Seismic network capability and magnitude completeness maps, 1960 – 2005 for Western Australia, South Australia and the Northern Territory.

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Abstract

Preliminary maps of earthquake detectability for WA, SA and the NT for the years 1960, 1970, 1980, 1990 & 2005 are presented here, based on the distribution of seismographs at each epoch. The method used here is an alternative to methods that analyse the shape of the frequency-magnitude distribution curve for events in an earthquake catalogue. This method may be the more useful technique in areas of low seismicity like Australia. The maps presented here are compared with other recent computations of Mc values, and suggest that those computations commonly over-estimated the completeness of the catalogue. However, the maps use sensitivity values for the seismographs that need to be verified by further studies. The values used here may underestimate actual seismograph capabilities. A swarm of earthquakes near Beacon WA in 2009 suggests an actual Mc value of 2.5 for the southwest Australia zone in 2009.

Introduction

Why are Magnitude Completeness (Mc) maps important?

Leonard et al. (2007) state "uncertainties in the earthquake catalogue limit the reliability of hazard models". One of the principal sources of uncertainty in any catalogue is periods of completeness of the catalogue in the various magnitude ranges. The completeness of the catalogue will vary with region and time, depending principally on the distribution and sensitivities of the seismographs deployed to detect earthquakes. The symbol **Mc** is used to refer to catalogue completeness, and is defined as the lowest magnitude above which all earthquakes in a space-time volume are detected (Weimer & Wyss, 2000).

In order to compute meaningful estimates of the frequency of earthquakes in a region, we must know if the historical record (in the form of a catalogue) misses significant events.

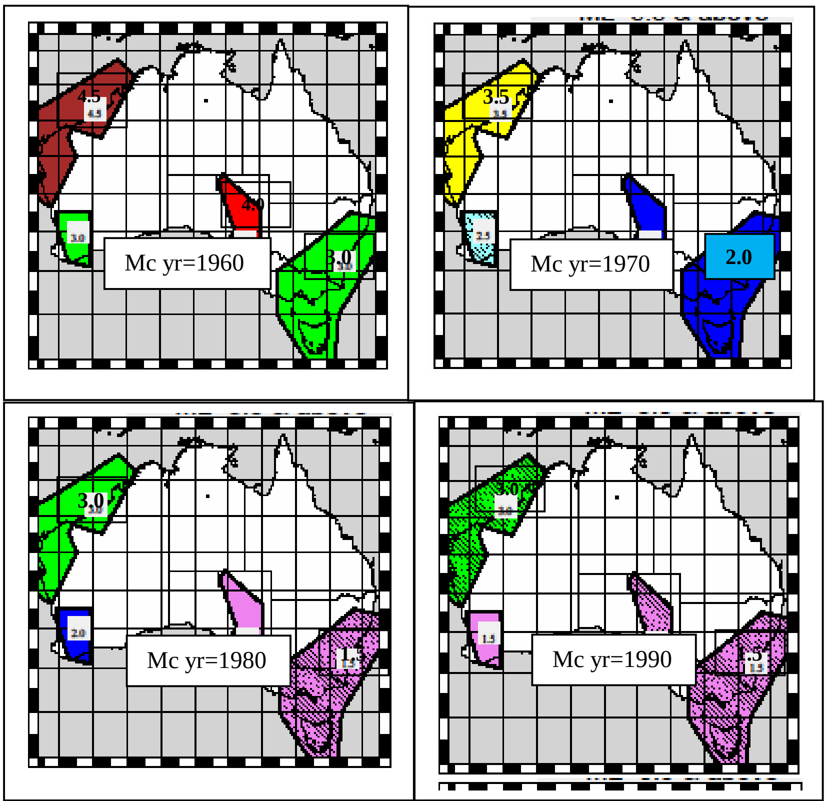


Figure 1 Plot of Mc values of zones as proposed by Leonard (2008)
Mauve – complete for mag 1.5 Blue- complete for mag 2.0
Pale blue – complete for mag 2.5Green = complete for mag 3.0
Yellow – complete for mag 3.5 Red – complete for mag 4.0
Brown – complete for mag 4.5

Previous estimates of Mc values in Australia

Leonard (2008), reviewed Australian seismicity, and proposed four seismic zones of "enhanced seismic activity" for the continent. These "super-zones" were basically an amalgamation of numerous zones proposed by earlier workers (e.g. Gaull et al. 1990). Completeness dates at various magnitude levels were proposed by Leonard for each zone, and his values are reproduced below (**Table 1).** To enhance these conclusions, four plots (**Figures 1A-1D**), for the years 1960, 1970, 1980 and 1990, based on Table 1, have been made.

