A new interpretation of the seismicity of the Mukinbudin/Bonnie Rock area of Western Australia

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Abstract

A magnitude 4.2 earthquake occurred near Bonnie Rock on 3rd January 2017 and was followed by ~ 55 aftershocks. A new seismograph (BR4) was installed in the area on 13th January 2017 and the aftershocks it recorded have allowed the source zone to be defined more precisely. To put the earthquake into context, the seismicity in the region since 1980 has been reviewed. New data from the independent Public Seismic Network have been used to improve epicenter quality for some events. Data from two field surveys, in 1992 and 2000, have also been retrieved and used in the analysis. It is suggested that most of the activity has come from two centres, but four other centres are also apparent. There are three centres of activity that are co-linear with the two major centres, and a new feature, the Bonnie Rock Seismic Lineation is proposed. The good earthquake locations made using the data from the BR4 seismograph suggest that the centre active in January 2017, as well as some activity from earlier years, may correlate with a nearby east-northeast trending fault on Jouerdine Hill.

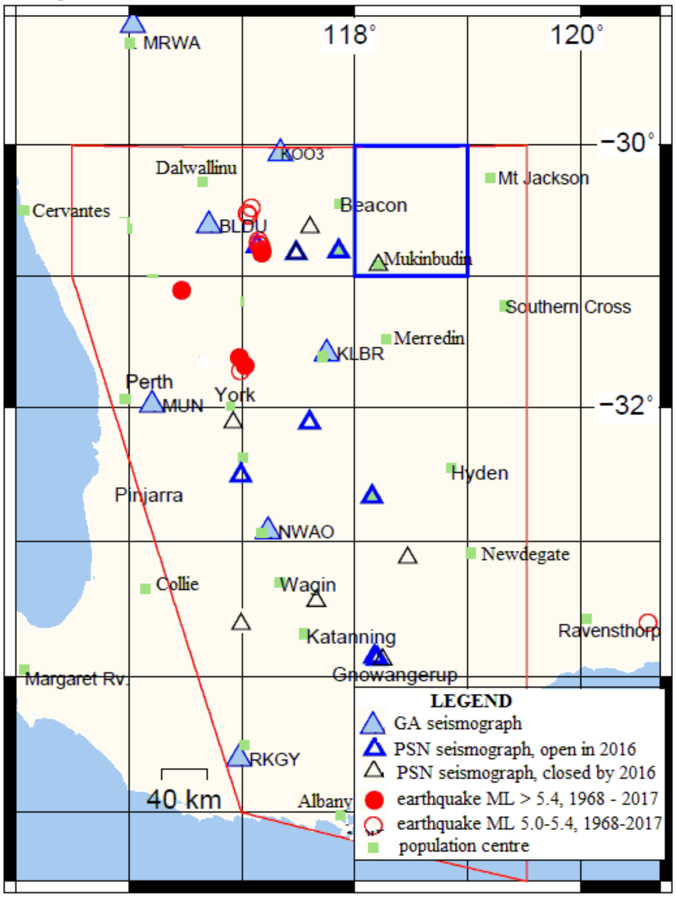
Keywords: seismicity, clusters, South west Australia

1 Introduction

1.1 Discussion of historical seismicity and seismic recording in the region

The Mukinbudin/Bonnie Rock region (MBR) is here defined as the square degree 30°-31°S, 118°-119°E (blue outline, Figure 1). Mukinbudin is a small town (population ~ 400) in the northern wheatbelt of WA, about 300 km NE of Perth, and Bonnie Rock is a disused railway siding about 40 km northeast of Mukinbudin (Figure 1). The wheatbelt region of WA is a well-recognised area of elevated seismic activity (e.g., Denham, 1987; Leonard, 2008), and has had two magnitude 6 earthquakes which caused significant local damage (Meckering October 1968 (Gordon & Lewis, 1980), and Cadoux June 1979 (Lewis et al., 1981)). Leonard (2008) defined the South West Australia (SWA) seismic region (red outline, Figure 1), and that definition will be used here. The largest earthquake in the MBR region was on 21st June 1968 (ML 4.7), and was located about 20 km north of Mukinbudin. However, the quality of monitoring at the time was poor. The

Figure 1 Seismograph stations in the SWA region and earthquakes ML > 4.9 since 1968

