A Review of the M_L(SA) Greenhalgh Magnitude Scale

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Abstract

The M_L(SA) magnitude scale was developed by Greenhalgh, Parham and Singh around 1985, using amplitudes from analogue recorders in a widely spaced network in South Australia. It followed two previous attempts to improve on the Richter magnitude that was used initially. However, its reliability was suspect due to the low dynamic range of recordings, and it had not been retested since high dynamic range digital recording became available. Most digital recording in South Australia in the years 2007 to 2020 however has been used to produce Bakun and Joyner magnitudes. Using peak displacement, or peak velocity with associated frequency, and other information we have produced M_L(SA) and Bakun and Joyner magnitudes for all individual station readings from 1975 to 2020. These show that the M_L (SA) scale is surprisingly robust over a wide distance range, with the median value varying by less than 0.1 magnitude units over the range 50 to 800 km. The 20th and 80th percentiles vary by up to -0.21 and +0.26 respectively. This is in contrast to the Bakun and Joyner equation which produces an increase of 0.6 magnitude units over the same range. Subdivisions of the data were examined, showing some variations, but general consistency.

Keywords: magnitude.

1 Introduction

The M_L(SA) magnitude scale was developed by Greenhalgh and others around 1985 (Greenhalgh and Singh, 1986 and Greenhalgh and Parham, 1986) using amplitudes from analogue recorders in a widely spaced network in South Australia. As the network only began in 1964, with high gain recorders introduced around 1970, the analysis relied on a moderately small data set with a low dynamic range. Small events were only recorded at close range, and larger events more at distance. The lead author of this paper has always considered that this might lead to inaccuracy. However the scale was used for selected stations in the South Australian network up to 2017, and has for a number of years been used by Geoscience Australia and Seismology Research Centre for events in the SA region. No detailed review of the magnitude scale has been carried out to date. To produce a reliable and consistent catalogue for any hazard study, a key requirement is confidence in the magnitudes.

2 Magnitude usage in the network

The Richter magnitude scale was developed in conjunction with the Wood-Anderson instrument, which graphed displacement, not velocity. This was the scale first used when the South Australian network began. It was clear that this had a distance bias with more distant stations recording higher values. This was first investigated by White (1968) who developed the m_L scale. The early type of instrumentation in the network had particular calibration characteristics. This lead White to use velocity, not displacement in the m_L scale. However, the introduction of different equipment which particularly amplified higher frequencies resulted in more research. Stewart (1975) produced the M_N scale. This was a complex formula, but was used consistently, with amplitudes and frequencies being stored digitally from 1978 onwards. This went hand in hand with a whole system calibration method. Greenhalgh, Parham and Singh were able to use these data in their analysis. As part of the revised magnitude scale, station corrections were calculated. Analogue stations with passive vertical sensors installed later followed this method, although sometimes without station corrections. With the advent of digital recording, and later, active sensors that were not amenable to the whole system calibration method, some stations used supplied or assumed instrument specifications, and resorted to the default Bakun and Joyner (1984) equation (in the EqFocus software by Seismology Research Centre) ignoring station corrections. With the state government pulling out of seismology, all remaining analogue stations were closed, and the Seismological Association of Australia (SAA) website magnitude information is presently using only Bakun and Joyner. From 2016 onwards, the magnitude usually used peak displacement rather than peak velocity and frequency using Waves software (Seismology Research Centre, 2021). This integrates the velocity waveform and uses a 2 to 10 Hz filter. It also allows the user to calculate magnitudes from stations operated by Geoscience Australia as calibration information is automatically available.

3 Data used for this project

In this study we used all events calculated by the network since 1976. This comprises mainly events in the Adelaide Fold Belt (or Adelaide Geosyncline), but includes the whole state and some events over the border in Victoria and New South Wales. We have recalculated Bakun and Joyner station magnitudes using original amplitudes, frequencies and displacements from 2007 to 2018. Where M_L(SA) station magnitudes already existed they have been used. A check showed that attempting recalculation of these might lead to some errors, as there was uncertainty about some calibration curves. Where recalculated Bakun and Joyner magnitudes are used, these may have some calibration errors. Data from a few stations for particular time periods were excluded due to obvious errors. Where frequencies were outside the range 1.4 to 25 Hz, these were likely to be unreliable and were removed. Also measurements at less than 15 km epicentral distance were removed as hypocentral depths, which are in the range 0 to 30km, are usually unknown. A comparison check of station magnitudes calculated using displacement instead of amplitude and frequency showed that they matched fairly well, with slightly less scatter using displacement.