Table 1 - Dates of Completeness for the Australian Earthquake Catalogue
From Leonard (2008)

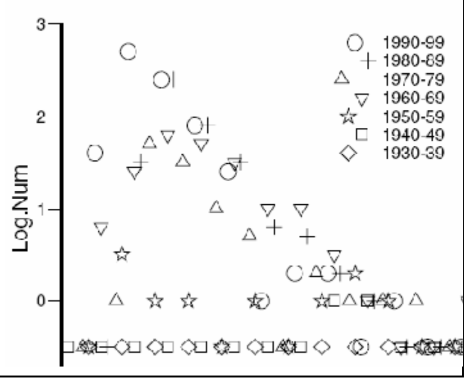
	Magnitudes						
Region	1.5	2.0	2.5	3.0	3.5	4.0	4.5
Southwest Australia	1990	1980	1965	1960			1880
Southern Australia	1980	1970			1965	1960	1880
Southeast Australia	1975	1970		1960		1955	
Northwest Australia				1980	1970	1965	1960

Where zones are hatched on Figure 1, specific values for that year were not given in Table 1, but it is assumed coverage has not improved since the previous value listed. The colour-coding system adopted is also used later in this report.

Methods of computing Mc

Three methods of computing Mc are described here. The first is a manual technique, and was the method used by Leonard (2008) to compute the values which have been graphed in **Figure 1**. It is based on the Gutenberg-Richter relation (log $N = a - bM$). This equation implies there is a log-linear increase in the number of earthquakes in each zone with decreasing magnitude. Using this method, the logarithm of the number of events in 0.5 magnitude unit bins was calculated and plotted by Leonard. Within each period tested, the magnitude below which the log-linear increase no longer applied was considered to be the completeness cut-off for the period. The catalogue was declustered prior to analysis. This is a process designed to remove aftershocks from the analysis (e.g., Sinadinovski, 2000). The plot used by Leonard (2008) to determine the cut-off dates for the southwest Australia zone is reproduced here as **Figure 2**. Leonard qualified his results by stating that because of the low numbers of events in each region, the method was "less refined" than was desirable.

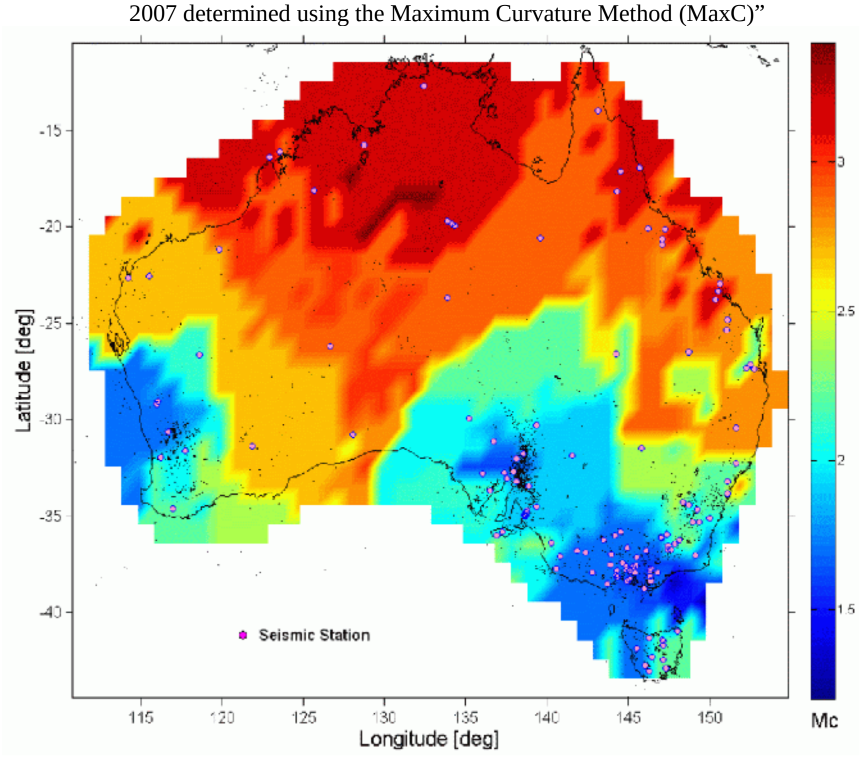
Figure 2 No. of earthquakes per decade in SWA (from Leonard, 2008)



The second method of computing Mc is an automatic procedure developed by Weimer & Wyss (2000) called ZMAP and also is based on the Gutenberg-Richter relationship. This method was used by Sagar & Leonard (2007) to produce an Mc map of Australia for the period 1998 – 2007, reproduced in **Figure 3**. ZMAP operates on the MATLAB platform, and is publically available via the internet. It is based on a linearity assumption of the cumulative frequency-magnitude distribution curve (FMD) introduced by Gutenberg & Richter (1944). It examines the numbers of events for a period at each magnitude level in a given catalogue, using either a fixed radius search or a fixed number of detected events.

