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Procedures and tools used in the investigation of New Zealand's historical earthquakes

Gaye L. Downes
Institute of Geological and Nuclear Sciences, Lower Hutt, New Zealand

Abstract
New Zealand's tectonic setting, astride an obliquely convergent tectonic boundary, means that it has experienced many large earthquakes in its 200-year written historical records. The task of identifying and studying the largest early instrumental and pre-instrumental earthquakes, as well as identifying the smaller events, is being actively pursued in order to reduce gaps in knowledge and to ensure as complete and comprehensive a catalogue as is possible. The task of quantifying historical earthquake locations and magnitudes is made difficult by several factors. These include the range of possible earthquake focal depths, and the sparse, temporally- and spatially-variable historical population distribution which affects the availability of felt intensity information, and hence, the completeness levels of the catalogue. This paper overviews the procedures and tools used in the analysis, parameterisation, and recording of historical New Zealand earthquakes, with examples from recently studied historical events. In particular, the 1855 *M* 8+ Wairarapa earthquake is discussed, as well as its importance for the eminent 19th century British geologist, Sir Charles Lyell, and for future global understanding of the connection between large earthquakes and sudden uplift, tilting and faulting on a regional scale.

Key words *New Zealand – seismicity – historical earthquake – earthquake catalogue*

1. Introduction

New Zealand's tectonic setting, astride the obliquely convergent tectonic boundary between the Pacific and Australian plates, means that it experiences a high rate of small to moderate earthquakes, many large earthquakes and occasionally, great earthquakes (figs. 1 and 2a,b). Beneath the North Island and Northern South Island (the Hikurangi margin), the Pacific Plate descends beneath the Australian Plate, the maximum depth of earthquakes generally increasing towards the North-East, while in the South West of the South Island, the Australian plate descends beneath the Pacific plate, with earthquakes to depths of *ca.* 140 km.

Between the two subduction zones is a transition zone, characterised by continental collision and dominated by the ~ 400 km long dextral strike-slip Alpine Fault.

Over 300 active faults (surface faults shown in fig. 3), exhibiting a range of rupture styles and characteristics, many capable of producing large to great earthquakes, have been identified throughout the country (see Stirling *et al.*, 2002). Large earthquakes also occur within the subducting slabs. The subduction interfaces in the North and South of the country are considered capable of large earthquakes, although no large events have been unequivocally identified along the Hikurangi margin in the historical record. Volcanism occurs at several locations in the North Island (fig. 1).

Mailing address: Dr. G. L. Downes, Institute of Geological and Nuclear Sciences, 69 Gracefield Road, P.O. Box 30368, Lower Hutt, New Zealand; e-mail: g.downes@gns.cri.nz

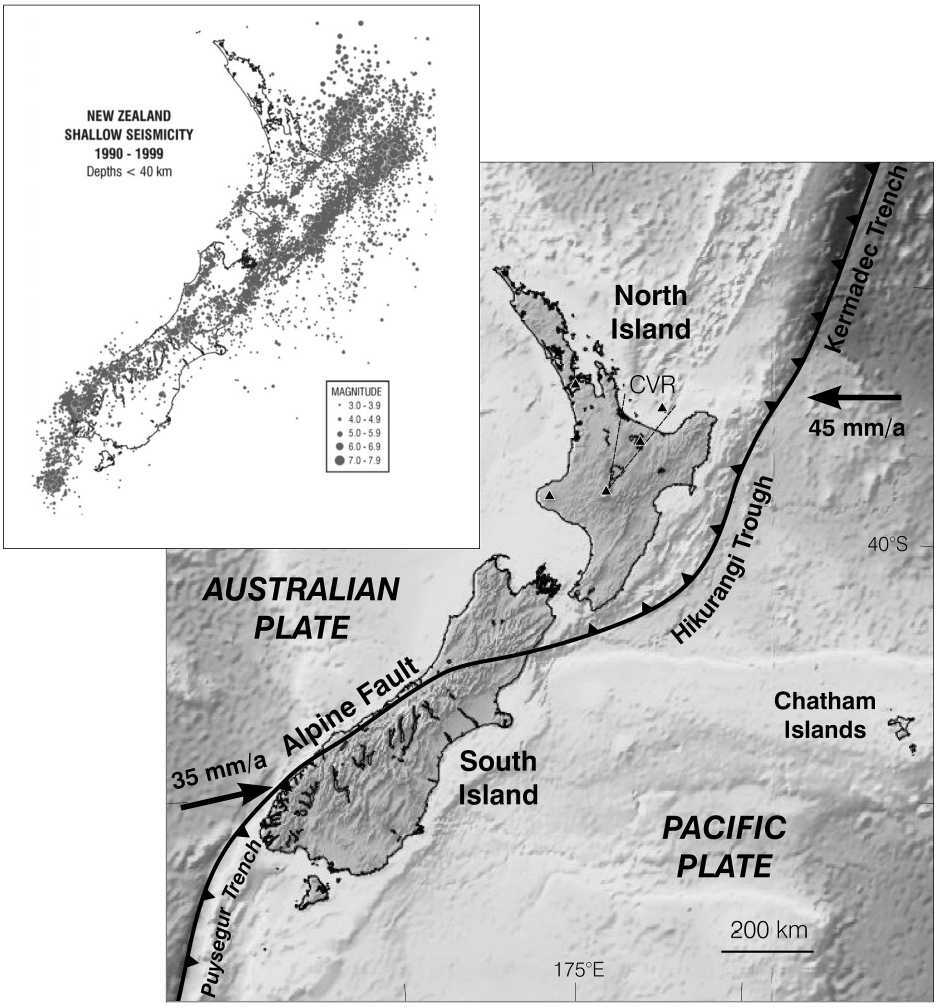


Fig. 1. Main tectonic features of the plate boundary through New Zealand, with north-west dipping subduction of the Pacific plate along the Hikurangi trench, and south-east dipping subduction of the Australian plate along the Puysegur Trench. The two zones are linked by a zone of continental collision, dominated by the dextral strike-slip transform Alpine Fault. Also shown are the main centres of onshore or near-shore volcanism (m), and the Central Volcanic Region (CVR), where back-arc spreading is occurring. Inset shows 10 years of shallow (depth < 40 km) seismicity.

Probabilistic Seismic Hazard Analysis (PSHA) techniques are already in use in New Zealand (Stirling *et al.,* 2002). New methodologies are being developed to extend PSHA techniques to probabilistic volcanic hazard analysis (Stirling and Wilson, 2002), probabilistic landslide hazard analysis (G. Dellow pers. comm.) and probabilistic tsunami hazard analysis (Downes and Stirling, 2001). The records of historical earthquakes, landslides, tsunami and volcanic events play important roles in the development of the probabilistic models, and there is ongoing research to ensure that the historical record is as complete and as comprehensive as possible. The recent move to introduce time dependence into probabilistic seismic hazard models means that the record of large shallow earthquakes becomes even more important.

Since organised European settlement (mostly from the British Isles) began in 1840, New Zealand has experienced at least 21 $M \geq 7$ shallow (depth ≥ 40 km) earthquakes near-shore or on-shore (fig. 2a,b). Few $M \geq 7$ on-shore shallow earthquakes have, however, occurred in what might be considered the modern instrumental era, that is, since the mid-1940s. Although two Milne seismographs were installed in New Zealand in 1900-1901, it was not until the mid-1940s that the New Zealand Seismic Network had developed sufficiently to allow routine calculation of instrumental locations for earthquakes of magnitude 4 and above within the central area of New Zealand (38°S-42ºS), provided all stations were operating. The record of $M \geq 7$ earthquakes (shallow and deep) is considered complete after 1943. The Modified Mercalli Intensity Scale was also adopted in 1943, replacing the Rossi-Forel Intensity Scale.

