Reviewing the 1 March 1954 Adelaide Earthquake, South Australia

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Abstract

The 1 March 1954 earthquake in South Australia is the most damaging earthquake to impact the densely populated Adelaide region since European settlement in the state. Previous interpretations of macroseismic data have associated the event with the Eden-Burnside Fault zone, with a presumed epicentre near Darlington. We assessed the validity of this observation by reviewing available macroseismic and instrumental data. We find that damaging shaking extended east from Adelaide into the Adelaide Hills, but without a well-defined locus of high intensities. These new findings question the conventionally assumed location for the 1954 Adelaide earthquake. Comparing macroseismic intensities from the 1954 earthquake with similar modern macroseismic datasets also suggests the 1954 event was perhaps larger than previously thought. Our work highlights the potential seismic hazards faced by large urban centres in Australia such as Adelaide.

Keywords: Adelaide, early instrumental earthquake, macroseismic intensity, 1954.

1 Introduction

The 1 March 1954 earthquake that struck the Adelaide region in South Australia at ~03:39 AM local time (~18:09 GMT, 28 February) is the costliest (e.g., *Sinadinovski et al.,* 2006) and the most damaging earthquake in Adelaide since European settlement in South Australia in 1836. Shaking effects from the event were widely reported in the local and national press, and a preliminary isoseismal map appeared in the local press within four days (*The News*, 5 March 1954). Based upon these press reports, a first-hand survey of the damage in southern Adelaide, and using information drawn from post-earthquake postal questionnaires from within and outside Adelaide that were sent to the Department of Mines in South Australia, *Kerr-Grant* (1956) drew the Modified Mercalli Intensity (MMI) isoseismals shown in **Figures 1** and **2**.

A later study by *Malpas* (1991) redrew the isoseismals within the Adelaide metropolitan region following a thorough compilation of press reports from South Australian newspapers and the same archived postal questionnaires. The isoseismals by *Kerr-Grant* (1956) are often reproduced in reference to this event (e.g., *Everingham et al.*, 1982). The highest intensities assigned by *Kerr-Grant* (1956) are in close proximity to the surface trace of the Eden-Burnside Fault, which runs along the eastern boundary of the Adelaide metropolitan area. This led *Kerr-Grant* (1956, p.177) to suggest that the earthquake was "*on or very close to the Eden-Burnside Fault*" and that its depth was "*evidently less than*" 2km (*Kerr-Grant*, 1956, p.181). The study by *Kerr-Grant* (1956) is the most widely referenced as indicating the source was associated with the Eden-Burnside Fault.

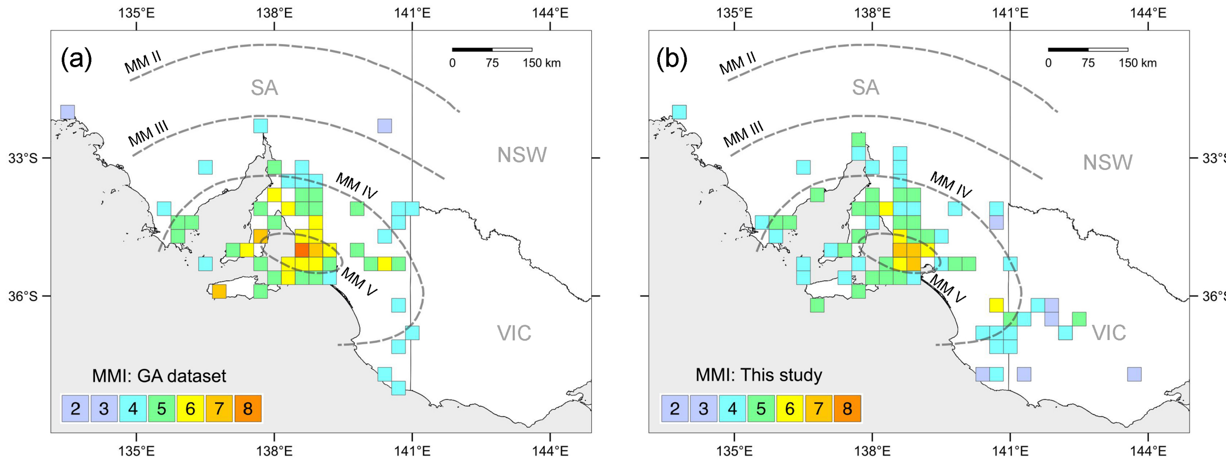

Figure 1. *MMIs from the GA dataset (left) and this study (right) are shown using a 0.3º x 0.3º grid. Dashed lines showing intensity contours by Kerr-Grant (1956) are displayed as a reference. Near-field intensities in Adelaide and in the Adelaide Hills are shown in* ***Figure 2****.*

Because the record of large (M_L > 5), damaging earthquakes in Australia is relatively sparse, it is important to constrain them as best we can. Here we consider whether constraints on the 1954 Adelaide earthquake's location and magnitude can be improved using newly available data and analysis (**Figure 2**). We revisit the 1954 Adelaide earthquake in the light of the new far-field shaking observations, with the assignment of macroseismic intensity at higher intensities (i.e., MMI >VI) being guided by diagnostics extracted from the European Macroseismic Scale (*Grünthal et al.*, 1998). Further, we invert our uniformly assessed intensity observations for magnitude and location using a newly developed intensity prediction equation for Australia and the Bayesian method developed by *Griffin et al.* (2019).