Figure 3 Mc Map of Sagar & Leonard (2007)

"Magnitude of Completeness (Mc) of the Australian Earthquake Catalogue (AEC) 1998-2007 determined using the Maximum Curvature Method (MaxC)"



As Sagar & Leonard (2006) state, the technique requires a significant number of events in the areas under consideration, in order to produce statistically significant results. It is questionable as to whether the Australian earthquake catalogue meets these requirements. Because of the low numbers of events, the search procedure used in ZMAP requires a very large radius to be applied to each grid position in some areas – e.g. in northern Queensland, it was necessary to use a search radius of 1500 km. Again, as Sagar & Leonard state, this raises the question of whether the subset of locations adopted represents the true detection capability of the network of seismic stations in the area.

The problem with the above technique can be stated in another way. In a low seismicity region like Australia, a seismograph may run for a long time, and unequivocally indicate that no earthquakes occurred in the region of the seismograph over a relatively long period. However, the ZMAP program would interpret the lack of events as indicating the catalogue for that region and times was incomplete, and therefore not include that time-space regions in its calculations of seismicity rates.

The map in Sagar & Leonard (2007) suggests that, over the time period sampled (i.e. 1998 to 2007), the Australian earthquake Catalogue is complete for earthquakes of magnitude 3.5 and above. The user can make other inferences of completeness in regions of interest.

The third technique of calculating Mc does not use the earthquake catalogue or the Gutenberg-Richter relation, but examines the distribution of seismic stations, & considers their sensitivities. This method uses a computer program called “Detect” and was developed by Cuthbertson (2006, 2007). It is applied here to the networks of seismic stations which have operated in Western Australia, South Australia and the Northern Territory, between 1960 and 2005.

Earthquake Magnitudes

It should be noted that each authority (e.g. Geoscience Australia, Mundaring Geophysical Observatory, Primary Industries and Resources, SA) has or had its own method of computing earthquake magnitudes, and there is the question of how closely the magnitude scales agree. At this stage of development of Mc maps it is not necessary to consider this factor, because the other uncertainties (e.g. station detectabiltity) are sufficiently great that they would outweigh the influence of uncertainties in magnitudes. However, at some stage the issue of different magnitude scales, and different ways of computing magnitudes by the various authorities will need to be addressed.

How the program works -- A description of the “Detect” program

The program uses the following **inputs** - two pairs of geographic coordinates, defining the area to be gridded, a table of seismic station coordinates that includes a value (1, 2 or 3) defining the sensitivity of each station, the minimum number of stations needed for a positive result (i.e. one, two, or three or more observations at any given point), and the desired grid interval. A grid point interval of 0.5 degrees was used for this study. The program computes a matrix of grid coordinates, with its estimation of the magnitude detection threshold at each point on the grid.

If it is assumed that three stations are needed to locate an earthquake, then the factor “3” is applied in the procedure. This has been used for the plots 1970 - 2005 presented below. However, if additional information, such as “felt” reports, is available, it is often possible to make reasonable earthquake locations using only two seismographs. This was often necessary in pre-1970s seismology when there were few seismic stations, and the graph for 1960 (Figure 5A) is a “two station location” detection map.

The Detect program can also produce an output showing detectable areas using one station alone. As an example, the early Perth station (PER) could be used to determine the number of Magnitude 5 and above earthquakes within a certain radius of Perth, without knowing exactly where they originated. This is limited, but useful information for earthquake recurrence studies.

More programs were written by the author to complete the mapping process. A program was written which rounded-up the values at the grid points at 0.5 ML unit intervals. Another then converted them to a value to suit the colour table used in the plotting program. The plotting program was written using GMT (a plotting package developed at the University of Hawaii).

Factors relating to data processing

Numerous decisions related to input data and data processing were needed. Firstly it was decided to cull out from the station lists all temporary stations, triggered stations or stations considered to be frequently out-of-service.

The stations were assigned a detectability capacity of 1, 2 or 3 as mentioned above, and will be described in more detail below. Most of the stations remaining after this cull were assigned a sensitivity value of “1” or normal sensitivity. However some were probably significantly less sensitive (for reasons of location and/or instrumentation), and were given the lower sensitivity value (i.e. "2"). The ultra-low value of 3 was not used.