The data set initially comprised 51,075 station magnitudes from 11,718 events over the years 1976 to 2020. This was reduced to 25,278 station magnitudes from 3,583 events after removal of station magnitudes at epicentral distances less than 15 km, events where there were less than four magnitudes, or where the epicentral distance range of the stations was less than 150 km. This resulted in less data from earlier years when there were less stations, and also when paper record saturation was more commonly a problem. The largest remaining earthquake was magnitude 5.0, and only 10 were above magnitude 4. While the main programs used did not normally include station magnitudes for distances over 600 km, somehow 328 such values were included in the data set.

4 Comparison of M_L(SA) with Bakun and Joyner

The EqFocus program from Seismology Research Centre used the Bakun and Joyner (1984) equation rather than the original Richter (1935) form. While the EqFocus program had the facility to change the magnitude equation, we did not make use of it. It did not have the capability to include station corrections. As outlined above, we used earthquakes where there were four or more station magnitudes registered over an epicentral distance range of at least 150 km. We used the station magnitude minus the average magnitude from all stations (event magnitude). Where the station magnitude is less than the event magnitude it will appear as a negative value. In the first test we binned these according to epicentral distance. Bins were 15 to 50 km, 50 to 100 km, then in 100 km bins to 800 km. In each bin percentiles were extracted and plotted at a mid-bin distance. The results are shown in Figures 1 and 2.

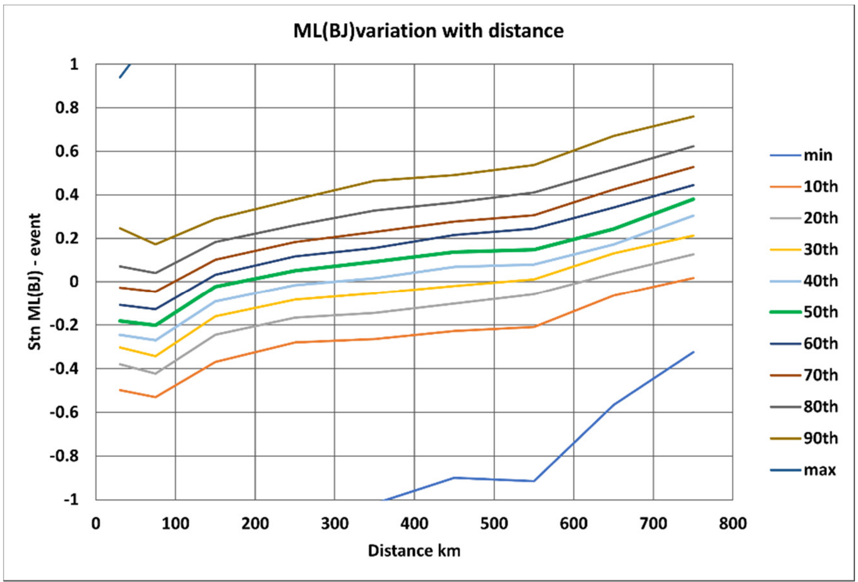

Figure 1. Station residuals using Bakun and Joyner magnitudes plotted with distance. Percentiles of values in each distance range (bin) are plotted near middle of bin.