Of the $M \geq 7$ shallow earthquakes since 1943 (fig. 2a,b), the 1968 M_w 7.1 Inangahua earthquake was the only event centred on-shore. It occurred in a mountainous, sparsely populated area. In consequence, there is a paucity of data on the effects of strong shaking on the modern built environment, and on «lifelines» (water, gas, electricity distribution systems, road and rail systems, etc.) in major population centres. This makes the development of robust relationships between well-constrained earthquake parameters (magnitude, location, depth and mechanism), intensity of shaking, and engineering parameters difficult. However, in the 100 years prior to 1943, at least 16 shallow earthquakes exceeded magnitude 7. Most were located on shore, most were within the main seismic areas (figs. 1 and 2a), and many occurred within or close to major population centres. Not only were large earthquakes more numerous in this era, but also they were generally larger (fig. 2b). Multi-disciplinary studies of these events are now providing much needed data for the earthquake engineering community, earthquake geologists, engineering geologists, seismologists and tsunami scientists. For the

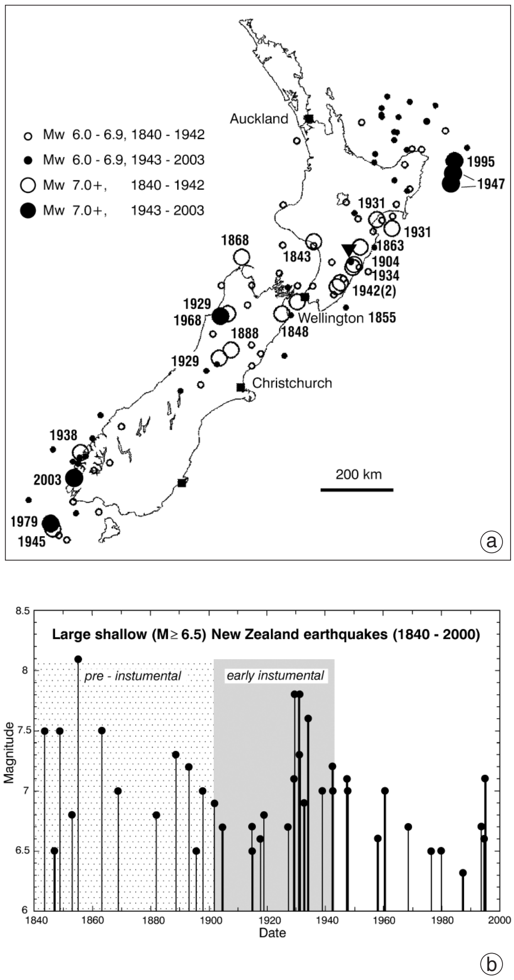


Fig. 2a,b. a) Known historical (post-1840) $M \geq 6.0$ shallow (depth ≤ 40 km) earthquakes, divided into two eras, pre-1943 and post-1942. Symbol (▪) shows the approximate location of the 1993 Tikiokino and 1958 Ashley Clinton earthquakes. b) Large earthquake timeline, showing the occurrence of large earthquakes ($M \geq 6.5$) in time since systematic European settlement in 1840.

purposes of the rest of this paper, the descriptor «historical» is used to refer to these pre-1943 earthquakes.

This paper discusses currently available resources, procedures and tools to analyse these historical earthquakes, with examples given from recent studies. Knowledge gaps, completeness levels and parameterisation of the catalogue are discussed. A study of the 1855 *M* 8+ Wairarapa earthquake illustrates the wealth of data available and how well the locations, effects and magnitudes of historical earthquakes can be constrained using multi-disciplinary techniques. The 1855 earthquake is of importance not only as New Zealand's largest historical earthquake, but also, it is of international interest because of its significance for the eminent British geologist of the 19th century, Sir Charles Lyell.

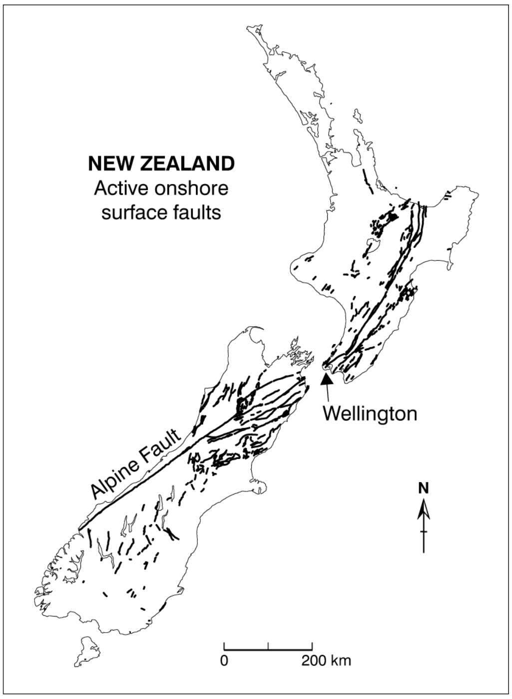


Fig. 3. Recognised active surface faults in New Zealand (for details see Stirling *et al.,* 2002).

2. Historical earthquake record

In comparison with European and Asian countries, New Zealand's written history is brief, going back just a little more than 160 years, reflecting the arrival of European settlers in New Zealand. Unlike Europe, New Zealand's history is uncomplicated by temporal and spatial variations in language or borders, making it possible for seismologists, geologists and earthquake engineers to unravel the historical earthquake record, largely without the necessity to engage historians, for example, to interpret manuscripts in ancient language forms. The occasional translation and interpretation of Maori, German, French, or Scandinavian language manuscripts is all that is needed. The last three languages reflect sparse early settlement by non-British immigrants.

2.1. *Completeness levels and knowledge gaps*

The completeness levels of the earthquake record depend on four main factors; whether there were people to record events, whether they created records, whether those records are available today in sufficient quantity for analysis of the earthquakes recorded, and lastly, whether those records have been searched out for earthquake information.

The first written account of an earthquake in New Zealand, on 11 May 1773, is found in the records of Captain James Cook's voyages of discovery to the southern oceans (Cook, 1777). Sealers and whalers arrived from the early 1790s. Most ships' logs and sailors' journals from this era are relatively inaccessible in overseas repositories, and require extensive, time-consuming searching for perhaps little reward. The result is that few have been searched exclusively by the author for geohazards information or as far as is known by other historical earthquake researchers in New Zealand. However, as historians interested in pre-1840 European settlers and sealing and whaling history search out and publish new material, information on large earthquakes and some tsunami events may be uncovered. Unfortunately, accounts are almost always tantalisingly brief and incomplete, often only record events at sea, and only record effects at one or two isolated sites.

Christian missionaries arrived in New Zealand from about 1814. Although excellent chroniclers of day-to-day domestic affairs and clerical duties, they lived for the most part in the northern part of the North Island, where seismic activity is low. By the time they extended their missionary activities to more Southerly areas in the late 1830s, systematic settlement of these areas by Europeans had just about begun.

The missionaries were responsible for developing the spoken language of the indigenous people, the Maori, into written form. Although several oral history records and legends referring to significant pre-European settlement geohazards events have been uncovered and approximately dated, there has as yet been no systematic searching for new events within existing published or unpublished material.

Hence, it is only from 1840 with the initiation of systematic European settlement, that there is a continuity of written historical material, and it is only from this time that the record of historical earthquakes has the potential to be complete. However, the completeness varies with time as the density and distribution of the population, as well as their predominant activity, changed (fig. 4). The general impression is that town dwellers kept