A decision on handling situations where there are two or more stations in close proximity (e.g. arrays) was needed. Two close stations both detecting a relatively distant event would suggest to the program that the event may become locatable, whereas in reality, arrivals from the second station are generally not used. This is particularly relevant for the ASPA and Warramunga arrays, and for this study they have been treated as a single station.

The problem of assigning detection capabilities to stations

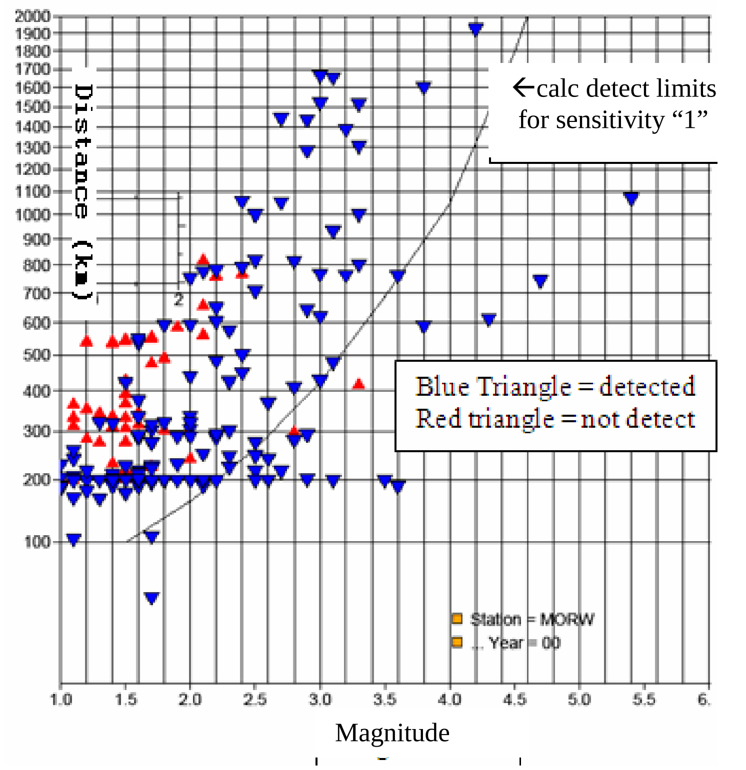
The "Detect" program needs to have a value of 1 (normal sensitivity) 2, (poor) or 3, (very poor) assigned to each station. These values reflect the distance at which each magnitude can be detected and a set of three curves was derived by Cuthbertson using a study of seismic stations in the Queensland network. The curves represent the distance at which there is a 90% likelihood of the earthquake being detected. The relationship between magnitude and detectability distance derived by Cuthberston (2006) was

$$1.04*M=1.077*\ln(R)-\ln(staxy)$$

where R is distance. Staxy is a value that can be changed to reflect the sensitivity of a station. For “normal” stations, the value used was 30.

The author made plots showing magnitude vs distance relationships for detectable earthquakes, using seismographs in Western Australia and South Australia. An example of such a plot for the station MORW (Morawa) in Western Australia (considered a sensitive station) is given in **Figure 4**. On this figure is also plotted the theoretical detection limits for sensitivity level “1” from the formula of Cuthbertson (above).

Figure 4 MORW detections, year = 2000



The plots for seismographs in WA/SA suggest that earthquakes at any given magnitude can be detected at far greater epicentral distances in WA/SA/NT than comparable earthquakes in Queensland. The reasons are not clear at this stage, but may be due in part to the lower seismic attenuation levels in the western half of the continent (Leonard et al, 2007). Variations in magnitude determination procedures may also be a factor. As the maximum sensitivity the Detect program can use is “1” it has been used for most stations. Some stations, which through the author's experience at the MGO were considered less sensitive, were assigned a value of 2. Similarly, after discussions with PIRSA personnel, some South Australian stations were also assigned a value of "2". These values may need revision in the future.

The final station list for each epoch, and the sensitivities assigned, are shown in **Table 2.**

The Plots output by the Detect program.

Six maps (**Figure 5, A-F)** have been presented, representing network detectability for each of the years 1960, 1970, 1980, 1990 and 2005, and a detailed version (using 0.2 degree grid spacing) of the 2005 plot for the region around Adelaide. At this stage, because of the uncertainties in the station detection values used, these maps should be considered a guide only. When better values are determined, and the program has been amended to accept these variations, the plots will need to be re-drawn.

The boundaries of the “southwest Australia” and “southern Australia” zones from Leonard (2008) are also indicated on these maps.

