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Modern Reappraisal of Historical Seismicity for Seismic Hazard Assessment in Australia

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Abstract

A robust record of earthquake activity in any given region is vital to identify regions of elevated seismogenic potential, define seismogenic sources and to help forecast future rates of seismicity. Records of earthquakes predating instrumentation and those occurring while instrumentation was still in its infancy might be used to augment the relatively short duration of the instrumental era in Australia. The events occurring during these seismological eras are often termed "historical earthquakes", and their study forms a valuable input for seismic hazard assessment. However, as with any scientific data, documentary evidence extracted from newspapers and other written materials is subject to uncertainties, incompleteness, and errors being repeated from a lack of a thorough modern re-examination of the available data. With application to seismic hazard in Australia, we revisit original sources to re-evaluate selected historical earthquakes such as the 1918 Queensland (QLD) and the 1954 Adelaide (SA) earthquakes. We discuss biases that impact the analyses of these and other historical earthquakes in Australia. Our study highlights the benefit of the critical evaluation of primary source materials to homogenise both archival and seismological materials, with modern observations, to improve our understanding of historical earthquakes in Australia. This will in turn will benefit future assessments of modern seismic hazard.

Keywords: 1918 Queensland earthquake, 1954 Adelaide earthquake, macroseismic intensity, historical earthquakes.

1 Introduction

An essential component to any seismic hazard assessment is a detailed record of earthquake activity that is as complete and as continuous as possible, in both space and time, with which to reliably estimate both the distribution and the rates of seismicity. Relative to the short duration of seismological instrumentation, studies of seismic hazard often incorporate information on earthquakes that occurred prior to the instrumental era, i.e., historical earthquakes. In the Australian context, this applies to seismicity occurring before, and during the early years of instrumentation that pre-date the 1960s (*Doyle and Underwood*, 1965). Numerous authors have attempted to describe individual historical earthquakes in Australia (e.g., *Hedley*, 1925; *Bryan and Whitehouse*, 1938; *Kerr-Grant*, 1956), to chronologically document historical seismicity on state-wide level (e.g., *Shortt*, 1884, *Todd et al.*, 1904, *Malpas*, 1991; *Rubenbach et al.*, 2020) and to compile national isoseismal atlases (e.g., *Everingham et al.*, 1982; *Rynn et al.*, 1987). The latter have served a crucial purpose with which to derive empirical macroseismic intensity attenuation relationships which can then be employed to estimate magnitudes for historical earthquakes (e.g., *McCue*, 1980). Compilations of historical and early instrumental earthquakes derived from these published works have been incorporated in many (e.g., *McCue*, 1975; *Drake*, 1976; *Rynn*, 1987; *Gaull et al.*, 1990) but not all (e.g., *McEwin et al.*, 1976) of the earliest seismic hazard assessments for Australia. The latest version of the NSHA (*Allen et al.*, 2023) and its predecessor (*Allen et al.*, 2020) also incorporates historical earthquake activity, as catalogued and documented in *Allen et al.* (2018).

To seamlessly incorporate historical earthquakes into modern seismic hazard studies with modern seismicity, epicentral parameters and magnitudes need to be uniformly estimated. Most large earthquakes in Australia since the late 1800s are well catalogued but the actual observations from individual locations used to assess macroseismic intensity and to develop isoseismal maps is very poorly documented. Uniformity is also lacking in terms of the intensity scales used. For example, some early 20th century studies used the Rossi-Forel Scale (e.g., *Hedley*, 1925) while more contemporary work tends to use the Modified Mercalli Scale (e.g., *Kerr-Grant*, 1956); these scales are not comparable. This is further compounded by the different interpretation of the diagnostics of a given intensity scale by different individuals. The apparent rate at which shaking intensity dissipates with distance also relies on various factors such as local site conditions, rupture directivity, and population density. These factors can undermine the use of isoseismal radii to compute magnitudes. The contouring of intensity data is also a process fraught with uncertainty, sometimes resulting in very irregular isoseismals (e.g., *Cotton*, 1921).