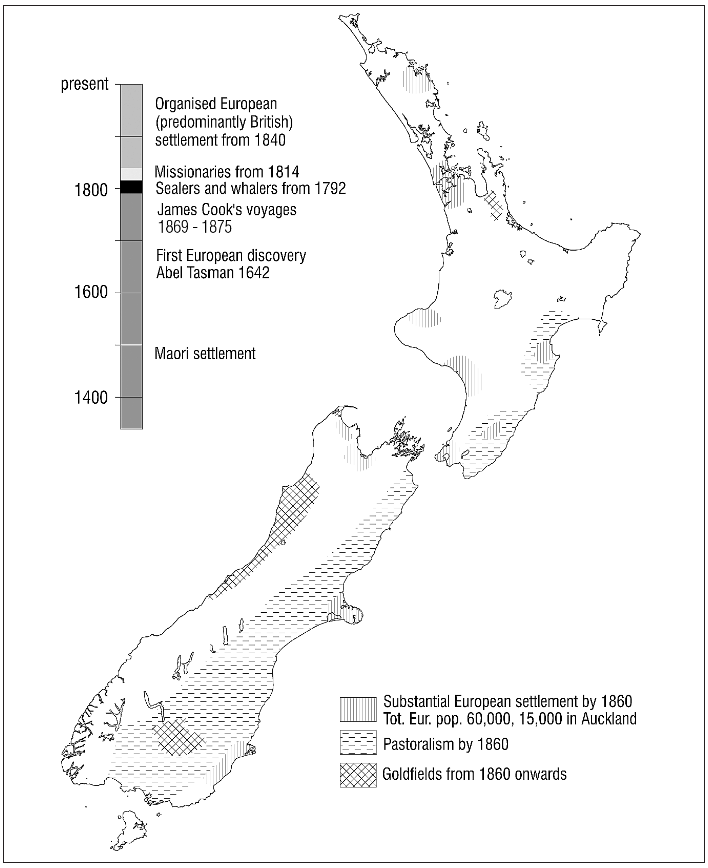
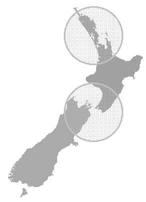
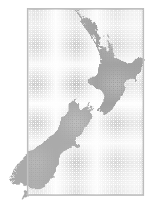
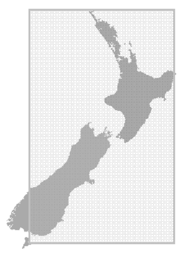


Fig. 4. The distribution and predominant activity of the New Zealand population in 1860s (adapted from Plate 30, McKinnon *et al.,* 1997).

Table I. Summary of the completeness levels of the historical earthquake part of the New Zealand National Earthquake Information Database.

Historical (onshore) Earthquake Catalogue Completeness	
Pre-1855 - pre-instrumental – Extensively researched and events data published (Eiby, 1968, 1973). Some revision probable with new data. – In-depth studies of major events completed, where data sufficient. – Complete to shallow $M \geq 6.5$ in central area and north only (estimated).	
1855-1900 - pre-instrumental – Most major/significant earthquakes probably identified through early catalogues, but most await in-depth studies. – Extensive research needed to identify all felt earthquakes, to ensure no major earthquakes have been missed, and evaluate known earthquakes. – Probably complete to shallow $M \geq 7.0$ onshore earthquakes, except in south west, and west coast until 1860s (estimated).	
1901-1942 - early instrumental – Most major/significant and many smaller earthquakes identified – Locations, MM intensities, isoseismal maps, and M_S for $M \geq 6.5$ and other selected earthquakes revised using available material. Smaller earthquakes, R-F intensities only. – M_W and source parameters obtained for largest events dating from 1917 using body wave modelling. – Major multidisciplinary studies on most $M \geq 7.0$ earthquakes – Many lesser events warrant in-depth studies, possibly resulting in location changes – Much available data in files (*e.g.* felt reports, newspaper clippings, pub. papers). – Complete to $M \geq 6.5$ over most of the country except Fiordland, increasing to $M \geq 4.0$ between 38ºS-42ºS by 1942 (estimated).	

more complete personal journals than pastoralists, who tended to record farm activities with very little detail about other activities.

The completeness of the earthquake record is also dependent on terrain. Even today, some parts of New Zealand are still virtually unpopulated because of high, glaciated or densely forested, rugged mountains that run in a spine along the west coast of the South Island. The record of earthquakes in Fiordland, in the south west of the South Island, is almost certainly seriously incomplete and locations very poorly constrained until the 1930s or later.

The last factor that affects the completeness levels of the earthquake record, which are summarised in table I, is how intensively historical information sources have been searched for earthquake data.

Table II. Summary of the parameters used in the historical earthquake part of the New Zealand National Earthquake Information Database.

National Earthquake Information Database (historical section) as at 2003

Computer database (Format: Oracle)
Earthquake parameters:
- Times UT, standard time adopted in 1868, pre-1868 times based on the assumption of local solar time;
- Epicentre – Latitude, longitude (the number of significant figures indicating reliability);
- Magnitude – M_W, M_S, M_L, M, or magnitude range (Class A $M \geq 7.5$; Class B M6-7.4; Class C M4.5-.9; Class D $M < 4.5$);
- Depth or depth class («C», crustal (*i.e.* there is no reason to suspect a deep focus); «S», shallow or upper crustal; «N», normal or lower crustal);
- Location code, indicating how earthquake parameters were determined: a number specifies the particular velocity model used in computer solutions;
  - «G» graphical solution;
  - «I» based on a large number of intensity data (*i.e.* reasonably reliable);
  - «F» based on a small number of intensity data points (*i.e.* very approximate);
  - «T» based on teleseismic data;
  - «M» a mistaken report;
  - «C» a confused reference (to some other phenomena).
- References to key papers only.
- No intensity data (intensity data, in form of place name and MM intensity, are included in the electronic database from 1943 only).

Paper copy only database
Intensity data:
- Pre-1943, intensity data as place name and intensity for many earthquakes but not all;
- Isoseismal maps, 123 available in *Atlas of Isoseismal Maps of NZ Earthquakes* (Downes, 1995), others in recent publications, others unpublished as yet.

Future (in planning)

Computer database (Format: Oracle)
Earthquake parameters:
- Uniformly assigned/determined epicentre and other epicentres, each with depth or depth class, and time as previous;
- Magnitude: all, as available, in separate fields with references;
- Mechanism and other rupture parameters, as available with references;
- Data sources, all relevant references, method of determination and reliability parameters;
- Metadata;
- Linked to other databases (*e.g.*, strong motion, active fault, landslide, tsunami, post-earthquake reconnaissance).

Intensity or effects data:
- Location defined by latitude, longitude (or NZ map grid reference) (+ references);
- Digitised isoseismal maps (+ references);
- Brief descriptive account of larger events (+ references);
- Descriptive summary of effects by place-name;
- Source material:
  - Intensity data entered using forms processing software;
  - Key-worded, annotated database of source material.

3. Pre-1855

The period prior to 1855 has been studied in detail (Eiby 1968, 1973), with every identified felt earthquake being listed, described and catalogued, assigned a magnitude or magnitude class, a location, a depth or depth class and a code to indicate how the earthquake parameters were determined (see table II for details). All source material used in the compilation of Eiby's catalogues was transcribed and bound in two volumes (Grouden, 1966; Grouden *et al.,* 1972). The 1848 *M* 7.5 Marlborough earthquake is the only event in this period with sufficient data to warrant an individual scientific paper.

Due to the priority of completing the later period (1855-1930), searching for new data on earthquakes in this period is not actively pursued at present. However, it is not unusual to find new accounts when searching for data on later period earthquakes. The finding of important new historical evidence on the 1848 Marlborough earthquake, the only earthquake in the period recently led Grapes *et al.* (1998) to relocate the earthquake from the Wairau Fault (Eiby, 1980) to the Awatere Fault (fig. 5). New evidence included accounts of damage, and the length and location of fault rupture – including an 1854 map delineating part of the Awatere Fault with the statement *«Opening made by the Great Earthquake of October 1847 [changed to 1848 on a later version of the map]»*. Based on a new isoseismal map and the historically observed >105 km rupture length and geologically estimated 6 m mean surface displacement, the magnitude was revised from *M* 7.1 (Eiby, 1980) to *M* 7.4-7.5 (Grapes *et al.,* 1998), using Dowrick (1992) and Smith (1995 a,b) MM intensity attenuation models, as well as Wells and Coppersmith's (1994) regression relationships. Surface rupture of >105 km is consistent with recent paleoseismological studies of the Awatere Fault (Benson *et al.,* 2001). Further, geological studies of the Wairau Fault indicate that it has not ruptured in historical times (Grapes and Wellman, 1986; Berryman *et al.,* 2000).