Figure 5 (A) 1960

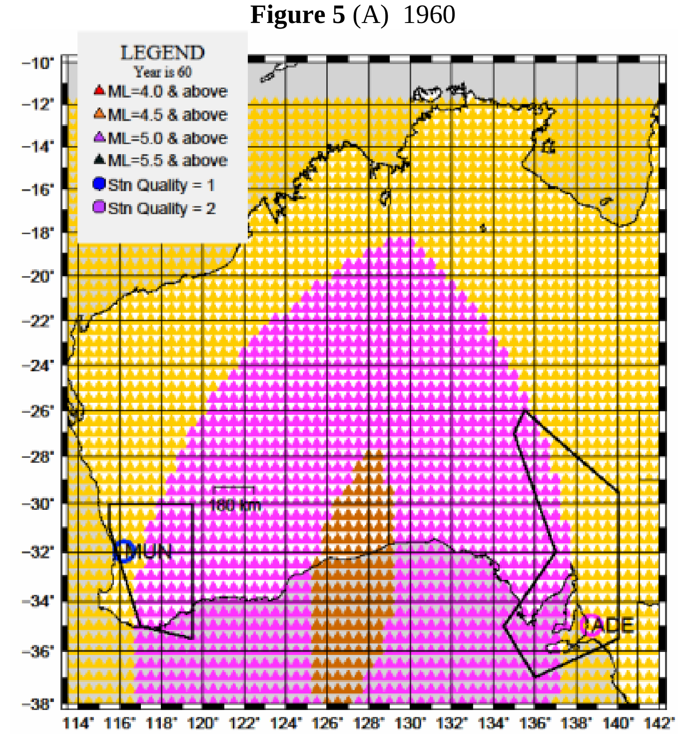


Figure 5 (B) 1970

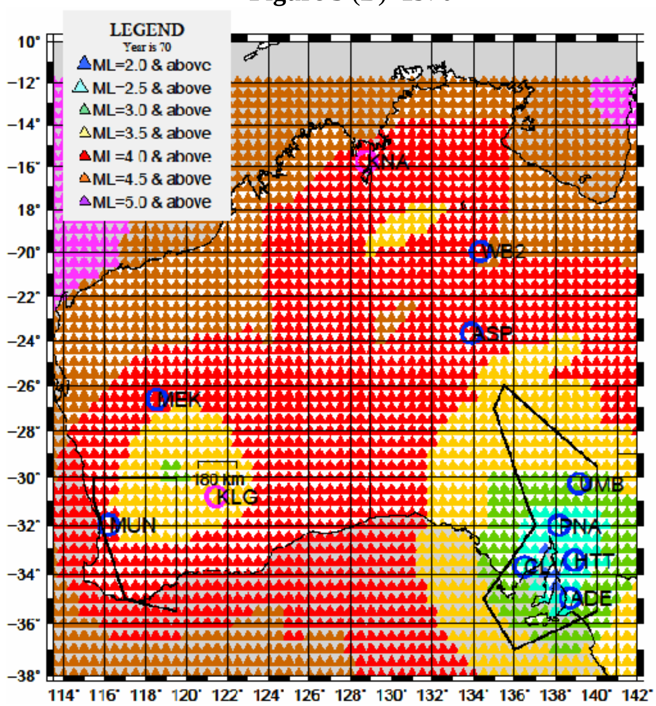


Figure 5 (C) 1980

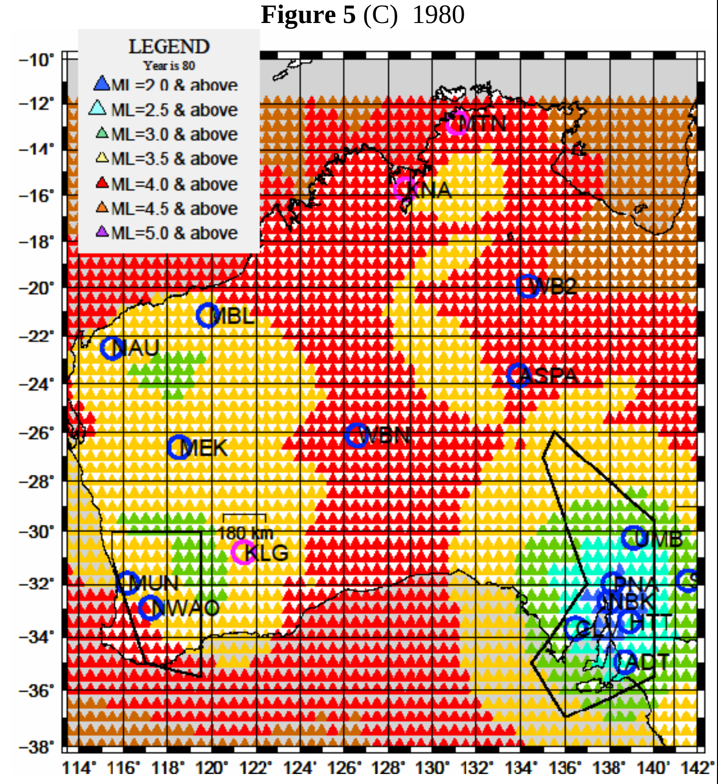
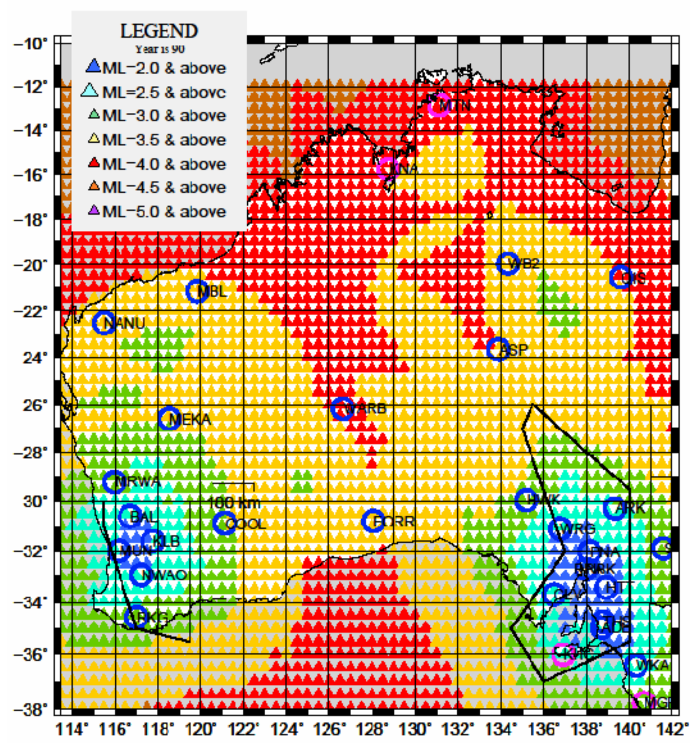


Figure 5 (D) 1990



As noted above, the 1960 map is a map of "two