2 Revised Historical Macroseismic Data

We addressed the aforementioned shortcomings by collating over 4,000 macroseismic intensity data points (IDPs; **Figure 1**) for historical earthquakes in Australia prior to 1950. In subsequent sections, we first discuss our approach to produce this robust and uniform dataset for Australia. We then draw attention to two significant historical events – the 1918 Queensland and the 1954 Adelaide earthquakes – to illustrate the benefits of this exercise.

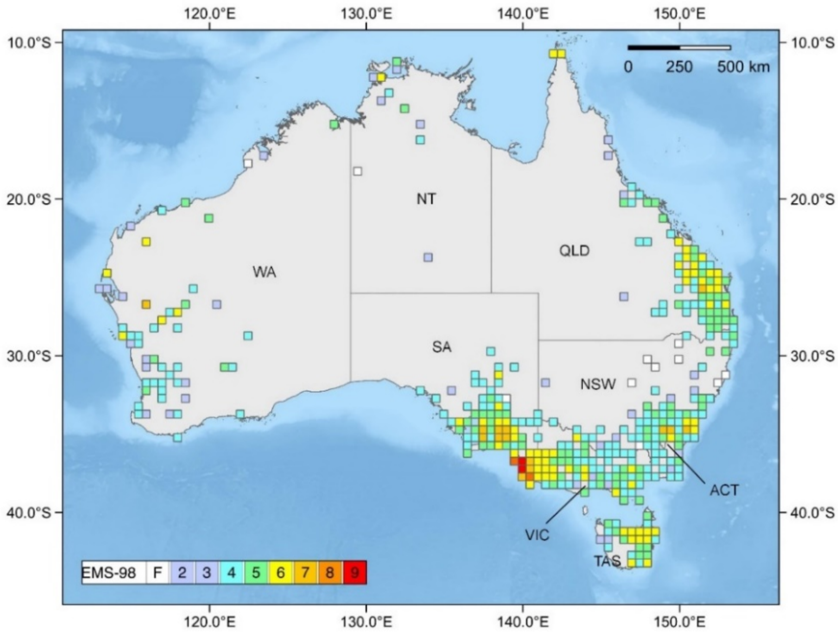

Figure 1. Gridded EMS-98 IDPs (1-degree cells) for pre-1950 earthquakes in Australia

Our data include large events for which published isoseismals exists (*Everingham et al.*, 1982; *Rynn et al.*, 1987; *McCue et al.*, 1995). These data also include intensity assignments for many of the hundreds of earthquakes felt in Victoria and Tasmania during an earthquake swarm in the late 19th century in the western Tasman Sea. We have been able to significantly increase the number of observations for some of the largest earthquakes such as the Beachport (South Australia) earthquake in 1897 (**Figure 2**). Our dataset also includes earthquakes in eastern Indonesia from *Martin et al.* (2022a) that were felt in northern Australia.