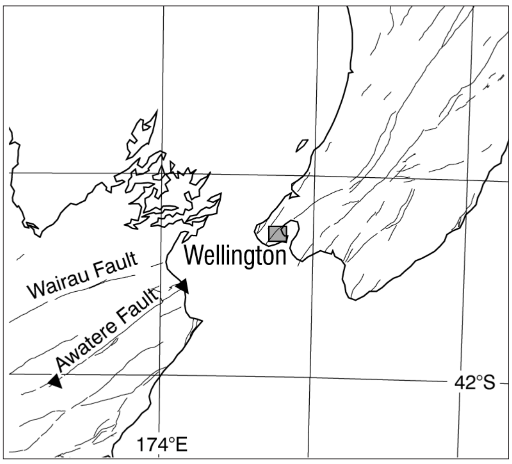


Fig. 5. Location map for the Wairau and Awatere Faults in the Northern South Island. Tick marks indicate the ~ 105 km of surface rupture of the Awatere Fault observed in the 1848 *M* ~ 7.5 Marlborough earthquake.

4. 1855-1900

The period 1855-1900 has not been studied in detail and it represents a knowledge gap. Although the record of $M \leq 7$ shallow earthquakes in the period is probably complete for a large part of the country, some may have been missed in remote areas, such as along the west coast of the South Island prior to settlement in the 1860s, and in the southwest of the South Island for the whole period. Further, few felt earthquakes other than the largest events have been identified.

There is much searching yet to be done to identify and evaluate the smaller events, to ensure that no significant events have been missed, and to intensively study the largest and/or most significant earthquakes. One example of a significant, but not large, earthquake is the 1869 *M* 5.0 Christchurch earthquake, well constrained by descriptive accounts and the extent of damage to a location within 5-10 km of the centre of Christchurch City at shallow depth (≤ 12 km) (Yetton and Downes, unpub. data). With no local events approaching this magnitude since 1869, this event is unique in Christchurch's history and hence important for seismic hazard assessment.

Of the four known magnitude $M \leq 7.0$ shallow earthquakes in this period, the 1855 *M* 8+ Wairarapa earthquake and the 1888 *M* 7-7.3 North Canterbury earthquake have been studied in detail (1855 earthquake: Eiby, 1990; Grapes and Downes, 1997; 1888 earthquake: Cowan, 1991), while the 1863 *M* 7-7.5 Waipawa earthquake and 1868 *M* 7-7.5 Cape Farewell earthquake are undergoing intensive investigation at present (Downes, unpub. data). Several smaller but significant earthquakes are also in the process of investigation, including three 1876 *M* 5+ Oamaru earthquakes (Reyners, pers. comm.), the 1869 *M* 5.0 Christchurch earthquake, the 1870 *M* 6 Banks Peninsula earthquake, the 1881 *M* 6 Cass earthquake (Yetton and Downes, pers. comm.), and the 1897 *M* 6+ Wanganui earthquake (Dowrick, pers. comm.).

5. 1900-1942

In the period 1900-1942, the record of $M \leq 7$ earthquakes is considered complete, and as the result of recent studies (Dowrick, 1994; Downes *et al.,* 1999; Downes *et al.,* 2001; Dowrick, 1998; Dowrick, unpub. data) the locations, magnitudes and intensity data of all $M \leq 7$ earthquakes, as well as many *M* 6+ earthquakes, are fairly reliable.

Table I summarises the knowledge gaps and completeness levels of the catalogue based on expert judgement by Eiby (1988) and the author rather than rigorous analysis.

6. Analysing historical earthquakes: gathering and interpreting data

6.1. *Resources*

Collecting data in the form of descriptive accounts, seismograph records, photographs, maps, charts, reports, scientific papers, etc. is but the first step, albeit the most time-consuming step, to analysing historical earthquakes. New Zealand is fortunate to have excellent archival resources from which to gather historical source material. Although newspapers and Government documents are prime sources of descriptive accounts of earthquakes (and other geohazards events), descriptive accounts and comments in diaries and journals kept by the early settlers have proved an excellent supplementary resource. The new settlements seem to have attracted a number of young, literate, scientifically curious people, who wanted to understand their new and foreign environment. Some were scientifically trained, some were trained in surveying, and many apparently studied, or at least intelligently observed, botany, geology or geography as leisure pursuits. The general populace seemed to be interested in scientific discovery and discussion also, many recording their thoughts and theories in their diaries, as well as in letters to newspaper editors.

Some of the most valuable resources are the files and archives of GNS. This organisation holds the scientific records of several predecessor organizations that were once part of the NZ Department of Scientific and Industrial Research (DSIR), in particular, the files of the New Zealand Geological Survey and DSIR Geophysics Division. These organisations, in turn, inherited files from their predecessors, back to the 1860s. Files relating to historical earthquakes include a large collection of earthquake felt reports (sent in by postmasters, telegraph operators, and later, the general public), post-earthquake geological reconnaissance files, newspaper cuttings, files of earthquake locations, unpublished earthquake catalogues, seismograph records (from 1900), earthquake analysts' books of phase arrivals (from the 1920s), as well as geological and geophysical reports and publications. GNS, a Government owned geological and geophysical research organisation, also maintains the earthquake, landslide, volcano and GPS (Global Positioning System) monitoring networks, as well as their associated databases, including the National Earthquake Information Database.

Other main national repositories of relevant resource material are:

– Archives of New Zealand (several locations), which holds predominantly Government papers, including parliament, Legislative and

Departmental records, photographs, some film archives, maps and charts, dating from the beginnings of plans to settle New Zealand in the late 1830s.

– National Library of New Zealand, Wellington, a non-lending library with extensive collections including books, including rare books, most New Zealand publications, government publications, magazines, newspaper archives, art works, maps, charts, photographs, as well as oral history records

– Alexander Turnbull Library, part of the National Library of New Zealand, Wellington, a non-lending library with extensive manuscripts and archives collections, which include private and business papers, journals and diaries, recollections, as well as Australian and New Zealand Joint Copying Project microfilms (see below for description).

– Te Papa Museum of New Zealand. Te Papa's Archives fall into two categories. The first consists of records generated by both the Museum and National Art Gallery from the time they were established in 1865 and 1930 respectively. The second category is made up of archives acquired by both these organisations since they began.

In addition, main libraries, museums and universities in each of the main cities, as well as libraries and small specialist museums in many of the smaller centres, each have their own collections, mostly relating to their area or region. Genealogical research has become very popular in New Zealand, and most libraries endeavour to cater for this audience. Interest in genealogy, as well as appeals by national and local archival organisations, have also lead to an appreciation of the historical value of old diaries and journals, many people now depositing the originals or copies in libraries and museums for safe keeping. Nevertheless, a large amount of material is still held privately, and stories of the destruction of fifty or more years of diaries dating from the 19th century are not uncommon.

Microfilms of many private papers and public documents held in British archives relating to Australia and New Zealand are also available in several libraries. The microfilms were created by the Australian and New Zealand Joint Copying Project, which operated from 1945-1993.

Historical newspapers are undoubtedly one of the best and most reliable sources of information. Fortunately, many small towns, as well as the provincial centres, published their own newspapers until well into the 20th century. They provide excellent coverage of what was happening in outlying villages and pastoral centres. Collections of provincial newspapers are almost complete, and most are available on microfilm at the National Library of New Zealand. Collections of many other newspapers and magazines are also very extensive, with microfilming an ongoing activity of the National Library of New Zealand with priority given to the most fragile collections. Some of the most complete collections are held by the publishers, some protected far more carefully than they were 10 years ago before their historical value was realised.

Another valuable resource is the listings of earthquakes felt by climatological observers published yearly from 1868 until 1902 in the Transactions and Proceedings of the New Zealand Institute, the forerunner organisation to the Royal Society of New Zealand. These listings were replaced in 1904 by the lists of events recorded on the Milne seismographs. Prompted by a meeting of the Australasian Association for the Advancement of Science in Christchurch in 1891, Hogben (1891) and Hector (1891) produced comprehensive lists of earthquakes, which were mainly based on the reports published in the Transactions and Proceedings of the NZ Institute mentioned above, but also including some newspaper and other minor reports (Eiby, 1988). These are the best early summaries of pre-instrumental shocks, but neither contains any index of severity beyond a few well recognised early shocks. Eiby (1988) provides a good summary of other published and unpublished lists of historical earthquakes.