2 Macroseismic Observations

In this study, we first examined descriptions of damage reports documented by *Kerr-Grant* (1956) and *Malpas* (1991). We supplemented this collection by revisiting original postal questionnaires sent to the Department of Mines (now archived at Geoscience Australia), and by examining additional newspaper reports from Victoria via the National Library of Australia's Trove portal. This allowed us to gather information from 263 locations to which we assigned macroseismic intensities. These macroseismic intensities differ in key aspects compared to the work of both *Kerr-Grant* (1956) and *Malpas* (1991). Most notably, instead of the intensity dataset stopping abruptly at the South Australia-Victoria border (**Figure 1a**), we were able to add data based upon a handful of accounts from Victoria as far east as Linton, near Ballarat (**Figure 1b**). We also report our observations as point data rather than isoseismals as the latter can be biased by the availability (or lack thereof) of observation points. We also assign upper and lower intensity ranges for some locations, especially above MMI VI.

At higher intensities, i.e., MMI >VI, our intensity assignments were guided by diagnostics extracted from the European Macroseismic Scale (EMS-98; *Grünthal et al.*, 1998). These criteria led us to assign MMI VI, VI-VII or VII within Adelaide, and in particular, in the region of Darlington which is conventionally accepted as the source of the 1954 earthquake. Our intensities are supported by descriptions by *Kerr-Grant* (1956, p. 183-184), in that the worst damage was to a house under renovation where two unbraced walls collapsed. In a handful of instances in Seacombe Park, ground motion caused cavity-walls to fail but did not result in the "*complete collapse*" of any buildings needed to assess Grade 5 damage (see *Grünthal et al.*, 1998). These observations permit MMI VII, that is, "*many buildings of vulnerability class A suffer damage of grade 3, and a few of grade 4*" (see *Grünthal et al.*, 1998).

The common assumption is that damage was extensive in Darlington and Seacombe Park, driven largely by dramatic press accounts. However, based on the descriptions in the report by *Kerr-Grant* (1956), in our opinion, higher intensities (MMI >VII) are unwarranted. Kerr-Grant (1956, p.180) also states, "*the maximum disturbance appeared to be confined to two or three elongated zones less than a hundred yards (~90m) wide in the vicinity of the suburbs of Darlington, Seacombe Park, and to a lesser extent, Beaumont*". On 8 March 1954, the Chief Engineer of the Public Works Department of South Australia wrote, "*very few buildings sustained damage of a major character although many hundreds of houses, offices, etc suffered minor damage*."

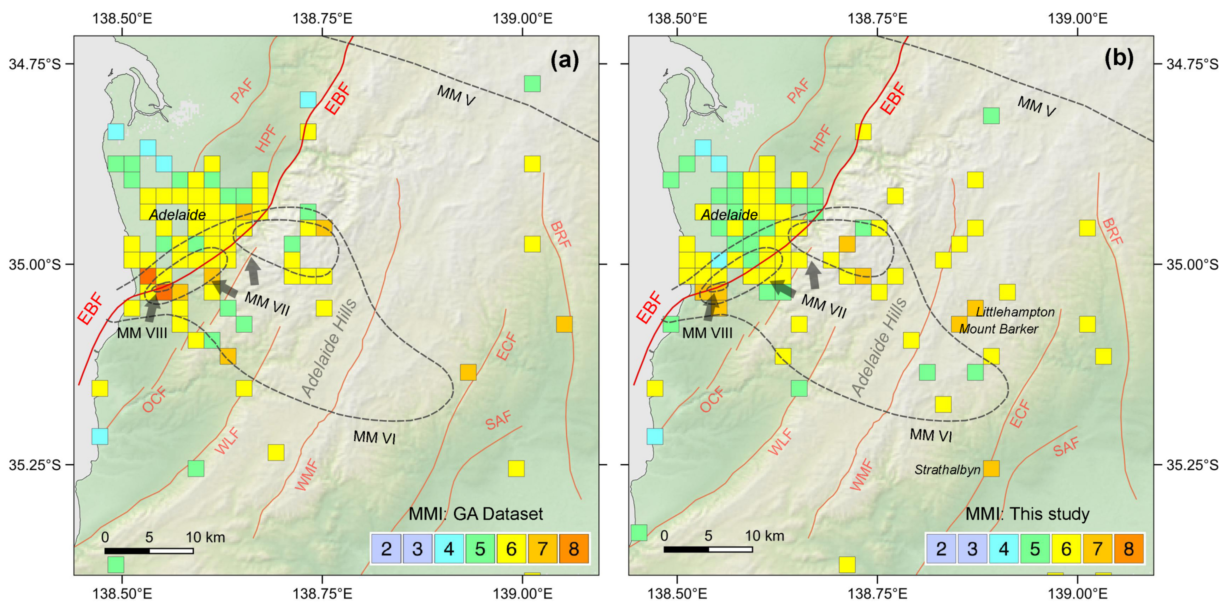

Figure 2: MMI intensities from the GA dataset (left) and this study (right) are shown using a 0.02º x 0.02º grid. Dashed lines showing intensity contours by Kerr-Grant (1956) are displayed as a reference. Active faults (red lines) are modified from the Australian Neotectonic Features Database. (BRF = 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.