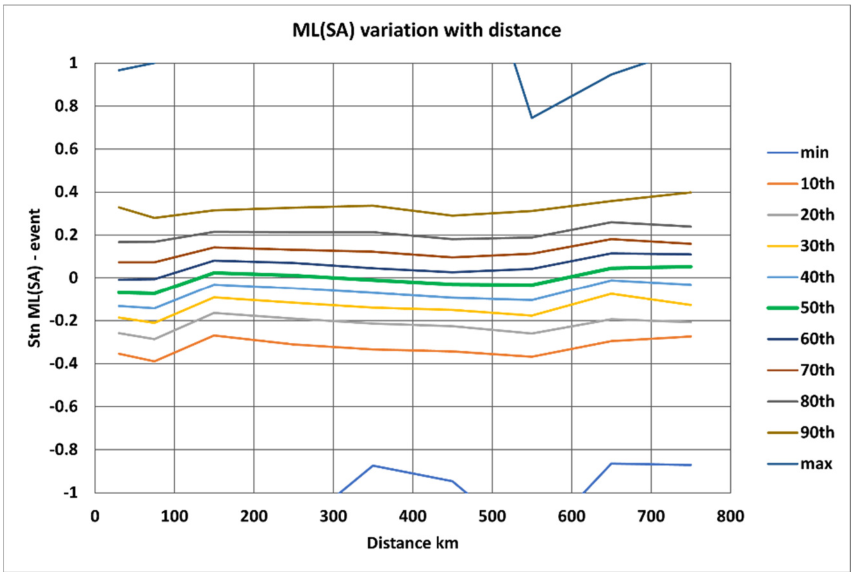

Figure 2 Station residuals using Greenhalgh and Singh (1986) magnitudes plotted with distance. Percentiles of values in each distance range (bin) are plotted near middle of bin.

Clearly the Bakun and Joyner (1984) equation is not a suitable scale to use in this region. It under-estimates magnitudes in the near-field and over estimates at distance, with this variation being about 0.6 magnitude units over 800 km (Figure 1). In comparison, the Greenhalgh scale is considerably better, with the median never being more than 0.1 magnitude units from the average (Figure 2). The 10th and 90th percentiles all fall within 0.4 magnitude units. This shows that the Greenhalgh scale is suitable for this region, possibly out to 800 km, although it was originally only intended for use up to 600 km, and the number of points in the final two bins are much lower.

5 Subdivision of data

5.1 Subdivision by epicentral area

Four zones were selected within the area of the events to examine possible variation in the active areas. These are shown in Figure 3. They cover the north of the Adelaide Fold Belt (AdGeoN) and the south (AdGeoS) which includes the majority of the events. There is an area over the Eyre Peninsula (EyrPen) and the South-east of the state (SthEst). These latter areas have far fewer events. We expanded the data set by including all events with three or more station magnitudes registered over a distance range of at least 100 km. The same bin values are used.

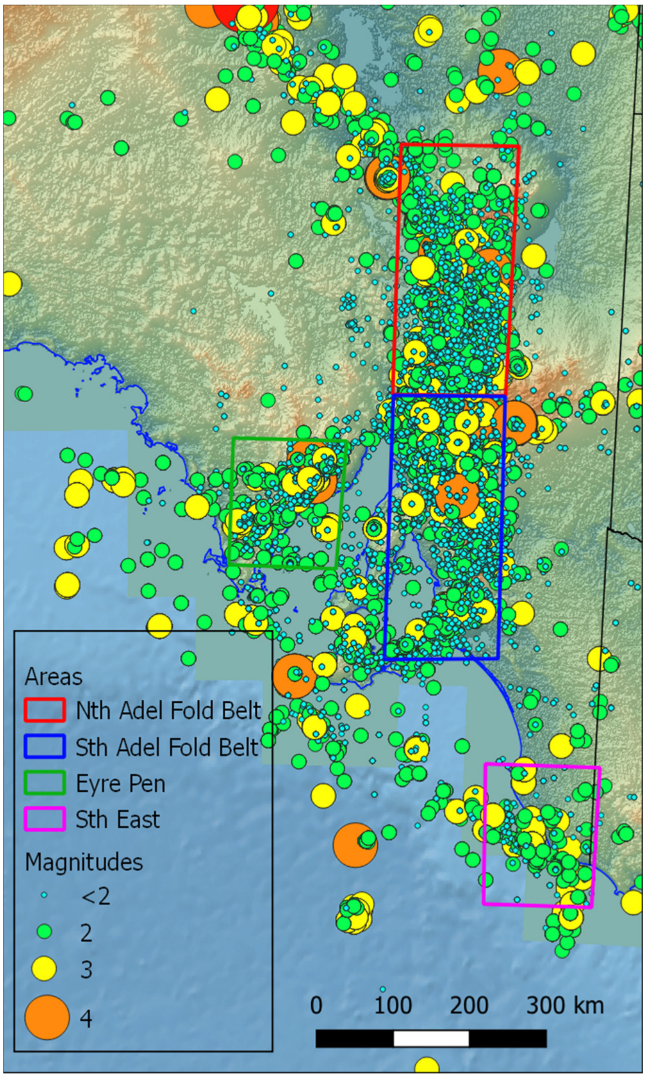

Figure 3 Four areas selected to compare variation of Greenhalgh magnitudes.