Sir James Hector, Director of the Geological Survey and the Colonial Museum, initiated an earthquake reporting network in 1868. All telegraph offices throughout New Zealand were instructed to calibrate their clocks with Wellington daily, and to report the times and effects of the earthquakes that they or the nearby community felt. Also, Government climatological observers were asked to report earthquakes as part of their duties (Eiby, 1988). Some of these reports are still in the files of the Institute of Geological and Nuclear Sciences, Wellington, or in the Te Papa Museum of New Zealand archives in Wellington. This earthquake reporting network worked well until the first few years of the 20th century when it fell into decay as leading seismological personalities became ill and died, and as the result of disruptions caused by the First World War (Eiby, 1988). The reporting of earthquakes and the keeping of files of felt reports started again in about 1921, when the first of the *New Zealand Seismological Reports* was published. Reporting of earthquakes seems to have become more comprehensive at about the time of the 16 June 1929 M_w 7.8 Buller earthquake and the 1931 M_w7.8 Hawke's Bay earthquake, New Zealand's severest earthquake in terms of casualties, with more than 250 deaths (see Downes, 1995). The files of the Institute of Geological & Nuclear Sciences contain many felt reports from this period, as well as extensive newspaper cuttings, photographs, geological and engineering reports, particularly on the effects of 1929 Buller and 1931 Hawke's Bay earthquakes. These two earthquakes were also very well reported in the scientific literature (for references, see Downes, 1995; Dowrick, 1998), in contrast to the March 1929 M_w 7.0 Arthur's Pass, 1934 M_w 7.4 Pahiatua, and 1942 June M_w 7.2 and August M_w 7.0 Wairarapa earthquakes (M_w from Doser *et al.,* 1999; Doser and Webb, 2003). In addition to the extensive newspaper and other information on the 1931 M_w 7.8 Hawke's Bay earthquake, which is summarised and analysed in Dowrick (1998), complete documentation on compensation claims for domestic housing damage in the epicentral area, amounting to many hundreds of files, was also found by Dowrick, enabling him to calculate the damage ratios for various types of housing as well as quantify the distribution of building damage for rock, and soft and firm soil sites (Dowrick *et al.,* 1995).

6.2. *Limitations*

Once source information on historical earthquakes has been assembled, several factors limit our ability to interpret it. Among the problems encountered in New Zealand are those caused by changes in place names through time from Maori to European names, or successions of European names, the same names applied to multiple locations, multiple names for the same location, and the corruption of Maori names as the Europeans attempted to write down what they heard. Reliable locations cannot be found for many Maori landmarks referred to in early manuscripts.

In addition, the social and political repercussions following the occurrence of strong shallow earthquakes near Wellington in 1848 and 1855 (fig. 2a,b) affected the way earthquake effects were reported in some publications for several decades (see Grapes and Downes, 1997). The 1848 M 7.5 Marlborough earthquake (Grapes *et al.,* 1998), which damaged or destroyed almost all brick buildings in Wellington and caused three deaths in a large aftershock, was enough to cause many settlers to leave (Eiby, 1980). The occurrence, eight years later, in 1855, of a second stronger, more damaging and frightening earthquake, the M 8+ Wairarapa earthquake meant that more settlers left (Grapes and Downes, 1997). More importantly for the Wellington colony's promoters, the earthquake had the potential to discourage prospective immigrants and to cause the other rival major settlements to consider that Wellington was unfit to be the centre of Government. As a result, the government of the day, as well as those who had invested heavily in the settlement, attempted to downplay the damage and distress both locally and in official reports and private documents that were sent to Britain. Analysts of historical earthquakes for some time after these earthquakes need to be aware that some accounts, particularly those from government or immigration authorities, might be distorted.

7. Analysing historical earthquakes: determining parameters

The two most important parameters usually sought for cataloguing historical earthquakes are magnitude (or magnitude range) and location (with an estimate of its accuracy). Our ability to determine these parameters divides New Zealand's large historical earthquakes into two categories – pre-instrumental period earthquakes, for which there are little or no useful instrumental data, and early instrumental period earthquakes, for which sufficient teleseismic data are available to permit the calculation of surface wave magnitudes (M_s), moment magnitudes (M_w), mechanisms and depths (from 1917), for shallow and some intermediate depth earthquakes. As will be shown, data on early instrumental period earthquakes, as well as modern earthquakes, have been used to develop the tools for assessing the effects of future earthquakes, but they are also invaluable for analysing pre-instrumental period earthquakes.

However, the most important requirement for analysing a region's historical earthquakes is an extensive knowledge of its tectonics, geology and recent seismicity. To obtain the best understanding and interpretation of historical data, the skills and knowledge of seismologists, earthquake and landslide geologists, geodesists, earthquake engineers, and tsunami scientists often need to be brought together.

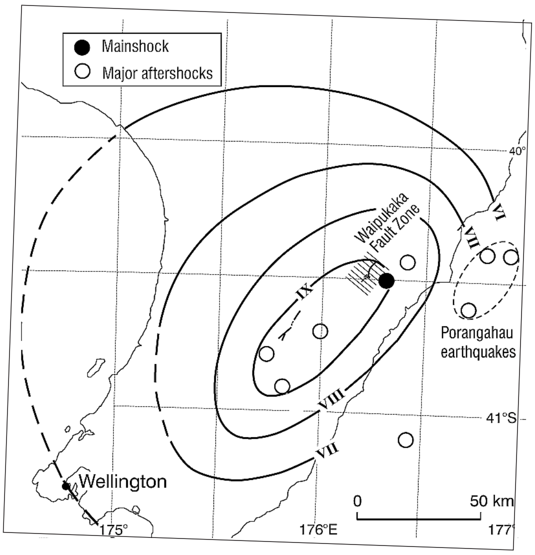
7.1. *Early Instrumental period earthquakes (1917-1942)*

Dowrick and Rhoades (1998) have determined M_s for all shallow earthquakes over magnitude 5.5 since 1900. Body wave modelling techniques have yielded source parameters (moment magnitudes, depths and mechanisms) for all $M > 6.0$ North Island, and $M \geq 6.3$ South Island, shallow and intermediate depth historical earthquakes that have occurred since 1917 (see Doser *et al.,* 1999, Doser and Webb, 2003). The tools developed from these recent studies make the task of locating and analysing historical earthquakes of the early instrumental period simpler.

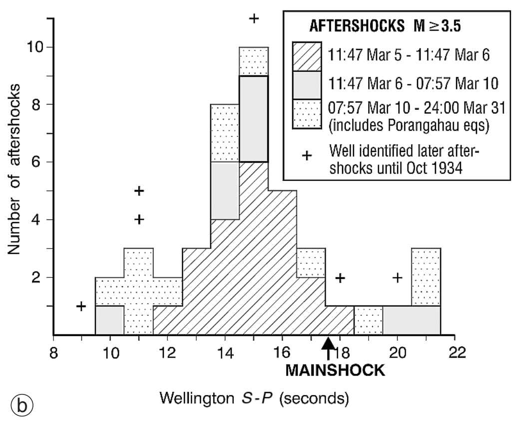
In the last ten years, all except one of the $M \geq 7.0$ shallow earthquakes from 1929-1942 have been studied in detail (Dowrick, 1994, 1998; Downes *et al.* 1999, 2001). These have resulted in well-constrained locations and isoseismal maps, as well as a wealth of data on the distribution of landslides and liquefaction, on microzone effects, on the vulnerability of lifelines (water, gas and sewage systems, road and rail, etc). In addition, much data have been found on the performance of various classes of structures, including reinforced concrete and retrofitted masonry buildings, some of which still exist today. All the studies involved the comprehensive collection and analysis of descriptive, scientific and engineering accounts of effects and damage from many sources. Several of the studies were multi-disciplinary or involved multidisciplinary collaboration and sharing of data (for example, Downes *et al.,* 1999; 2001, Schermer *et al.,* 2003). Of the two studies that involved mainshock and aftershock relocations using early local seismograph records, the study of the 1934 M_w 7.4 Pahiatua earthquake (Downes *et al.,* 1999) and its associated paleoseismological study (Schermer *et al.,* 2003) were particularly successful.