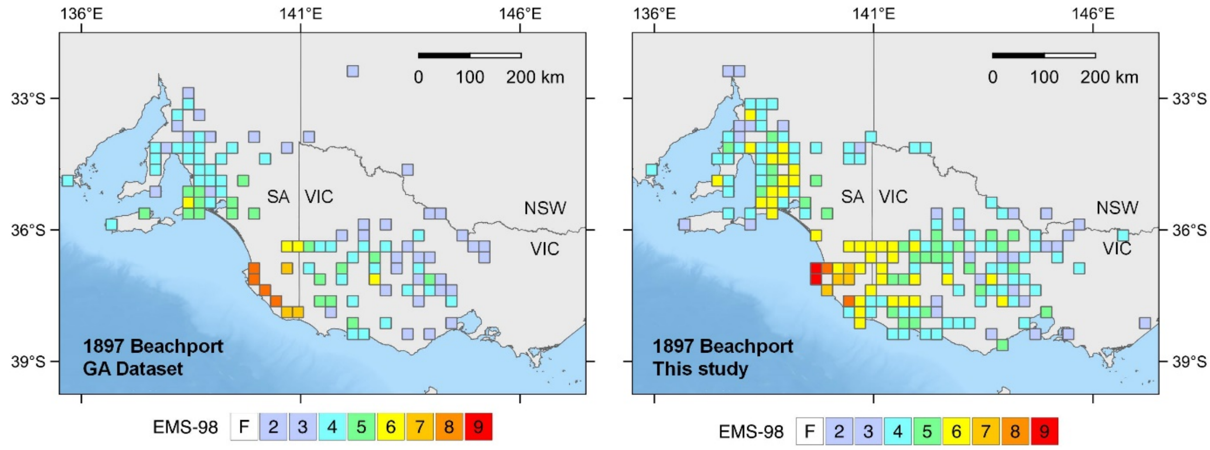

Figure 2. Gridded EMS-98 IDPs (0.25-degree cells) for the 1897 Beachport, South Australia earthquake from the GA Data (left) in comparison to those from this study (right).

The primary sources of archival information that we considered when constructing this dataset were local and regional newspapers. These were either consulted digitally via the Trove Newspaper Archive or in person at the National Library of Australia or other State Libraries. We supplemented these materials with additional newspaper reports from New South Wales, Queensland and Victoria accumulated by the late John ("Jack") Rynn from the Department of Geology at the University of Queensland in the early 1980's (*henceforth UQ collection*) preserved at Geoscience Australia (GA) and at the University of Queensland. Another useful repository of materials were the compilations for South Australia by *Malpas* (1991). On a handful of occasions, we also consulted reports written after significant earthquakes that discussed damage and other effects (e.g., *Hedley*, 1925; *Bryan and Whitehouse*, 1938; *Kerr-Grant*, 1956).

In a marked shift from the past, we have utilised the European Macroseismic Scale (EMS-98; *Grünthal et al.*, 1998) to assign intensity instead of the Modified Mercalli Intensity scale (MMI; *Wood & Neumann*, 1931; *Richter*, 1958). Both the MMI and the EMS-98 scales are successors of older intensity scales such as the Mercalli-Cancani-Sieberg scales (MCS; *Sieberg*, 1912) developed with European conditions in mind. The EMS-98 stands apart in its revised form (*Grünthal*, 1998) in that it stipulates non-region-specific definitions and recommended guidelines with which to assess intensity. We find that this leads to more robust intensity assignments at higher levels of shaking (≥ 6 EMS) especially where data on indigenous, traditional, and non-European building typology are meagre or missing, and when modern fragility curves are unavailable. This is pertinent because of the vulnerability of different construction types to seismic loads. For example, a single-storied masonry Federation-era building would be more likely to sustain damage than a more flexible, single-storied, wood-framed Queenslander type building when subjected to the same level of seismic shaking. The failure to account for these differences in building types can lead to biases in the observed macroseismic field.

At non-damaging levels of shaking (< 5 EMS) we considered diagnostic indicators, that is, definitions or guidelines for each level of intensity (*Grünthal*, 1998) with adjective and adverb modifiers such as “not heavy” or “heavy”, “moderate”, or “very”. To distinguish between “few” (≤ 5%), “many” (up to 50%), and “most” (up to and greater than 75%) we used percentage counts from *Medvedev et al.* (1965). Adverb distinctions such as “few”, “many”, and “most” are necessary in keeping with the statistical nature of EMS-98 (*Grünthal*, 1998; *Tertulliani et al.*, 2016), but we reiterate *Martin and Hough’s* (2016) observation that both modern and historical documentary sources can often be devoid of these.

We did not assess secondary effects such as ground failure, liquefaction, and landslides but we note that future assessment needs to formally quantify a way to incorporate these observations. We also do not include intensity values from published isoseismal maps or other previous studies in our database as recommended by *Ambraseys et al.* (1983). Following another recommendation by *Ambraseys et al.* (1983), intensities were also not converted between intensity scales although we remain cognisant of the congruence between MMI and EMS-98 (*Musson et al.*, 2010).