station locations". Thus, this plot assumes an earthquake could be located using MUN and ADE alone, the only two stations operating in the region in 1960.

Critical dates and stations for Mc maps

Figure 5 (E) 2005

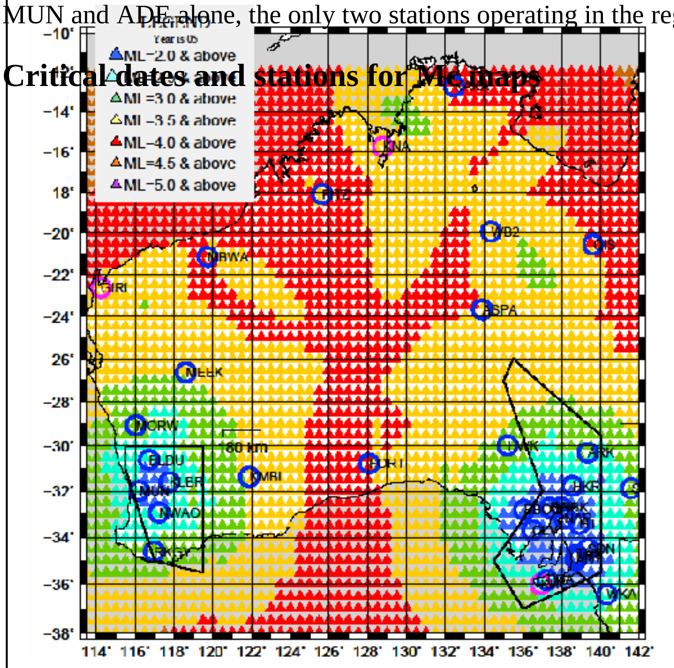
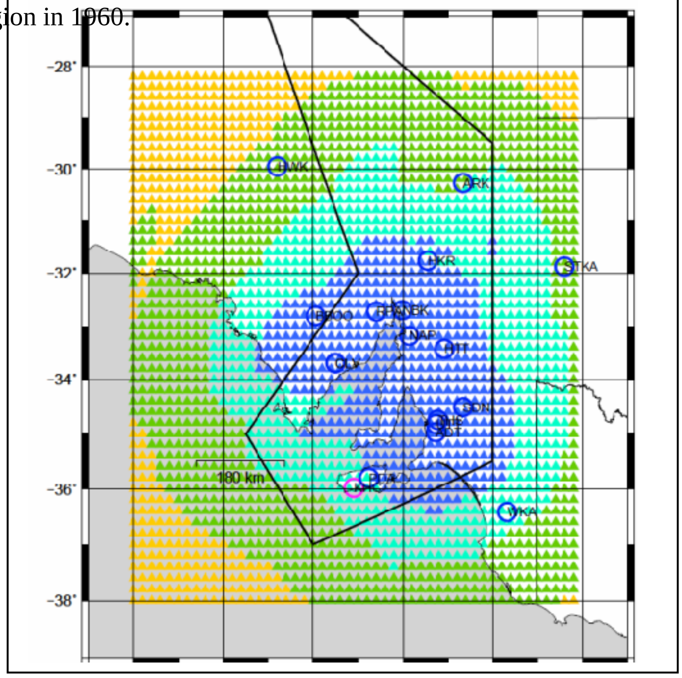