Prior to these studies, the location of the 1934 earthquake had an uncertainty of 100 km, the distribution of intensity of shaking data was sparse, and no surface fault rupture was known to be associated with the earthquake. Taking into account the shallow depth determined in preliminary (now published) source mechanism results of Doser and Webb (2003), Downes *et al.* (1999) found new instrumental locations for the mainshock and aftershocks, which correlated well with the newly determined well-constrained intensity distribution (fig. 6a,b). Further, the fortuitous location of a Wood Anderson seismograph almost along the apparent strike of the fault plane allowed an estimation of the approximate length of the fault plane using $M > 3.5$ aftershock *S-P* intervals. The *S-P* intervals also suggested the mainshock epicentre lay at one end of the fault, consistent with the intensity distribution.

Given the new location and the shallow depth of the earthquake, Schermer *et al.* (2003) investigated active faults in the area, including trenching several of the «freshest» looking fault scarps. The latter resulted in the identification of surface fault rupture in the Waipukaka Fault zone (fig. 6a,b), which had clearly occurred since European settlement of the area because of the presence of charcoal (the area was heavily forested until after 1874) and historical artefacts (glass objects and the sole of a shoe) em-



(a)



(b)

Fig 6a,b. a) Relationship of the instrumental locations of the 1934 M_w 7.4 Pahiatua earthquake and its aftershocks to the MM intensity isoseismal map and the Waipukaka Fault zone. b) The distribution of *S-P* intervals recorded on Wellington Wood Anderson seismograms. Note that the five earthquakes with *S-P* intervals of 19-21 seconds include the Porangahau earthquake sequence (M_L 5.0, M_L 4.6, M_L 5.6) five days after the mainshock, as well as the offshore M_L 5.2 earthquake just south of 41ºS within 26 h of the mainshock.

bedded in the rupture zone. The 1934 earthquake is the most likely earthquake to have caused that rupture.

Recent research in the early instrumental period has not been confined to the largest earthquakes, or to the shallow earthquakes. To provide the data to develop new attenuation of intensity models, Dowrick (see Dowrick and Rhoades, 1999) and Downes have developed new isoseismal maps for another 30 or so well-constrained pre-1943 smaller events as well as a number of large earthquakes in this period not yet the subject of in-depth studies. Previously, for these events, there had been either no isoseismal map, or the existing map had been based on a conversion of Rossi-Forel to MM intensities without sighting original reports. These data, together with data from the individual large earthquake studies, including some pre-1900 events (those which have a magnitude independent of intensity of shaking distribution, that is, from fault length or dislocation model), and data from modern era earthquakes were used to develop robust MM intensity attenuation relationships involving magnitude, focal depth, source mechanism, fault orientation, and regional characteristics parameters (Dowrick and Rhoades, 1999). It should be noted here that the sparseness of the population and hence sparseness of intensity points for New Zealand typically result in simply contoured elliptical isoseismal patterns.

Dowrick's isoseismal map revisions (see Dowrick and Rhoades, 1999) and the large earthquake studies have also made it possible to refine descriptors in the New Zealand version of the Modified Mercalli Intensity Scale (Dowrick, 1996). One problem encountered when applying the MM Scale to early historical earthquakes is the difficulty in determining high intensities in the near absence of masonry buildings in historical rural settings. In historical times, most domestic housing was of wood construction, with brick, reinforced or unreinforced, chimneys depending on the era.

The tools, as outlined above, provide the means to analyse pre-instrumental earthquakes, as well as smaller earthquakes not yet studied in the early instrumental period. Other useful tools are the relationships between size and extent of earthquake induced landsliding and other ground damage, and earthquake magnitude and location, MM intensity, topography and geology, developed by Hancox *et al.* (2002). These relationships were based on detailed study and mapping of landslides and other ground damage caused by 22 well-constrained historical earthquakes from 1848-1995, only two events being pre-1900. The relationships are useful for identifying the epicentral region of pre-instrumental earthquakes, most particularly in the absence of intensity data based on building or contents damage, which is the preferred and more reliable basis for assigning intensities. However, the refinement of ground damage descriptors in the MM scale, developed by Hancox *et al.* (2002) also, do help constrain the types and extent of damage observed within in each intensity level.

7.2. *Pre-Instrumental or very early instrumental earthquake period (pre-1917)*

Our ability to locate and determine reliable magnitude, epicentre and depth parameters for earthquakes in this period is clearly dependent on the variable data quantity and quality allowed by the distribution of the population, on whether a surface fault rupture was identified, and on whether the earthquake was shallow or deep.

The shallow (depth < 40 km) earthquakes are easier to locate, but still present some difficulties. The best location of a large pre-instrumental earthquake that can be hoped for is the identification of the fault on which it occurred, or which was ruptured to the surface. However, not all $M \geq 7$ shallow earthquakes rupture to the surface, at least in parts of New Zealand. Although four shallow (upper plate) strike-slip $M_w \geq 7.0$ earthquakes occurred (onshore) in the North Island between 1931 and 1942, only two are known to be associated with surface rupture (Doser and Webb, 2003). In one of these, the 1931 M_w 7.8 Hawke's Bay earthquake (~ 30 km deep), a surface rupture of only 15 km was observed, although surface deformation occurred in a region 90 km long and 17 km wide (Hull, 1990).

Even in the ideal circumstance of a surface rupture being identified for an earthquake, defining a single parameter as the

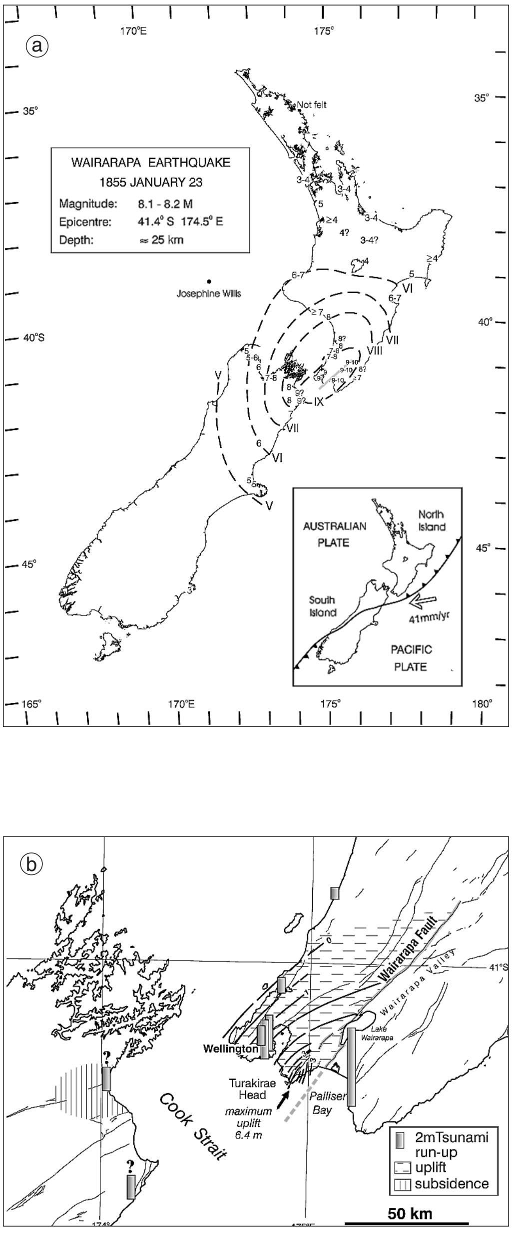


Fig. 7a,b. a) Location and isoseismal map of the 1855 *M* 8+ Wairarapa earthquake, showing b) the location of the Wairarapa Fault, regional deformation, the location of maximum uplift, and tsunami run-up.