3 Location! Location! Location…?

The new data at hand has had some unexpected outcomes. In a previous study, *Martin et al.* (2022b) discussed new observations (**Figure 3**) from the 1954 Adelaide, South Australia earthquake. These new observations permit a change in the classical interpretation of the location of the 1954 earthquake by considering reports of damage in the Adelaide Hills (**Figure 3b**), and numerous observations of disturbances to the water table in the region of Mount Barker, that were previously overshadowed by damage in the City of Adelaide itself. These new pieces of evidence led *Martin et al.* (2022b) to suggest that a more appropriate location for the 1954 earthquake epicentre was, in fact, in the Adelaide Hills. We inverted our intensity observations for magnitude and location using the Bayesian method developed by *Griffin et al.* (2019), supported by a newly developed intensity prediction equation for Australia (unpublished) calibrated to moment magnitude by the second author based on Australian macroseismic intensities. This new location (see **Figure 3** in *Martin et al.*, 2022b) is further to the east of its conventionally accepted location as a shallow event on the Eden-Burnside Fault zone in the suburbs of Darlington and Seacombe (e.g., *Kerr-Grant*, 1956).

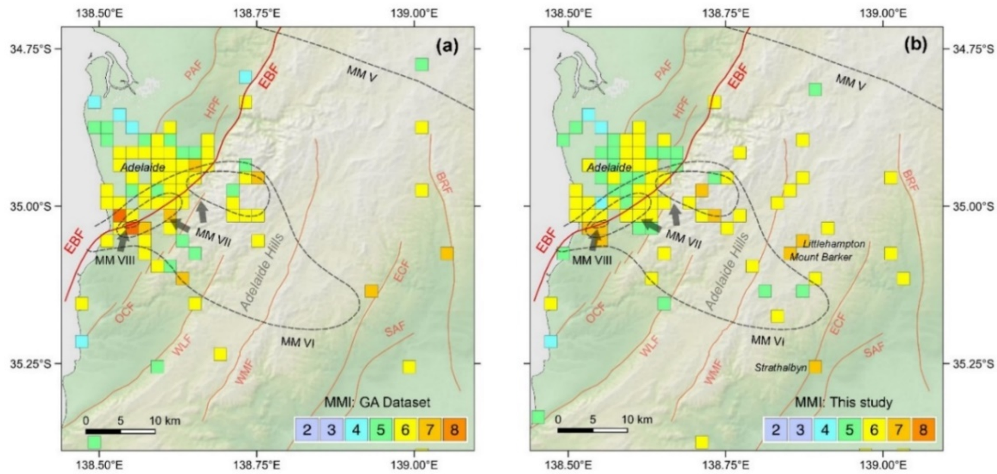

Figure 3. MMI intensities from the GA dataset (left) and Martin et al. (2022b; right) are shown as gridded squares. Dashed lines show intensity contours from Kerr-Grant (1956) that are displayed as a reference. Red line shows active faults (BRF = Bremer Fault; EBF = Eden-Burnside; ECF = Encounter Bay Fault; HPF = Hope Fault; PAF = Para Fault; SAF = Sanford Fault; WLF = Willunga Fault; WMF = Williamstown-Meadows Fault. Figure from Martin et al. (2022b).

Surprisingly the 1954 Adelaide earthquake is not alone in terms of a previously poorly constrained epicentral location. Our investigations have unearthed new evidence with which to modify the epicentral location of the 1918 Queensland earthquake. This event, and its relocation, has been described in detail by *Martin et al.* (2023) and we summarise those findings here. This earthquake is the largest earthquake in eastern Australia (*at the time of writing*) in at least the past ~150 years. It was extensively felt in eastern Queensland and in parts of northern New South Wales. We collected reports from 225 individual locations for this event (**Figure 4**). Almost all previous studies (e.g., *Hedley*, 1925; *Burke-Gaffney*, 1951; *Gutenberg and Richter*, 1954) repeat the offshore epicentral location (-24° S, 154° E) proposed by the Riverview Observatory in 1918. The currently accepted location (-23.50° S, 152.50° E) for the 1918 event in the GA hazard catalogue (*Allen et al.*, 2018) is from *Everingham et al.* (1987). As with the 1954 Adelaide earthquake, attention was largely focused on the minor damage sustained by masonry structures in coastal towns such as Gladstone and Rockhampton. These damage observations were used to support an offshore source.