Although damage in Adelaide was widely reported in the press, damage from rural communities was less-well determined as also acknowledged by *Kerr-Grant* (1956, p. 177). This might explain the isoseismals drawn by *Kerr-Grant* (1956) not including places such as Mount Barker. This is surprising as the Mount Barker Courier (3 March 1954) reported "*So many reports have been received from Mount Barker that it would be impossible to list the individual damage*" and that "*buckets and even wheelbarrows were used in many instances to carry out fallen plaster*". The same newspaper went on to describe further damage within the same town and in nearby Littlehampton. Although many of these accounts lack reports of fallen chimneys, the widespread damage is characteristic of Grade 3 damage being sustained by many buildings which warrants MM VII. We have also assigned intensities up to MMI VII at other communities in the Adelaide Hills such as Strathalbyn. Though these accounts from the Adelaide Hills are fewer in number, the descriptions of damage appear to be on par with damage in the Adelaide metropolitan area. At sites both in south Adelaide and in the Adelaide Hills, we cannot rule out shaking effects being amplified (or deamplified) in soft sediments. Similarly, we suspect topographic effects might explain observations in the hilly suburbs of Belair and Blackwood, and the damage sustained at Tapley's Hill.

MM intensities for an aftershock at ~5:45 am on 3 March 1954 are shown in **Figure 3**. Many of these accounts were devoid of information with which to assign intensity (*white squares*). The lack of felt accounts from areas further to the west in the Adelaide region is noteworthy.

Overall, we find that while damaging shaking extended east from Adelaide into the Adelaide Hills, the absence of a well-defined locus of higher intensities is significant. It is also evident from **Figure 2** that the isoseismals from both *Kerr-Grant* (1956) and *Malpas* (1991) do not fully account for the newly documented observations, including damage, to the east in the Adelaide Hills. We believe this is possibly suggestive of a deeper hypocentral source which contravenes the popular notion that the 1954 earthquake was shallow (e.g., *Kerr-Grant*, 1956). The absence of a locus of high intensity also renders it difficult to confidently identify the Eden-Burnside Fault, or any other mapped structure in the region, as the source of this earthquake.

3 Macroseismic Relocation

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 calibrated to moment magnitude (unpublished) and based on Australian historical macroseismic intensity observations. Our solution (**Figure 3**), along with the uncertainty contours (95%, 50% and 25%), suggests an epicentre further to the east within the Adelaide Hills. This location is distant from the conventional location on the EBF in the vicinity of Darlington.

A very preliminary epicentre was reported by Kerr-Grant (-35^o S, 138.5^o E) that appears in the Riverview seismological bulletin for 1954. The earliest instrumental epicentral location by the Bureau Central International de Séismologie or BCIS (purple star, -35.60^o S, 138.50^o E, **Figure 3**) was refined by *Bolt* (1955; -34.75^o S, 138.67^o E). *Bolt* (1955) also provides a geographic (*or geodetic*) latitude i.e., -34.93^o S for this solution. This is the epicentre currently in the GA Earthquake Catalogue (black star, -34.93^o S, 138.67^o E, **Figure 3**). *Bolt* (1958) revised this location again (blue star, -35.44^o S, 139.25^o E, **Figure 3**) with a small number of phases not previously considered. All these instrumental locations show large spatial uncertainty and do not permit the identification of a causative structure. The instrumental location computed by *Bolt* (1955) lies proximal to the Eden-Burnside Fault (EBF). *Bolt* (1955) emphasises that while this "*maybe significant… the uncertainty of the determination is… greater than 1 ½ miles*". The focus of our study was an analysis of the macroseismic effects, but we hope that a future relocation will allow us to formally review both the instrumental location and its uncertainty.

Despite the apparent severity of the 1954 earthquake, teleseismic instrumental observations are very limited. This event was not recorded in New Zealand (*Bolt*, 1955; *Kerr-Grant*, 1956) and we did not find phase arrivals in station bulletins from other locations, such as in Indonesia. This is striking compared to the many regional and teleseismic phase arrivals available for earthquakes in the same magnitude range (M_S 5.5 ±0.5) such as those in the Simpson Desert in 1938 and 1941, and to the east of Tasmania in 1946. Those seismological observations can be found in the International Seismological Summaries (https://storing.ingv.it/ISS/index.html) and station bulletins (*Di Giacomo et al.*, 2022).

4 Hydrological and Environmental Effects

Earthquakes can cause sustained or short-lived changes in groundwater aquifers due to changes in pore pressure and hydrogeological parameters of the groundwater system through static stress changes and seismic waves (see *Liao et al.* (2021) and references therein). Following the 1954 earthquake, there were numerous reports of new springs forming, the reactivation of old springs, the shutting down of existing springs and increased hydrological discharge in streams, mainly in the Adelaide Hills (Circles with **S** in **Figure 3**). Some of these resulted in waterlogged soils that failed; it is unclear if these were coseismic or post-seismic gravity driven failures.