The median values are plotted in Figure 4. Most values still fall within 0.1 magnitude units of the average. Only the South Adelaide Fold Belt shows a peak in the 100-200 km bin. The

North Adelaide Fold Belt values are too high at short distances and low when over 500 km. The Eyre Peninsula zone is low in the 50 - 100 km bin. These are still relatively small variations when compared to the biases of the Bakun and Joyner results.

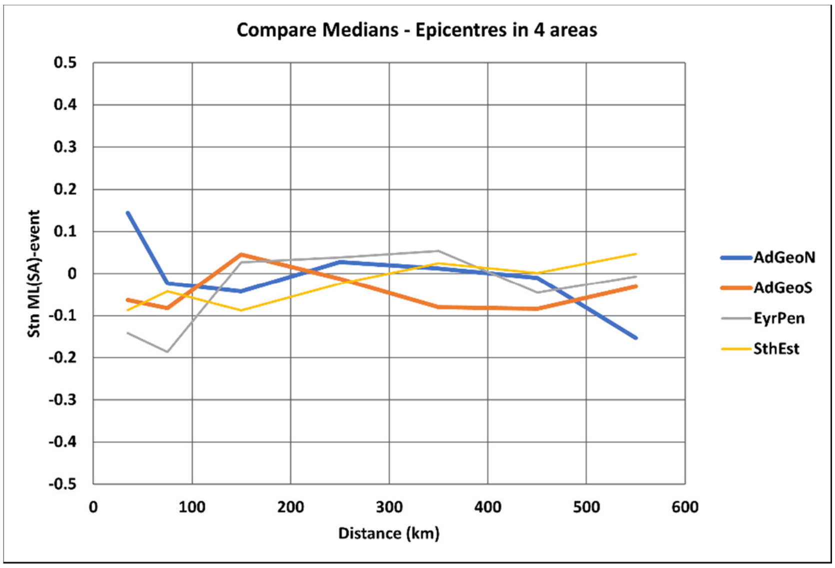

Figure 4 Median magnitude residuals (without other percentiles) for Nth Adelaide Fold Belt (AdGeoN), Sth Adelaide Fold Belt (AdGeoSth), Eyre Pen and Sth East.

5.2 Smaller bin size

Using the data set for the full area, a smaller bin size was tried, using 20 km bins from 20 to 400 km. This again used the original limits of at least a 150 km range and at least four station magnitudes. The results for the Greenhalgh scale are shown in Figure 5. Again the median is always within -0.1 and 0.1 magnitude units. There is an obvious minimum near 70 km which shows in all percentiles, and a maximum near 170 km that mostly shows in lower percentiles. The maximum at 170 km is possibly a result of direct and Moho-reflected waves giving some enhancement.

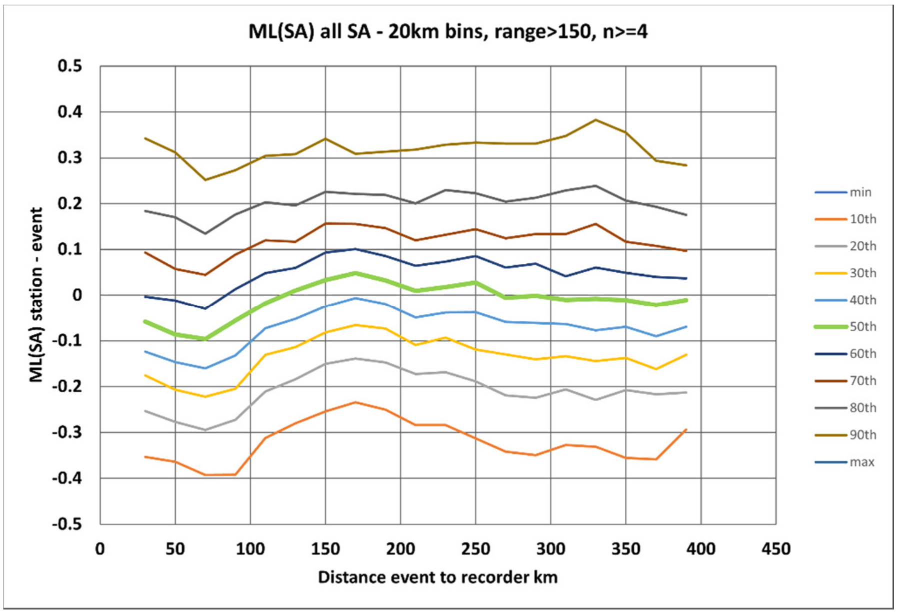

Figure 5. Percentile curves of magnitude variation with smaller distance bins than Figure 2. Data is for the whole area.