However, we have found new evidence that points to severe shaking at inland locations to the south-west of Gladstone. The strongest evidence comes from the owner of a cattle station at Camboon who described severe shaking; in his words "*I could scarcely keep my feet, the place was rocking so*". Minor damage was reported from a few inland locations such as Banana (*Hedley*, 1925) but owing to the low-rise, wood-frame, Queenslander-type buildings that made up the building stock in these remote areas no major damage is reported. Not only did we document these effects, but we also documented a long sequence of felt aftershocks that lasted as long as a year at Camboon (*Bell*, 1931). Two large aftershocks have been identified previously (*Rynn et al.*, 1987) that were felt in the Bundaberg-Gladstone region within hours of the mainshock. However, none of the subsequent shocks were perceived anywhere else except in the region of Camboon. Neither this zone of aftershocks, nor the region of strongest shaking is consistent with an offshore epicentre leading us to suspect an onshore source.

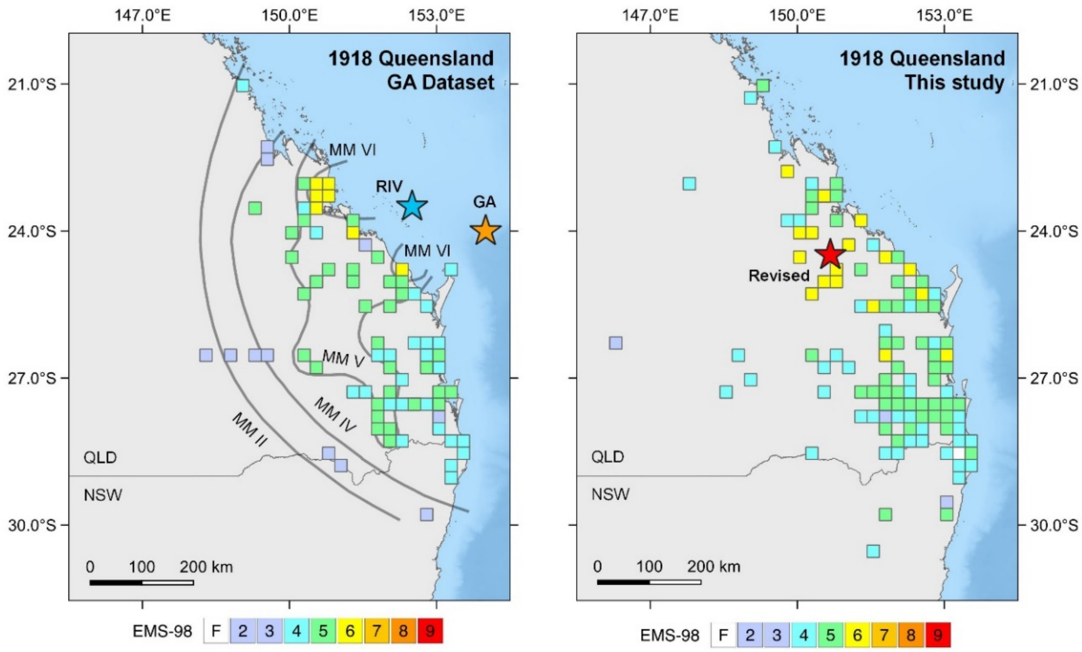

Figure 4. The isoseismal contours prepared by Jack Rynn and published in Everingham et al. (1982) are shown on the left. Stars indicate all epicentral estimates: Riverview (RIV; blue star), Everingham et al. (1987, GA; orange star) and revised location from Martin et al. (2023; red star). Gridded EMS-98 IDPs (0.25-degree cells) from the GA dataset and the Martin et al. (2023) study are also displayed.