The most significant of these effects were in the vicinity of Mount Barker. This includes the appearance of new springs and the flooding on two properties (*Mount Barker Courier*, 10 March 1954; *Malpas*, 1991) in eastern Mount Barker. A tract of farmland in Mount Barker Springs also became so waterlogged up to a distance of 50 yards (~45m) from Mount Barker Creek that "*a tractor became bogged down*" (*Mount Barker Courier*, 10 March 1954). About 100 yards (~90m) to the east of this location (Easternmost circle with **G** in **Figure 3**), "*it was found that a slide, of nearly three times as much ground, had moved down from the foot of a hill. The line of dry grass which showed where the paddock had previously been level was at least eight feet down in the sunken area*" (*Mount Barker Courier*, 10 March 1954). In Mount Barker, underground tanks were damaged "*a number of which lost the whole of their storage through cracked walls and caving in*" (*Mount Barker Courier*, 3 March 1954).

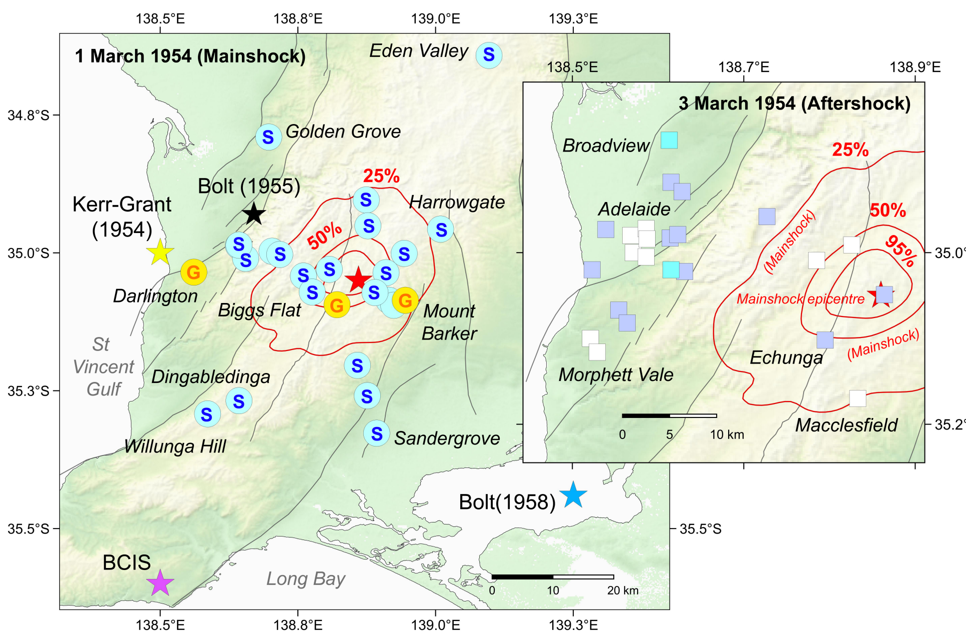

Figure 3. *Stars indicate the macroseismic epicentre determined in this study (red star on both maps) and epicentres from previous instrumental relocations being the Kerr-Grant (yellow), BCIS (purple star), Bolt (1955, black star) and Bolt (1958, blue star). Red contours (both maps) display the 25%, 50% and 95% uncertainties for the posterior distribution for the macroseismic epicentral location of the mainshock on 1 March (red star). Blue filled circles (S) show locations of new springs or changes in the flow of pre-existing springs and where springs went dry. Orange filled circles (G) show locations of ground failure from liquefaction or waterlogging, and a rockfall in quarry. Smaller map shows sites where the 3 March 1954 aftershock was felt using the same scale as* ***Figure 1****. White squares indicate sites where the aftershock was felt but intensities could not be assigned for lack of adequate descriptive information. Active faults (grey lines) are modified from the Australian Neotectonic Features Database.*

It is worth noting that our relocated epicentre lies within the region of the Adelaide Hills from where many of these reports were forthcoming (Circles with **S** in **Figure 3**). Such phenomena suggest substantial coseismic displacement and strong ground motion that typically occurs near the epicentre, especially in light of the fact that daily rainfall totals from the Bureau of Meteorology indicate much of the month of February 1954 was notably dry.

Cracks in the ground were also observed in Darlington and Seacombe, but *Kerr-Grant* (1956) remarked that these "*did not show any appreciable movement*" and were likely related to the subsidence of soil downhill. A large fall of rock of ~700 tons also occurred at the Mount Barker Quarries that took workmen four days to clear (*Mount Barker Courier*, 10 March 1954). .

5 Magnitude Estimates

The GA earthquake catalogue lists a preferred magnitude of M_L 5.4 for the 1954 earthquake at the time of writing. *Greenhalgh and Parham* (1986) report $M_{L(SA)}$ 5.3 ±0.3 which is repeated by *Everingham et al.* (1987). In a review of surface wave magnitudes of Australian earthquakes between 1913 and 1959, *Everingham et al.* (1987) report a preferred surface-wave magnitude (M_S) of 4.9. We believe this is the average (M_S 4.92) of two M_S values they compute using the Prague surface-wave formula (*Vanek et al.*, 1967) and the *Marshall and Basham* (1973) approach, i.e., M_S 5.17 (A_N) and M_S 4.7, respectively. The *Marshall and Basham* (1973) magnitude of M_S 4.6 reported by *Everingham et al.* (1987), we infer, is the average (M_S 4.67) using both North American and Eurasian path correction terms (PΔ), i.e., M_S 4.45 and M_S 4.9, respectively. The use of the *Marshall and Basham* (1973) approach by *Everingham et al.* (1987) is surprising as it is intended for periods (T) of about 12s.