5.3 Mid-ray subdivision

Given that most earthquakes are likely to be shallow, the Moho reflection point will be near the mid-ray point between the event and the recorder. Station values were selected on the location of the mid-ray point being in one of three areas shown in Figure 6. The selection zones are significantly different to the earlier test due to the spread of mid-ray points. The 150 km minimum range and minimum of four station magnitudes were used, and the 20 km bin size. The resultant medians are shown in Figure 7. The 170 km peak shows again, but only in the south Adelaide Fold Belt region. Apart from this, the general features of the north and south fold belt areas are a little different from Figure 4, suggesting that it is being affected by the changed data selection. It should be remembered again that these are quite small variations compared with the normal scatter of magnitude values.

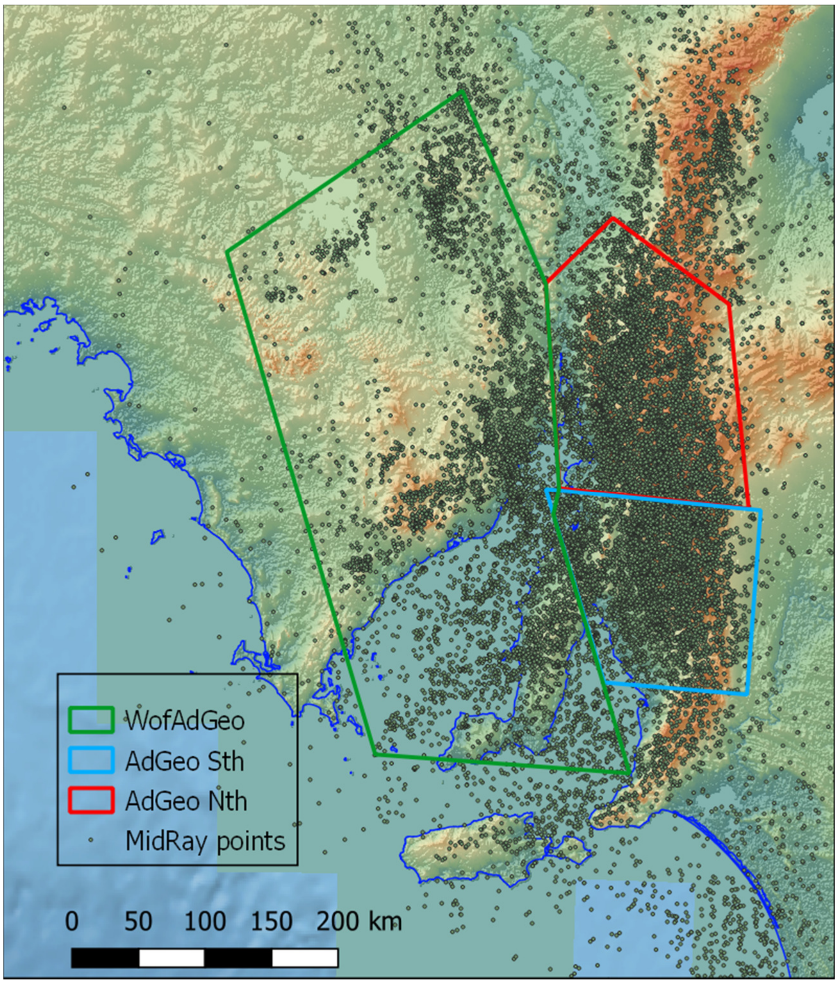

Figure 6 Map showing points midway between event and recorder (mid-ray) and the modified selection areas, North Adelaide Fold Belt (AdGeo Nth), South Adelaide Fold Belt (AdGeo Sth) and a wide area west of the Fold Belt (WofAdGeo).

