earthquakes. Bulletin of the New Zealand National Society for Earthquake Engineering 32: 55–89.

Eiby GA 1968. An annotated list of New Zealand earthquakes, 1460–1965. New Zealand Journal of Geology and Geophysics 11: 630–647.

Elder DMG, McCahon IF, Yetton MD 1991. The earthquake hazard in Christchurch: a detailed evaluation. Research Report to the Earthquake Commission (EQC). Christchurch, New Zealand Soils and Foundations Ltd.

GeoNet Hypocentre Database 2012. www.geonet.org.nz/resources/earthquake/ (accessed 10 March 2012).

GeoNet Moment Tensor Solution Database 2012. www.geonet.org.nz/resources/earthquake/ (accessed 10 March 2012).

GeoNet Shaking Map 2012. http://www.geonet.org.nz/earthquake/quakes/3437105g-shaking.html (accessed 16 January 2012).

Pettinga JR, Chamberlain CG, Yetton MD, Van Dissen RJ, Downes G 1998. Earthquake hazard and risk assessment Study (Stage 1 – Part A): Earthquake source identification and characterisation. Canterbury Regional Council Publication U98/10.

Pettinga JR, Yetton MD, Van Dissen RJ, Downes GL 2001. Earthquake source identification and characterisation for the Canterbury region, South Island, New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering 34: 282–317.

Reyners M, Ristau J, Cowan H, Pettinga J 2010. The seismotectonic context of the 2010 Darfield earthquake. Geoscience Society New Zealand Miscellaneous Publication 129A: 236.

Stirling M, Yetton M, Pettinga J, Berryman KR, Downes GL 1999. Probabilistic seismic hazard assessment and earthquake scenarios for the Canterbury region, and historic earthquakes in Christchurch. Stage 1 (Part B) of Canterbury Regional Council's earthquake hazard and risk assessment study. Institute of Geological and Nuclear Sciences client report 1999/53. Lower Hutt, GNS Science.

Stirling MW, Pettinga J, Berryman KR, Yetton M 2001. Probabilistic seismic hazard assessment of the Canterbury region, New Zealand. Bulletin of the New Zealand Society for Earthquake Engineering 34: 318–334.

Stirling M, Gerstenberger M, Litchfield N, McVerry G, Smith W, Pettinga J, Barnes P 2008. Seismic Hazard of the Canterbury Region, New Zealand: new earthquake source model and methodology. Bulletin of the New Zealand Society for Earthquake Engineering 41: 51–67.