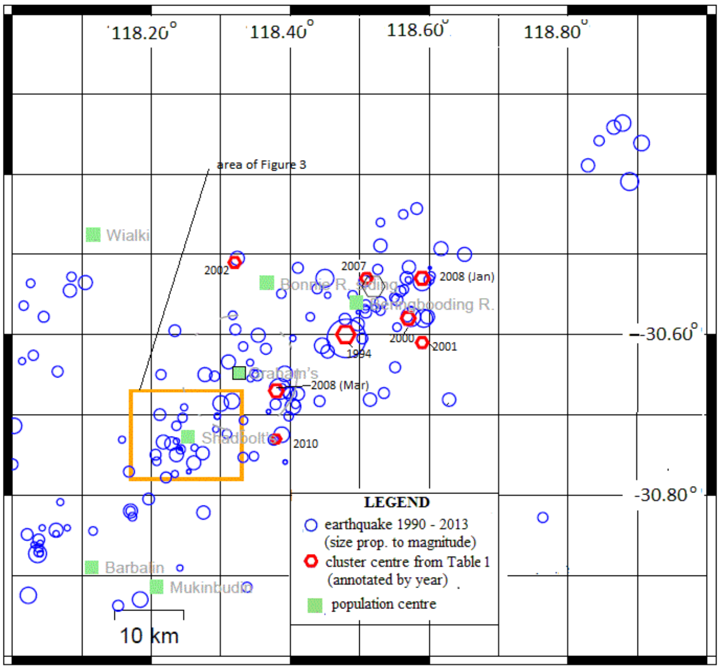


first seismograph in the SWA region was opened in 1959 near Mundaring, and by 1968, only Narrogin (NWA), Kalgoorlie (KLG) and Meekatharra (MEK) had been added to the network. The latter two stations were relatively distant, meaning that many low magnitude events (ie. < ~ML 2.5) may have passed undetected. It also meant that location errors were relatively large (estimated up to ~ 50 km).

There have been two magnitude 4 events in the MBR region since 1968. Seismicity of the region between 1990 and 2013 is shown in Figure 2. An event on 26 April 1994 (ML 4.1) had few (located) aftershocks, but the event on 3rd January 2017 (ML 4.2), had over 50 located aftershocks. The seismicity in the SWA region had been at very low levels for several years, and the 3rd January 2017 event was the first magnitude 4+ event in the SWA region since an ML 4.2 event north of Koorda in June 2009.

Earthquake clustering is an important feature of seismicity in the SWA region. Denham et al. (1987) noted that spatial clusters of earthquakes were a feature of the SWA region. Leonard (2008) produced a declustered catalogue of Australian earthquakes, where "dependent" events (foreshocks and aftershocks) were removed, leaving only "main shocks". However, the definition of an aftershock can be difficult, as explained by Ghasemi et al. (2013). Leonard (2008) noted that the SWA region showed the most pronounced clustering, and 63% of events were removed in the declustering procedure (against an average of 39% for Australia as a whole). Recent studies of the region by Dent (e.g. Dent 2014; 2015; 2016) suggested that about 90% of events could be emanating from cluster locations, of which 36 have been identified so far (Dent, 2016). The high degree of clustering was perhaps the reason for Ghasemi et al. (2013) to state the "aftershock sequences are more productive in WA than elsewhere".

Figure 2 Earthquakes in the MBR region, 1990-2013



It is possible that the "higher productivity" of aftershocks could be due to the shallow nature of events in the region. Geoscience Australia (GA) has assigned depths of 10 km to most solutions since December 2016. Although GA has given depths of 17 km or more to some earlier events, the author considers such depths dubious, and that no convincing case has been made for any event in the SWA region to have a focal depth greater than 10 km. Probably, most focal depths are considerably less than 10 km.

1.2 Notes on seismic networks and earthquake locations

Leonard (2008) noted that locations in the GA earthquake catalogue are generally poor, because of the sparse distribution of seismic stations in Australia, and that about 40% of locations had uncertainties of 10 km or more, although some Australian regions where there was a higher density of seismographs (including the SWA zone) had generally better locations. However, the author considers the MBR region should be excluded from this "better quality" descriptor, because it falls outside of the network of local seismographs.

Studies by Dent (e.g. Dent, 2014, 2015) have attempted to show that when better locations are achieved, the earthquake clusters are much more tightly clustered spatially than plots of GA data suggest.

To get improved earthquake locations when an earthquake cluster occurs, field instruments are sometimes deployed, and three such surveys have been conducted in the MBR area. The first was between late 1992 and early 1993, to record a group of small earthquakes north of Mukinbudin. The second was in June 2000, east of the Bonnie Rock siding, and the third was a single station installed southeast of Bonnie Rock after the ML 4.2 event of January 2017. These deployments will be discussed later in this report.

GA locates earthquakes in southwest Australia using a core of six seismic stations (MUN, KLBR, BLDU, NWAO, MRWA and RKGY – see Figure 1). Large earthquakes are also recorded at more distant stations, e.g. MEEK, KMBL, but these have little bearing on determining the final earthquake location. There is an average of about 200 km between recording stations in SWA, but ideally, for greater location accuracy, separation would be about half this value or less.