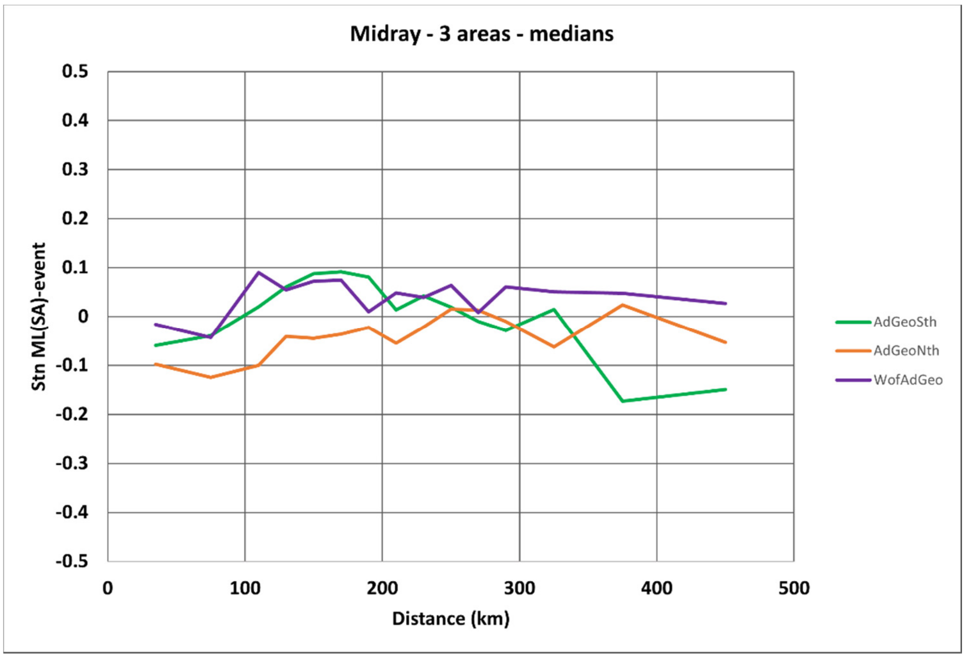

Figure 7 Median values for mid-ray points for the three areas mapped in Figure 6.

6 Other data adjustments

6.1 Site corrections

Softer soils principally result in higher ground motion in the 1 to 10 Hz frequency range . While use of the vertical channel reduces this problem, it is not eliminated.. Other factors can also cause systematic variations. Greenhalgh calculated station corrections for analogue sites running in 1985. No further station corrections have been calculated since that time. Figure 8 shows the difference between station magnitude and event magnitude for a number of digital stations, binned at 0.05 magnitude units. While most stations peak near zero, there are clearly some that do not, despite all these stations being on rock. For a more rigorous assessment of station and event magnitudes, station corrections should be applied throughout. For station corrections to become a standard part of processing, this requires station-specific amplitudes to be stored, but not used in magnitudes, prior to a reliable station correction being calculated.