We used the Prague formula (*Vanek et al.*, 1967) to calculate M_S 5.17 and M_S 5.05 using the maximum amplitudes on the north-south (A_N = 13μ; T = 8s) and east-west (A_E = 10μ; T=8s) components of the seismograph at Riverview. Using the vector sum of the same two components, we calculate M_S 5.4. We acknowledge that these values might be unreliable as we use data from just one station. In the absence of other regional observations, the shorter than ideal period (T < 20s) and distance (Δ <20°) to Riverview also make its use with the Prague formula (*Vanek et al.*, 1967) tenuous. However, if these M_S values were to be considered reliable, based on the accepted relationship between M_S and M_W for Australia (see *Allen et al.*, 2018, p. 16), it would be equivalent to M_W ~5.38 to ~5.54.

Table 1. *Summary of magnitude estimates for the 1954 Adelaide Earthquake. $M_{L(I)}$ and $M_{W(I)}$ refer to a local and moment magnitude scales, respectively based on macroseismic data. $M_{L(SA)}$ is a local and M_S and $M_{S(M\&B)}$ are surface wave instrumental magnitudes. M_S and $M_{S(MB)}$ values are computed using the Prague formula (Vanek et al., 1967) and the Marshall and Basham (1973) approach, respectively. $M_{W(I)}$ is computed using the Griffin et al. (2019) approach.*

Data	Magnitude Type	Magnitude Value	Reference
Instrumental	$M_{L(SA)}$	5.3	*Greenhalgh and Parham* (1986)
Instrumental	M_S	4.9	*Everingham et al.* (1987)
Instrumental	$M_{S(M\&B)}$	4.6	*Everingham et al.* (1987)
Instrumental	M_S	5.4	**This study**
Macroseismic	$M_{L(I)}$	5.4	*Everingham et al.* (1982)
Macroseismic	$M_{L(I)}$	5.7	*McCue* (1980)
Macroseismic	$M_{L(I)}$	6.0 - 6.2	*Malpas* (1991)
Macroseismic	$M_{W(I)}$	6.0	**This study**

This leads us to echo *Bolt* (1955), that the paucity of instrumental observations outside Australia for this event suggests its magnitude was not large, and we suspect, likely well below M_L 6. Again, this appears to be supported by the limited number of regional and teleseismic phase observations, and amplitudes, compared to those available for the 17 April 1938 and 4 May 1941 Simpson Desert earthquakes. For those two earlier events, *Everingham et al.* (1987) computed magnitudes of M_S 5.5 and M_S 5.8 respectively.

We also compute a mean intensity magnitude ($M_{W(I)}$) of 6.0 (5.4 – 6.3 at 95% confidence) using the distribution of macroseismic data and an intensity prediction model for historical Australian earthquakes. *Everingham et al.* (1982) report $M_{L(I)}$ 5.4 which is an $M_{L(I)}$ value determined using an intensity prediction equation for Australia calibrated with local magnitude (M_L) and isoseismal areas (see *McCue*, 1980). Slightly higher magnitudes have been computed by *McCue* (1980; $M_{L(I)}$ 5.7) and *Malpas* (1991; $M_{L(I)}$ 6.0 to 6.2).