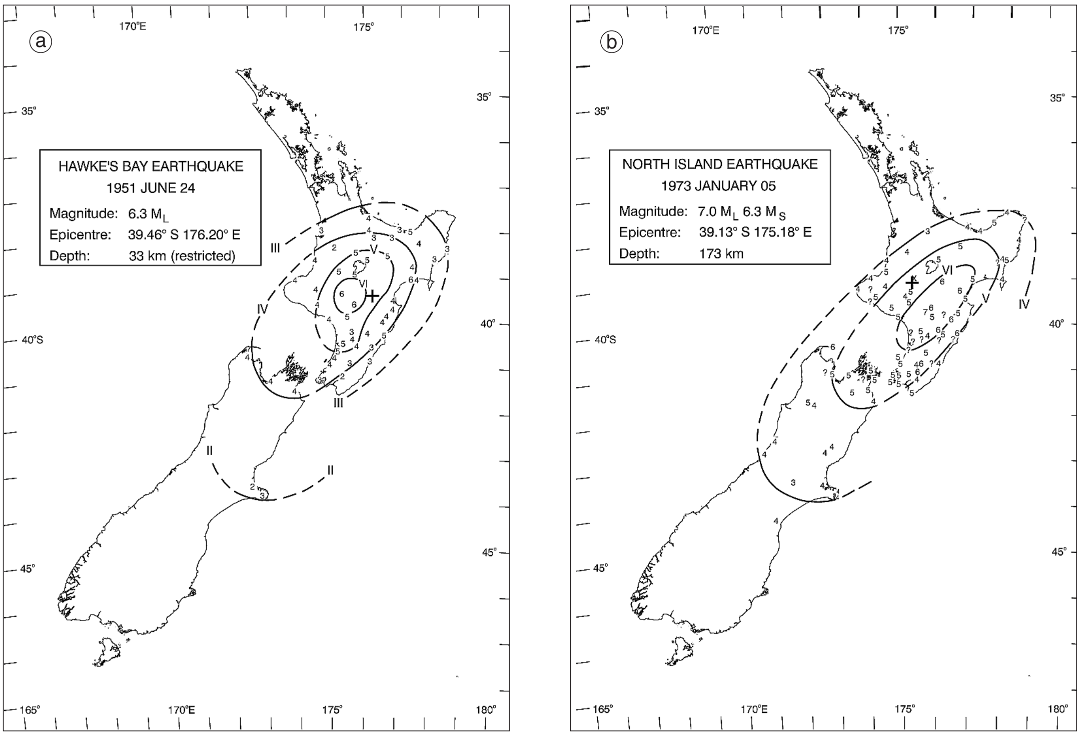


Fig. 8a,b. Similarity of the isoseismal maps of the 24 June 1951 M_L 6.3 33 km deep Hawke's Bay earthquake (a) and the 5 January 1973 M_L 7.3 ~ 170 km deep North Island earthquake (b) illustrates that, in the case of sparser intensity data points than shown here, differentiating between moderate magnitude shallow and large magnitude deep historical earthquakes may be difficult.

earthquake's location in a parametric catalogue can be a problem. For example, the 1855 *M* 8+ Wairarapa earthquake (see fig. 7a,b) ruptured about 100 km of the onshore part of the Wairarapa Fault with a possible 30 km more off shore (Grapes and Wellman, 1988; Grapes and Downes, 1997). The best fit dislocation modelling of the recorded deformation in this event suggests that the Wairarapa Fault could curve down towards the west to meet the plate interface some 20 km or so west of the surface expression of the fault at a depth of 25 km (Darby and Beanland, 1992; Grapes and Downes, 1997). Historical descriptive accounts suggest that the earthquake initiated closer to one end than the other (Grapes and Downes, 1997), but whether, for catalogue purposes, it is reasonable to use this information or to merely identify the generic centre of the fault as the earthquake's epicentre is a question that still needs to be addressed.

In the absence of a surface fault rupture, unequivocally identifying whether an earthquake is shallow or deep is not without problems. Firstly, large earthquakes deep in the subducting slab (> 70 km) can produce isoseismal patterns that resemble moderate magnitude shallow regional earthquakes (fig. 8a,b). This problem will arise mostly when the intensity data are sparse, and the descriptive accounts are too imprecise to identify an *S-P* interval or aftershocks.

A second problem arises because the presence or absence of aftershocks is not always a clear indicator of shallowness. The occurrence of a large number of aftershocks most often indicates a shallow crustal shock, or an event in the upper seismicity band of a double-banded Benioff zone, and the paucity or absence of aftershocks usually indicates a much deeper event or one in the lower seismicity band of a double-banded Benioff zone (Robinson, 1994). Pacific Rim plate interface earthquakes can be aftershock-rich, or aftershock deficient (Singh and Suárez, 1988). Aftershock deficient subduction interface earthquakes have been shown to characterise several subduction zones or parts of subduction zones around the world (Singh and Suárez, 1988) and it is possible that the Hikurangi margin includes one of these zones. For example, the mechanism of the aftershock deficient 1993 M_L 5.9 Tikokino earthquake at a depth of 25 km (see fig. 2a,b) has been shown to be consistent with the earthquake rupturing the plate interface (Reyners *et al.,* 1997). Although the data are too poor to constrain their depths, two other low aftershock producing events have occurred within 50 km, the 1958 M_L 6.1 Ashley Clinton earthquake (restricted to a depth of 33 km) (see Downes, 1995), and the 1904 M_S 6.9 M 7+ Cape Turnagain earthquake (Downes, in prep.) (locations shown in fig. 2a,b). The problems locating the 1904 earthquake exemplify the problems of unequivocally defining depths for historical earthquakes.

For the reason that early earthquakes are vulnerable to revision with new data, all reports of felt earthquakes in the pre-instrumental period will be summarised in a descriptive catalogue, similar to that produced by Eiby (1968, 1973). Transcription and key-wording of source material has been completed for some of the larger earthquakes and is under way for the pre-1900 catalogue, to facilitate future revision and to maximise the usefulness of the catalogue for researchers in many fields.

8. Catalogue parameterisation

The format and extent of the data in the historical earthquake part of the present National Earthquake Information Database are summarised in table II. There are some inadequacies in this database, and an expansion of it is in the planning stages. The fields under consideration for inclusion in this database are indicated in the second part of table II.

One of the inadequacies of the present database is that none of the felt intensity data on pre-1943 earthquakes has been included in the electronic part of the catalogue, that is, the data exist only in written form on paper. Another serious inadequacy is that, although epicentres of historical earthquakes were assigned or determined in a uniform and consistent manner when the electronic database was set up in the late 1980s, epicentres have been assigned recently in a variety of ways, which are not always readily apparent in the method of determination parameters. A more serious flaw in the database is that it allows only one entry for some fields where multiple entries might be more appropriate, and some parameters, such as source mechanism, are not included at all. Another problem that needs further consideration is that of epicentres of large historical earthquakes generally not being comparable to instrumentally determined epicentres – possibly resolvable by including parameters in the database that better describe source location and rupture area. In developing the new database, such inadequacies and problems will need to be addressed.

The database, for both modern and historical earthquakes, should be able to adequately represent all available reliably determined earthquake location, source, magnitude and effects parameters (and their method of determination, reliability parameters, etc.). It should also attempt to satisfy those users who require uniformly determined epicentral or source parameters (for example, for statistical analysis of earthquake occurrence in time and space), as well as those who require the most accurate location, source and rupture propagation parameters derived from special studies, and those who require detailed information on earthquake effects. Hence, multiple entries in some fields, as well as new fields, are required, as well as a database interrogation interface that allows researchers to choose the set of parameters most appropriate to their research.

9. 1855 January 23 *M* 8+ Wairarapa earthquake

The 1855 January 23 *M* 8+ Wairarapa earthquake is New Zealand's largest earthquake since organised European settlement in 1840. This earthquake, and to a lesser extent, the 1848 *M* 7.5 Marlborough earthquake, had a significant social and economic effect on the future nation and building style of New Zealand (Grapes and Downes, 1997). As far as its effects on the environment, the earthquake ruptured to the surface along the Wairarapa Fault, with what is recognised today as 9-14 m of dextral motion and up to 3 m vertical motion at the fault (Grapes and Wellman, 1988; Grapes and Downes, 1997) (fig. 7a,b). Regional uplift occurred west of the fault, with up to 3 m uplift along the south coast of the North island coast recorded at the time by surveyors and others, based on changes in the levels reached by the tides along the coast (Grapes and Downes, 1997). A local maximum has been shown to have occurred near Turakirae Head, geologically (McSaveney and Hull, 1995; McSaveney and Downes, 2003), and historically, in an 1868 property survey map that delineates the pre-uplift high tide mark (see Grapes and Downes, 1997). The earthquake caused damage to the built and natural environment over a very wide area, with up to 9 deaths. A significant tsunami swept through the Cook Strait Region reaching a maximum recorded height of 9-10 m above sea level at the time, and up to 5 m in locations now occupied by the suburbs of Wellington City.