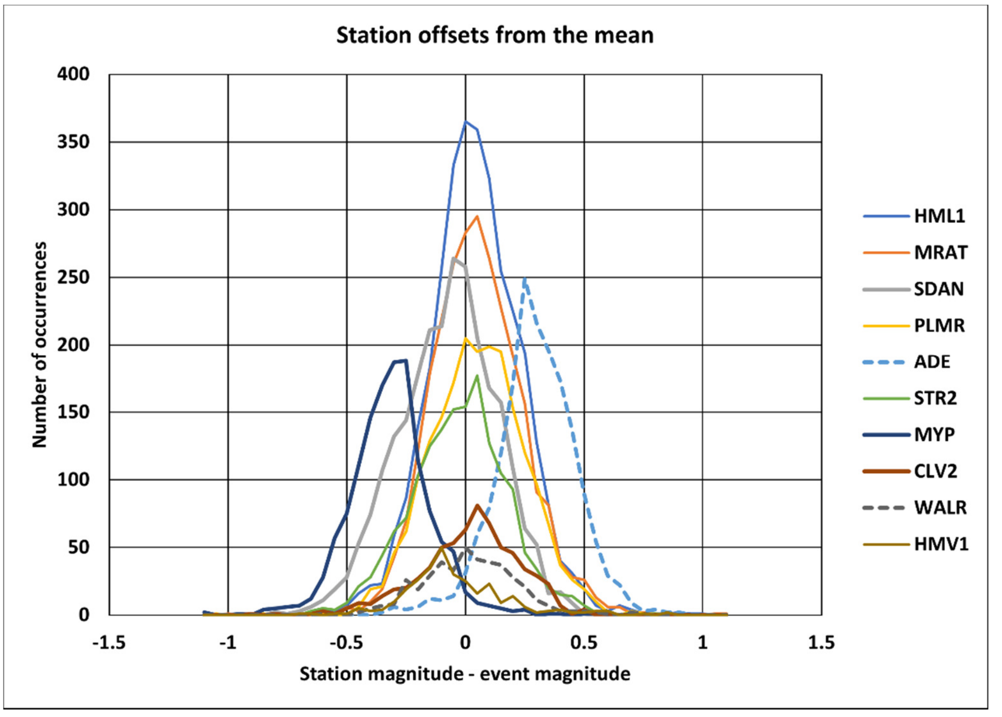

Figure 8. Difference between station magnitude and event magnitude for selected stations,with occurrences binned at 0.05 magnitude units.

6.2 Wood-Anderson conversion factors

Greenhalgh assumed a Wood-Anderson magnification of 2800, damping 0.8 and natural period 0.8 sec. It has since been documented that 2080 is a more indicative value (Uhrhammer and Collins, 1990. This would result in a difference of 0.13 units ($\log_{10}$ 2800/2080). If a damping value of 0.7 is assumed (Glanville et al, 2020) the difference is reduced to 0.07. Where magnitudes were derived from displacement, and thus no frequency has been specified, a value of 2600 was used as the most likely value among the most used frequencies.

6.3 Scale definition point

Richter (1935) used a scale definition that referred to equivalent size at 100 km. Bakun and Joyner (1984) produced a scale closely matching Richter between 40 and 400 km and improved response for Central California for closer distances, such that:

$$ML(BJ) = 0.7 + \log_{10}A_{WA} + \log_{10}(D_h) + 0.00301 * D_h \quad (1)$$

where A_{WA} is the WA displacement amplitude in mm and D_h is hypocentral distance. The Greenhalgh equation assumes:

$$ML(SA) = 0.7 + \log_{10}A_{WA} + 1.1 * \log_{10}(D_e) + 0.0013 * D_e \quad (2)$$

where D_e is epicentral distance. The Greenhalgh equation is similar to Richter from 50 to 200 km.

Hutton and Boore (1987) proposed linking local magnitude scales at a hypocentral distance of 17 km for more meaningful comparisons across regions. This has distinct merit from a hazard point of view, however it may prove problematic in Australia until there is a much better handle on earthquake depths over larger areas. It is clear in the foregoing analysis that there is more variation across areas at distances of less than 100 km.

7 Further discussion

7.1 Reliability of amplitude based scales

Magnitude based on velocity and frequency has been used fairly consistently for many decades with high gain 1 Hz sensors. This has resulted in a large amount of reliable data. The use of integrated displacement amplitudes, calculated from the velocity waveforms has been a helpful advance, but it has changed little. The 1 Hz sensors ensure that magnitudes up to at least magnitude 4 are reliably recorded, although filtering at 2 Hz may induce some saturation.

Duration magnitudes were regularly calculated by some observatories, however this practice fell into disuse with the advent of triggered digital recording. These magnitudes tended to be fairly robust. A check of South Australian data showed that the 10^{th} and 90^{th} percentiles of station magnitude minus average event magnitude were less than 0.2 magnitude units from the mean for events where four or more values were calculated.

Moment magnitude is prominent in research work, however it is not routinely recorded by any observatory in Australia for events under magnitude 5, so that it is not possible to comment on its robustness.

The Gutenberg-Richter plots of amplitude-based scales for well monitored areas produce highly linear series. This is feature is particularly valuable in estimating the recurrence of larger events, and its value should not be forgotten or downplayed.

7.2 How far have we come in Australia?

As is common elsewhere on the globe, magnitudes have been a continuing problem in this country. Whereas from 1969 to 1990 there were seminars and much research, this has not been the case in the last 20 years. As a forerunner to future work on magnitudes, the lead author believes that availability of waveforms, response information and calculation methods would be of considerable value. In this regard, Geoscience Australia took a significant step forward by making all station data available through IRIS, and likewise the availability of Seismometers in Schools data is of benefit. Further steps are required from all observatories in Australia, including the Seismological Association to improve data and metadata availability. One of these is to list individual station magnitudes. This will encourage observers to see whether these magnitudes are reproducible by others, without which there can be limited confidence in published values.

8 References

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