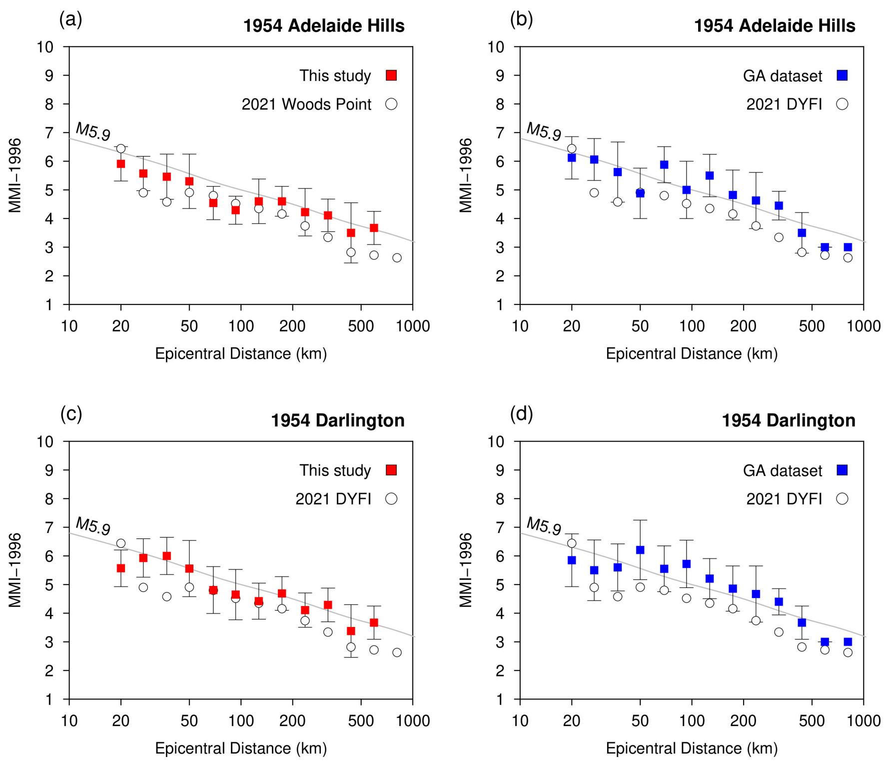

***Figure 4**. MM intensity versus distance plots for the 1954 earthquake considering an epicentre in the Adelaide Hills (Figures 4a and 4b) and the conventionally assumed epicentre in Darlington (Figures 4c and 4d). Median MMIs within logarithmically equal distance bins are displayed for the intensities from this study (red squares) and from the GA dataset for 1954 (blue squares). Error bars indicate one standard deviation. These values are compared to the median DYFI MMIs (open grey circles) from the M_W 5.9 Woods Point, Victoria earthquake in logarithmical equal distance bins. Grey line shows the predicted intensity decay curve for a M_W 5.9 earthquake in eastern Australia.*

A comparison of GA's "Did You Feel It? (DYFI)" intensities (*Allen et al.*, 2019) from the well instrumented M_W 5.9 Woods Point, Victoria, earthquake with our dataset and that from the GA DYFI dataset appear to suggest the 1954 event was at least as large as the 2021 event, and possibly much larger (**Figure 4a**, **b**). This difference in intensities between the 1954 and 2019 datasets is similar regardless of the location of the earthquake in the Adelaide Hills or in Darlington (**Figure 4**). The equivalence of far-field DYFI observations with hand-curated intensities is a topic that deserves further consideration. Traditional, hand-curated observations that may be derived from media reporting of the most severe observations (*Hough and Pande*, 2007). Relative to these observations, it is possible that the abundance of internet-derived DYFI observations may lead to a reduction of intensity. Although hand-curated intensities have been shown to be consistent with automated, internet-derived DYFI intensities from India (*Bossu et al.*, 2017), this observation in the Australian setting is pending validation. Nonetheless, these comparisons appear to support the $M_{W(I)}$ ~6.0 that we have determined using macroseismic data alone given its good correspondence with macroseismic data from the M_W 5.9 Woods Point, Victoria, earthquake.

The above magnitude estimates are summarised in **Table 1**. Although each individual magnitude estimate is fraught with uncertainty, and comparing the different magnitude types is ($M_{L(SA)}$, M_S, etc.) is not a strictly an "apples-to-apples" comparison, it is striking that the macroseismic magnitudes are consistently lower than the instrumental ones (this study obtains $M_{W(I)}$ =6.0 and M_S=5.4 for macroseismic vs. instrumental magnitude). One explanation for this discrepancy between instrumental and macroseismic magnitudes could be that the 1954 earthquake had a high static stress drop. An earthquake's static stress drop is known to influence the strength of ground motion (see *Hanks and Johnston*, 1992) including in Australia (e.g., *Allen*, 2012). Furthermore, among the many factors that can influence static stress drop (see *Yang et al.*, 2021), increasing hypocentral depth is known to play an important role (e.g., *Allen et al.*, 2004). It seems plausible that the static stress drop from the 1954 earthquake was higher in comparison to the average static stress drops of the events used to calibrate the intensity prediction model that we use in our calculations and in **Figure 4**.

6 Discussion

The modern analysis of the 1954 Adelaide earthquake is plagued by the classical problems faced in the study of historical and early-instrumental earthquakes, including poor or limited seismological data and spatially incomplete or inadequate macroseismic observations. The observations presented here lead us to question the conventionally accepted epicentral location of the 1954 Adelaide earthquake as it is incompatible with the intensity observations at hand from this event, in particular the observations of damage in the Adelaide Hills.

Macroseismic intensity is known to be subjective (see *Hough and Page*, 2011) and the preservation of observations can be biased by population density and socio-cultural factors (e.g., *Hough and Martin*, 2021; *Martin et al.*, 2020, 2022). We suggest that the greater density of population in the immediate region of Adelaide in 1954 may have biased the intensity field estimates of previous studies, simple due to the greater number of observations there and the higher likelihood of damage in a built-up environment that is simply due to the greater number of buildings. This is a fact *Kerr-Grant* (1956) was no doubt aware of by his own admission and it undoubtedly influenced the isoseismal contours he drew. Still, the marked absence of a locus or "bull's eye" of high intensity that we document, is also apparent in previous work (*Kerr-Grant*, 1956; *Malpas*, 1991). This, we believe, suggests that either the source was deep, or was in a sparsely populated area.

The mean macroseismic intensity magnitude computed by us for the 1954 earthquake is $M_{W(I)}$ 6.0 (5.4 – 6.3 at 95% confidence) using macroseismic effects. It is worth noting that the intensity magnitudes computed by previous studies (*McCue*, 1980; *Malpas*, 1991) using macroseismic effects also lie in the same range. These three, independent magnitude values are surprisingly large in light of the unusually limited or non-existent regional and teleseismic seismological observations and given that all instrument magnitudes estimates are 5.4 (this study) or less. Aside from the likelihood that all the instrumental magnitudes reported previously are fraught with high uncertainty, another explanation for the discrepancy between macroseismic and local and/or regionally determined instrumental magnitudes could be that the 1954 earthquake had a static stress drop that is higher than most Australian events (at least those that were used to determine the intensity prediction model we use).