Although this earthquake has been well known as the New Zealand's largest earthquake and its effects generally recognised for some time (for example, see Eiby, 1989), the mammoth task of compiling and analysing all the historical data, started independently by seismologist, G. Eiby, and geologist, R. Grapes, was continued and expanded in a collaborative project by Grapes, and Downes (a seismologist) after Eiby's death, and only completed in 1997 with a comprehensive analysis of the earthquake and its effects (Grapes and Downes, 1997). Before his death, Eiby published a paper showing that a tradition of significant uplift in a small part of the Wellington region was not supported by geological evidence (Eiby, 1990), exemplifying the problems historical earthquake analysts have in identifying fact and fiction. In the case of the 1855 earthquake, reminiscences in particular frequently confuse the effects with those of the previous large earthquake near Wellington in 1848.

The analysis of the 1855 earthquake by Grapes and Downes (1997) is an illustration of the techniques in analysing historical earthquakes in New Zealand used in the last few years, following the example set by Eiby with his pioneering comprehensive analysis of the 1848 Marlborough earthquake (Eiby, 1980). Using over 200 historical documents as the primary data source for their analysis, but also taking into account the results of more recent geological, geomorphological and seismological investigations of the deformation, Grapes and Downes (1997) discuss most aspects of the earthquake including:

– Mainshock magnitude and epicentre, using attenuation models, dislocation models of the earthquake (Darby and Beanland, 1992), and structural and tectonic models developed from seismicity beneath Wellington (Robinson, 1989) to constrain the magnitude and likely fault plane.

– Felt intensity distribution.

– Descriptive account of the effects of the mainshock on people (including casualties) and man-made structures by location throughout New Zealand. A résumé of contemporary building techniques is included.

– Effects on the environment from strong shaking such as fissuring, liquefaction, sand boils, lateral spreading, settlement and landslides.

– Effects on the environment from tectonically produced uplift and faulting, including biological (death of seashore animal and plant life) and atmospheric effects: tsunami and seiche; aftershock occurrence; social response and recovery.

Historical documents included contemporary personal diaries, letters and journals, newspaper reports and articles, memoranda and reports of the Wellington Provincial Government as well as later reminiscences, extracts from published scientific papers, maps and surveys, sketches and art works, books and other articles.

Table III. Reliability, events and effects keywords used the compilation of transcriptions of source material for the 1855 *M* 8+ Wairarapa earthquake.

Reliability	Event	Effects
Primary	Mainshock	Artesian well effects
Primary/reminiscence	Aftershocks	Artworks/maps/charts
Secondary	Background information	Atmospheric effects
		Biological effects
		Building damage
		Casualty/injury
		Faulting
		Ground damage
		Response/recovery
		Tsunami/seiche
		Uplift/subsidence
		Volcanic effects

Notes: Primary = contemporary eyewitness account; Primary/reminiscence = eyewitness reminiscences; Secondary = second or third hand account; Artworks = sketches and paintings portraying earthquake effects; Background = relevant background information, mainly relating to uplift/subsidence, building construction techniques, or social conditions. Other keywords are self-explanatory.

Although most of the papers were found in New Zealand archives, several were sourced from Britain, sometimes through intermediaries. For example, the published accounts of the British geologist, Sir Charles Lyell, who, in 1856, first recognised the importance of the earthquake as causing the greatest deformation and fault rupture then known, are of prime importance as are his private letters (Lyell, 1856c), and note books (Lyell, 1856d), which were transcribed from the originals and supplied to the authors by Leonard G. Wilson (U.S.A.).

Much of the data is presented in Grapes and Downes' (1997) paper with extensive quotations from the source material, especially where conflicting accounts on important aspects have been found. All material is analysed with an understanding of geographical, social and political conditions at the time. The reliability of the material is taken account of so that first-hand accounts, that is, those which were recorded no more than several years after the earthquake, and in which there are no obvious inconsistencies or confusion with other earthquakes, are valued most highly.

In addition, Downes and Grapes (1999) have transcribed, key-worded, referenced, cross-referenced, and annotated the source material (over 250 pages), in such a way that it can readily be made into a searchable computer database in the near future, so that extracts relating to any particular aspect or effect of the earthquake and/or from any particular location can be recovered simply and quickly. Reliability, events and effects keywords (location keywords are not listed) are given in table III. Many of the extracts are annotated to provide some insight about the author, the reliability of the account, or about important details contained within the extract. Compilation of the source material in such a manner provides the means for further detailed studies or reinterpretation, as new evidence – historical, seismological, geotechnical, geomorphological or geological – becomes available.

9.1. *The 1855 earthquake, Sir Charles Lyell and global understanding*

The private and published papers of the eminent 19th century British geologist, Sir Charles Lyell, are the only contemporaneous scientific accounts and evaluations of the 1855 earthquake's effects on the landscape (for example, Lyell, 1856a–d; 1868). As such, they provide data crucial to understanding of the faulting and regional deformation that accompanied the 1855 M 8+ Wairarapa earthquake. The 1855 earthquake was also of great importance for Lyell (Downes and Grapes, 1997), as it provided him with invaluable evidence to support his Uniformitarian theories.

In 1856, Sir Charles Lyell gave two papers on the geological effects of the 1855 New Zealand earthquake, one to the Royal Institution in London and the other, to the Geological Society of France. Lyell's evidence was no doubt gathered from reports extracted from New Zealand newspapers, the New Zealand journal, the Reverend Richard Taylor's book, Te Ika a Maui (Taylor, 1855), all transcribed in Downes and Grapes (1999), but his understanding of the geological effects of the earthquake were principally derived from interviews with three New Zealand eyewitnesses. He met the three men in London on number of occasions in early 1856, as well as maintaining a correspondence. One of the eyewitnesses was the son of the distinguished geologist, Gideon Mantell, Lyell's friend and colleague. Another was a Royal Engineer who was, at the time of the earthquake, working on a coastal road in the area of maximum uplift. The third eyewitness was a land owner in the South Island, whose interests included geology.

Lyell recognised the 1855 earthquake as «yielding to no other in magnitude of its geological and geographical importance» (Lyell, 1856a). In a lecture, given by a colleague on his behalf to the Geological Society of France, Lyell refers to «the formation of a great fault and of an upheaval which is greater in vertical height and horizontal extent than all dislocations of this kind that I [*i.e.* Lyell] am aware of to date» (Lyell, 1856b [translated from French by G. Lamarche (NZ)]). Lyell also included data on the 1855 earthquake in vol. 2 of his *«Principles of Geology»*, stating that «the geologist has rarely enjoyed so good an opportunity... of observing [in the effects of the 1855 New Zealand earthquake] one of the steps by which those great displacements of the rocks called «faults» may in the course of ages be brought about. The manner also in which the upward movement increased from north-west to south-east explains the manner in which beds may be made to dip more and more in the given direction by each successive shock» (Lyell, 1868).

For Lyell, the connection between large earthquakes and sudden uplift, tilting and faulting on a regional scale was indisputably demonstrated, as was the principle that geological features of the landscape could be explained as the sum of sudden incremental changes rather than by cataclysmic events. These results were expounded in his books, which were well read by geological students around the world. Through these, the 1855 New Zealand earthquake was influential in advancing global understanding of earthquakes, faulting, regional deformation and the geological record.

10. Conclusions

In this paper, the principles and procedures used by the author and others in analysing New Zealand's historical earthquakes have been outlined. It will have been noted that the work of identifying and analysing events is not complete, but is actively being done so that researchers in seismic and other geological hazard events have the best possible data on which to base their assessments of hazard and risk.

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