Unfortunately, as with the 1954 Adelaide earthquake (*Bolt*, 1955-56), instrumental observations are few. The best instrumental evidence for the 1918 earthquake comes from the Riverview observatory in Sydney where the shock was recorded by two seismographs – a Wiechert and a Mainka. The arrival times were picked by observatory staff, and these were subsequently published in the Riverview Seismological Station bulletin. Using the ak135 velocity model (*Kennett et al.*, 1995), the S-P arrival times derived from this publication have supported an offshore source, at a distance of ~10.5^{o} from Sydney. But over the course of our investigations, we found written correspondence in the UQ Collection between Walter Bryan, a renowned Queensland geologist, who, just as the authors of this study, questioned this offshore source. In communication that ensued between him and the Riverview Observatory, it became clear that the arrival picks could be erroneous. We double-checked these picks by consulting the original seismograms for the event preserved at GA repicking the arrivals which now yielded much shorter S-P times. These now correspond to a distance of ~9.1^{o} which corresponds with the distance from Sydney to both the region of high intensities, and the area with documented aftershocks.

4 Conclusion

We have catalogued over 4,000 macroseismic observations for historical earthquakes in Australia. Our dataset is the first attempt at putting together a uniformly assessed, location-based collection of macroseismic data points, and in this manner, it differs from previous work (e.g., *Everingham et al.*, 1982; *Rynn et al.*, 1987; *McCue et al.*, 1995) which focused on re-drawing isoseismal maps or preparing atlases of published isoseismal maps. Our work is an ongoing exercise and once completed it will be a handy reference for the actual observations utilised to construct intensity or isoseismal maps. Thus, it will be beneficial for future scholarship on historical earthquakes in Australia.

It is worthwhile underscoring that the historical record can be influenced by geopolitics and socioeconomics (*Ambraseys et al.*, 1983; *Hough & Martin*, 2021). In the Australian context, we anticipate there will be gaps in the documentary record owing to the Australian Frontier Wars in the 18th to the early 20th centuries (see *Grey*, 1990). The displacement and loss of Indigenous communities during these conflicts will have resulted in the loss of oral traditional histories. Likewise, any written documentary evidence by squatter and settler outposts would also be lost during skirmishes and the destruction of property during these frontier conflicts. It is also important to bear in mind that surviving documentary source materials available in Australia since the late 18th century tend to be predominantly in English. This inference can be drawn from the largely British-driven populating of Australia from its early days as a penal colony. Therefore, it is highly likely, that as with other colonized regions such as Indonesia (*Martin et al.*, 2022a), documentary evidence on historical earthquakes in Australia will tend to closely track the geospatial political and economic footprint of colonization. This in turn could be interpreted to imply that the current historical earthquake narrative fails to account for the experiences of Indigenous Australians whose habitation of Australia predates colonization, and the experiences of Asian, Pacific Islander and non-English speaking European immigrant communities, who arrived at various times in the 18th and mid-20th centuries (*Price*, 1987).

The unexpected results of our re-evaluation of the 1918 Queensland (*Martin et al.*, 2023) and the 1954 Adelaide earthquakes (*Martin et al.*, 2022b) underscores the importance of reviewing older, historical earthquakes and relying on original materials as much as is feasible. In light of these findings, we reiterate the conclusion arrived upon by *Martin et al.* (2022b), that the known unknown (*Rumsfeld*, 2011) is that the 1918 and 1954 earthquakes might not be the only outliers in the known record of historical and early instrumental earthquakes in Australia. Given that there are such grave inconsistencies between the evidence at hand, in terms of their catalogued magnitudes, locations and/or associated tectonic features, for two of the largest earthquakes in Australia, it is more than probable there are other events out there too with similar inconsistencies.

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