Figure 5 (F) ADE region, 2005



Certain dates and stations stand out as being particularly significant for the Mc maps. Thus the dates of installation of early Australian seismographs are important, and for the area studied here, PER (1901) ADE (1958) are very important. Next was MUN (1959) and an upgrade of the Adelaide station to World-Wide Standard Seismograph standard in 1962. Multi-station locations became possible in WA with the installation of KLG in 1964 and MEK in 1967. The far north of Western Australia achieved better coverage with the installation of an instrument on the Ord River dam at Kununurra (KNA) in 1965. However, this instrument was not very sensitive, and was only useful for very large events.

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Table 2 Stations and sensitivities used in this study

1960	1970	1980	1990	1990	1990	*2005*	*2005*	*2005*
			WA	SA	Other	*WA*	*SA*	*other*
MUN 1	MUN 1	MUN 1	MUN 1	ADE 1	ASPA 1	MUN 1	ADE 1	ASPA 1
ADE 1	ADE 1	ADE 1	ADE 1	HTT 1	WRA 1	ADE 1	HTT 1	WRA 1
	KNA 2	KNA 2	KNA 2	NBK 1		KNA 2	NBK 1	STKA 1
	KLG 2	KLG 2	KLG 2	CLV 1		KLG 2	CLV 1	QIS 1
	MEK 1	MEK 1	MEK 1	PDA 1		MEK 1	PDA 1	KAKA 1
	CLV 1	CLV 1	CLV 1	BBOO 1		WARB 1	BBOO 1	MTN 2
	ASPA 1	ASPA 1	ASPA 1	HKR 1		BLDU 1	HKR 1	
	WRA 1	WRA 1	WRA 1	WKA 1		KLBR 1	WKA 1	
	HTT 1	HTT 1	HTT 1	THS 1		RKGY 1	THS 1	
	UMB 1	NBK 1	NBK 1	KHC 2		KMBL 1	KHC 2	
	PNA 1	WARB 1	WARB 1	ARK 1		MORW 1	ARK 1	
		NWAO 1	BAL 1			FITX 1		
		MTN 2	KLB 1			FORT 1		
		UMB 1	RKG 1			GIRL 1		
		PNA 1	KMBL 1					
			MRWA 1					

Most important for Australian seismicity were the installation of arrays at Alice Springs in 1970 (December) and Warramunga (NT) in 1965. These stations were particularly sensitive and had an important influence on earthquake detectability across the entire continent. However, it should be noted that, particularly early in the station histories, communication of seismic data to other interested agencies, was not as effective as was desirable, due in part to the military aspects of these arrays.

More recently, dectectability in central Australia has actually diminished with the closure of Warburton (WARB) in 1999, and the vandalism of its replacement at Docker River (NT) in 2000. Also vandalism at MUN has meant poorer monitoring of the southwest Australia zone since late 2007 to the present.

In certain well-monitored areas, such as the Adelaide region there is now a degree of redundancy, such that the temporary loss of one station does not significantly change the effective Mc coverage. Triggered seismographs and strong-motion instruments assist in this regard.

Discussion

Historical data

Without the assistance of instrumental data, the historical record is the only source of information for the earthquake catalogue. To achieve relatively "complete" coverage using this method ideally assumes a relatively dense, uniform population density, with observations finding their way to the print media. This assumption is not valid in most of WA/SA/NT, particularly prior to the surge in mining activity in the mid 20^{th} century. In addition, the felt earthquake observations need to be "inverted" to produce earthquake locations and magnitudes, and large uncertainties are also involved in this procedure, particularly with scant data to work with. Therefore, conclusions regarding completeness using this method must be suspect.