Although our results differ from the widely held notion that the 1954 earthquake was the result of a very shallow earthquake (*Bolt*, 1955; *Kerr-Grant*, 1956) on or near the Eden-Burnside Fault (*Kerr-Grant*, 1956), our results do not identify another causative fault source. The observations documented by us appear to be in favour of a deeper hypocentre than previously considered, and one located further east beneath the Adelaide Hills. Deeper (10-25km) instrumental seismicity in the Flinders ranges (*Balfour et al.*, 2015) and in the Adelaide Hills (*Love and Wallace*, 2015; *Love*, 2010, 2014) suggests the presence of several active structures here, not limited to those with surface expressions. This region is structurally characterised by an east-dipping listric tectonic architecture that soles out at a depth of ~15km (see *Flöttman and James*, 1997). We hypothesise that any of these mapped or unmapped structures, including the deeper sections of the Eden-Burnside Fault, could potentially have been the source for the 1954 earthquake.

In conclusion, we underscore the known unknown (*Rumsfeld*, 2011) that in addition to the uncertainties surrounding the magnitude and location of the 1 March 1954 Adelaide earthquake, it might not be the only earthquake in Australia for which there is an inconsistency in terms of a catalogued magnitude and location, and the macroseismic evidence. This leads to a more wide-reaching comment that while the distinct relationship of the attenuation of shaking intensities with static stress drop is appreciated for modern, instrumented Australian earthquakes (e.g., *Allen et al.*, 2004; *Allen*, 2012), the same cannot be said for the majority of historical earthquakes in Australia whose catalogued magnitudes have been derived from non-uniformly assessed macroseismic data with little to no instrumental data.

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8 References

Allen, T. I. (2012). Stochastic ground-motion prediction equations for southeastern Australian earthquakes using updated source and attenuation parameters, *Geoscience Australia Record 2012/69*, Canberra, 55 pp.

Allen, T. I., G. Gibson, A. Brown, and J. P. Cull (2004). Depth variation of seismic source scaling relations: implications for earthquake hazard in southeastern Australia, *Tectonophys.* **390,** 5–24, doi:10.1016/j.tecto.2004.03.018.

Allen, T. I., M. Leonard, H. Ghasemi, and G. Gibson (2018). The 2018 National Seismic Hazard Assessment for Australia: earthquake epicentre catalogue, *Geoscience Australia Record 2018/30*, Canberra, 51 pp, doi: 10.11636/Record.2018.030.

Allen, T., A. Carapetis, J. Bathgate, H. Ghasemi, T. Pejić, and A. Moseley (2019). Real-time community internet intensity maps and ShakeMaps for Australian earthquakes, *Australian Earthquake Engineering Society 2019 Conference*, Newcastle, New South Wales.

Balfour, N., P.R. Cummins, S. Pilla and D. Love (2015). Localization of intraplate deformation through fluid-assisted faulting in the lower-crust: The Flinders Ranges, South Australia, *Tectonophysics*, Vol. 655, pp.97-106, doi: 10.1016/j.tecto.2015.05.014.

Bolt., B. (1955-1956). The epicentre of the Adelaide earthquakes of 1954 March 1*, Journal and Proceedings of the Royal Society of New South Wales*, Vol 89-90, pp 40-43.

Bolt., B. (1958). Seismic travel-times in Australia*, Journal and Proceedings of the Royal Society of New South Wales*, Vol 92, pp 64-72.

Bossu, R., M. Landès, F. Roussel, R. Steed, G. Mazet-Roux, S. S. Martin, and S. E. Hough (2017). Thumbnail-based questionnaires for the rapid and efficient collection of macroseismic data from global earthquakes, *Seismological Resesearch Letters*, Vol. 88, no. 1, pp. 72–81, doi: 10.1785/0220160120.

Clark, D., and A. McPherson (2011), Large earthquake recurrence in the Adelaide region: a palaeoseismological perspective, *Australian Earthquake Engineering Society 2011 Conference*. Barossa Valley, South Australia.

Di Giacomo, D., D. Olaru, A. Armstrong, J. Harris, and D.A. Storchak (2022), The ISC Electronic Archive of Printed Station and Network Bulletins. *Seismological Society of America*, Vol. 93, 2A, pp. 749-752, doi: 10.1785/0220210262.

Everingham, I.B., A.J. McEwin and D. Denham (1982), Atlas of isoseismal maps of Australian earthquakes, *Bureau of Mineral Resources, Geology & Geophysics Bulletin*, Vol. 214, 177 p., Canberra.

Everingham, I.B., D. Denham and S.A. Greenhalgh (1987), Surface-wave magnitudes of some early Australian earthquakes, *BMG Journal of Australian Geology and Geophysics*, Vol. 10, pp. 253-259.

Flöttmann, T., and P. James (1997). Influence of basin architecture on the style of inversion and fold-thrust belt tectonics - the southern Adelaide Fold-Thrust Belt, South Australia, *Journal of Structural Geology,* Vol. 19**,** pp.1093-1110, doi: 10.1016/S0191-8141(97)00033-3.