Conclusions from maps produced using the Cuthbertson procedure

The method of Cuthbertson shows network capability at a given date, based on the seismic stations operating at that date. Thus individual maps can be made for any desired date, which is an advantage over the ZMAP procedure, where a time interval must be used. The minimum time interval that can be used will depend on the number of events, and hence the seismic activity, or the region examined. Sufficient events must be present in each cell to compute a meaningful frequency-magnitude curve.

The following inferences can be made from the maps presented here.

a) The Australian Earthquake catalogue (AEC) is complete for magnitude 5.5 and above events in 1960.

b) The AEC is complete for events of magnitude 4.5 and above in 1970.

c) The AEC is complete for events of magnitude 4.0 and above in 1990 (with the possible exception of small areas on the tip of Cape York).

d) The AEC is complete for events of magnitude 4.0 and above in 2005.

e) The Mc values suggested by Leonard (2008) for the zones he defined are in general probably too low –i.e. completeness levels were less than suggested. In particular, seismic coverage in the year 1960 was very limited, and unlikely to permit the seismic detection capabilities he suggested. In addition, many of his zones suggest completeness down to magnitude 1.5 in 1990, which, if the zones are considered in their entirety, suggests detection capabilities that have not been achieved in 2005 (or later).

Other conclusions depend on the area of interest. However, it should be remembered that the values presented here are probably conservative –i.e. completeness levels are likely to be better than suggested by the maps. When new values of station detectabilities are determined and applied to the program, the dates for complete coverage at each magnitude interval will probably be pushed backwards in time.

The factor of station reliability has not been addressed here. Seismic stations sometimes experience significant periods of "down" time, but this information is not available to the general public. Future revisions of these maps will need to review station operational periods more closely.

It should also be noted that this method treats the area under consideration as a single network. In reality, the seismic stations used here were/are under the jurisdiction of several different agencies, and difficulties in communications means that some potentially locatable earthquakes may in fact go un-detected.

Inference from the 2009 Beacon, WA earthquake swarm

An important swarm of earthquakes NW of Beacon in January 2009 (Dent, this volume) presents a unique opportunity to estimate the current Magnitude Completeness status of the southwest Australia zone of Leonard (2008). There were about 280 located earthquakes in this swarm, and their frequency-magnitude distribution forms a classical log-linear plot as used in the Gutenberg-Richter relationship (1944). Such a relationship is not normally observed in earthquake swarms, but this swarm was exceptional in the numbers of events within it.

The log-linear plot of event numbers vs magnitudes (Dent, 2009) shows a constant increase in the numbers of events with decreasing magnitude, until magnitude ML 2.3. This indicates that there were most probably relatively large numbers of smaller events which were not detected or located. This in turn indicates that the Magnitude Completeness level at this location in the southwest Australia zone (i.e. approximately 30.2 degrees south, 117.7 degrees east) is 2.3 or greater, and consequently the Mc level for the southwest Australia zone must have this value or greater. Since 0.5 magnitude increments are normally applied to Mc maps, it can be stated that the Mc value for the southwest Australia zone in 2009 is, at best, magnitude 2.5. This conclusion agrees remarkably well with the Mc plot for 2005 (Figure 5E), which shows the Beacon area to be close to the boundary between Mc values of 2.5 and 2.0. It also illustrates another important point in that, even though events of magnitude 2.0 or less in the Beacon area could normally be readily identified and located, they sometimes were not, possibly for reasons like over-loading of the seismic analysts because of the large numbers of events. Note also that administrative decisions can also play a part in Mc levels. The Mundaring Observatory did not report/locate events of magnitude less than 2.0 before the mid 1990's, even though approximate locations often could be made.

Conclusions

Computation methods for Mc values which use the Gutenberg-Richter relation have to be used with caution in low-seismicity regions like Australia, and maps produced to date which utilise this method are questionable. An alternative method using seismic station distribution/sensitivities, with maps presented here, produces very different values, and suggests that Mc values are far less complete than previously suggested. However, this method needs further refinement.

In addition, previous estimates of Magnitude completeness for the pre-instrumental era, using historical anecdotal material, for the western half of Australia, may also be optimistic.

The "Detect" program by Cuthbertson provides a method for quantifying detection capabilities of the Australian seismograph network, replacing values that were basically inferred earlier. The maps presented here may be based on conservative estimates of station detection capabilities, and much refinement is still required. This method may be more reliable in a low seismicity region like Australia, than an alternative method based on earthquake frequency-magnitude distribution curves.

The Beacon 2009 earthquake swarm indicates that the Mc level for the southwest Australia zone in 2009 is probably closer to 2.5, rather than the value of 1.5 previously suggested.

Acknowledgements

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