Greenhalgh, S.A., and P.T. Parham (1986), The Richter earthquake magnitude scale in South Australia, *Australian Journal of Earth Sciences*, Vol. 33, 4, 519-528, doi: 10.1080/08120098608729388.

Griffin, J., Nguyen, N., Cummins, P. and Cipta, A., 2019. Historical Earthquakes of the Eastern Sunda Arc: Source Mechanisms and Intensity-Based Testing of Indonesia's National Seismic Hazard Assessment Historical Earthquakes of the Eastern Sunda Arc. *Bulletin of the Seismological Society of America*, Vol. 109, 1, pp.43-65, doi: 10.1785/0120180085.

Grünthal, G. (Editor) (1998), The European Macroseismic Scale EMS-98, Conseil de l'Europe, Cahiers du Centre Européen de Géodynamique et de Séismologie, Vol. 15, Luxembourg, 101 p., doi : 10.2312/EMS-98.

Hanks, T. C., and A. Johnston (1992). Common features of the excitation and propagation of strong ground motion for North American earthquakes*, Bulletin of the Seismological Society of Americ*a, Vol. 82, pp. 1–23, doi: 10.1785/BSSA0820010001.

Hough, S. E., and P. Pande (2007). Quantifying the "media bias" in intensity surveys: Lessons from the 2001 Bhuj, India, earthquake, *Bulletin of the Seismological Society of Americ*a, Vol. 97, pp. 638–645, doi: 10.1785/0120060072.

Hough, S.E., and S.S. Martin (2021), Which earthquake accounts matter? *Seismological Research Letters*. Vol 92, No 2A, pp. 1069 – 1084, doi: 10.1785/0220200366.

Hough, S.E., and M. Page (2011), Toward a consistent model for strain accrual and release for the New Madrid Seismic Zone, central United States, *Journal of Geophysical Research*, Vol. 116, p. B03311, doi: 10.1029/2010JB007783.

Kerr-Grant, C. (1956), The Adelaide earthquake of 1st March 1954, *Transactions of the Royal Society of South Australia*, Vol. 79, pp.177-185.

Liao, X., G. Wang and Z. Shi (2021), Sustained changes in well water levels following a large earthquake: Possible evidence of permeability decreases in a shallow ground water system, *Geophysics Research Letters*, Vol 48, 1, doi: 10.1029/2020GL090232.

Love, D. (2010), Mount Barker earthquake – 16th April 2010 Magnitude 3.7, *Australian Earthquake Engineering Society 2010 Conference*, Perth, Western Australia.

Love, D. (2014), The Belair Earthquake, 6th January 2014, Magnitude 2.6, *Australian Earthquake Engineering Society 2014 Conference*, Lorne, Victoria.

Love, D., and A. Wallace (2015), Recent results from the Adelaide seismic network, *Proceedings of the Tenth Pacific Conference on Earthquake Engineering,* 6-8 November 2015, Sydney, Australia

Malpas, K. (1991), Adelaide 1954 Earthquake, South Australia. Unpublished report, Flinders University: Adelaide.

Marshall, P.D. and P.W. Basham (1973), Rayleigh wave magnitude scale M_S, *Pure and Applied Geophysics*, Vol. 103, pp. 406-414.

Martin, S.S., Y. Wang, M. Muzli, and S. Wei (2020). The 1922 Peninsula Malaysia Earthquakes: Rare intraplate seismicity within the Sundaland block in Southeast Asia, *Seismological Research Letters*, Vol 91, No 5, pp. 2531 – 2545, doi: 10.1785/0220200052.

Martin, S.S., P.R. Cummins, and A.J. Meltzner (2022). Gempa Nusantara: A database of 7380 macroseismic observations for 1200 historical earthquakes in Indonesia from 1546 to 1950, *Bulletin of the Seismological Society of America*, pp. 1–23, doi: 10.1785/0120220047.

McCue, K. (1980). Magnitude of some early earthquakes in southeastern Australia, *Search*, Vol 11, pp. 78-80.

Musson, R. (1998). Intensity assignments from historical earthquake data: issues of certainty and quality, *Annali di Geofsica*, Vol. 41, 1, pp. 79-91, doi: 10.4401/ag-3795.

Rumsfeld, D. (2011). Known and unknown: a memoir. Penguin.

Sinadinovski, C. S. Greenhalgh and D. Love (2006), Historical earthquakes: a case study for Adelaide 1954 earthquake, *Australian Earthquake Engineering Society 2006 Conference*, Canberra, Australian Capital Territory.

Vanek, J., Zatopek, A., Karnik, V., Kondorskaya, N. V., Riznichenko, Yu V, Savarenski, E. F., et al. (1962). Standardizatsya shkaly magnitud. *Izv. Akad. Nauk SSSR, Ser. Geofiz*, 2, 153–158 (in Russian; English translation. Bull. USSR Acad. Sci., 2,108–111)

Yang, H., M. Quigley, and T. King (2021) Surface slip distributions and geometric complexity of intraplate reverse-faulting earthquakes, *Geological Society of America Bulletin*, doi: 10.1130/B35809.1.

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