1.3 The "Public Seismic Network"

GA's seismic network in the SWA region has been gradually augmented since 2006 by the deployment of independent "Public Seismic Network" (PSN) stations (Dent et al., 2009), and at the end of 2016 there were eight such stations operating in SWA, (blue triangles in Figure 1). For this report, the most significant stations are Beacon (2009-2012), Koorda (2011 onwards), and Bencubbin (2014 onwards). GA does not use PSN data in its routine locations, as the format is incompatible with GA data processing methods. In this report, many of the events in the MBR region have been relocated using the EQLOCL program, incorporating PSN data where possible.

Table 1 Principal events within clusters in the Mukinbudin- Bonnie Rock region, 1990 – June 2017

Date	GA (lat)	GA (lon)	No. ev#	Mag (ML)	Auth!	Place	Preferred location	ID	Comment
19-Jan-1993	-30.74	118.24	16	2.0		Shadbolt's	-30.74, 118.24	A	Good-from field data
13-May-1994	-30.60	118.48	3	4.1	1	Mukinbudin		B	Poor – little phase data
05-Jun-2000	-30.58	118.57	7	2.9	1	Beringbooding	-30.57, 118.59	C	Good-from field data
03-Jan-2001	-30.87	118.04	8	2.8		Barbalin	-30.86, 118.05	D	Poor-avge of 2 big events
27-May-2001	-30.61	118.59	4	2.3	1	Beringbooding		E	
17-Oct-2002	-30.51	118.32	2	2.5	1	Bonnie Rock		F	
20-Apr-2007	-30.53	118.51	10	2.3	1	Beringbooding		G	
18-Jan-2008	-30.53	118.59	5	2.8	1	Beringbooding		H	
24-Mar-2008	-30.67	118.38	7	3.0	1	Nr. Graham's		I	
03-Nov-2010	-30.73	118.38	14	2.2	1	Nr. Graham's		J	
30-Jan-2011	-30.53	118.11	3	2.5		Wialki	-30.54, 118.09	K	Poor-avge of 2 big events
10-Sep-2013	-30.34	118.88	3	2.7		Mt Jackson	-30.34, 118.90	L	Poor-avge of 3 events
10-Jul-2014	-30.49	118.62	4	2.5	2	Beringbooding		M	
03-Jan-2017	-30.61	118.45	50	4.2		Graham's	-30.66,118.42	N	Good-from field data
05-Jun-2017	-30.75	118.05	13	2.9		Welbungin	-30.82 118.05	O	North of location D

estimated number of events in cluster group

! Authority: 1= cluster from Dent (2016), 2= Dent (2015)

In a recent investigation of clustered seismicity in the SWA region during the period 1990-2016, Dent (2016) identified 98 cluster groups, of which eight are within the MBR region. These cluster groups are listed in Table 1(Auth=1 in column 6), and the GA location of the principal event in each group is shown in red on Figure 2. They will be discussed in this report, along with other significant events in the MBR region since 1990.

Earthquake location procedures and history

Earthquake locations in WA until April 2000 were the responsibility of the Mundaring Geophysical Observatory (MGO) from its inception in 1959, until April 2000, when its functions were transferred to GA in Canberra. Computer locations were introduced to the MGO in the early 1990's, and Table 2 summarises significant changes in location procedures that have occurred since monitoring commenced in SWA in 1959. Most of the earthquake solution data from before 2000 has not been found, and therefore the location quality cannot be assessed. However, many of the epicentres from 2000 onwards can be reviewed, and some relocations have been made for significant events.

The whole of the GA catalogue for the period 1990 – 2013 is plotted on Figure 2. This plot shows a "cloud" of seismicity, with a distinct northeast trend. The largest event of the period was an ML 4.2 event southeast of Bonnie Rock on 26 April 1994, with only one located aftershock. However, it seems probable that there were others, just not located.

Table 2 Important dates for changes to GA's location methods

Period	Location method	Model used	Auth-ority
Aug 1959-Mar 89	Map & protractor	WA1	MGO
Apr 1989-Jan 90	EQLOCL	WA1	MGO
Feb 1990-Mar 00	EQLOCL	WA2	MGO
Apr 2000-July 09	EQLOCL	WA2	GA
Jul 2009-May 14	Antelope	WA2	GA
May 2014-2017	Antelope	IASPEI	GA
Dec 2016-present	All events given 10 km depth		

For analysis in this report, the catalogue since 1990 has been divided into three time periods, period A (1990 – 2013), period B (2014-2016), and period C, from January 2017 onwards.

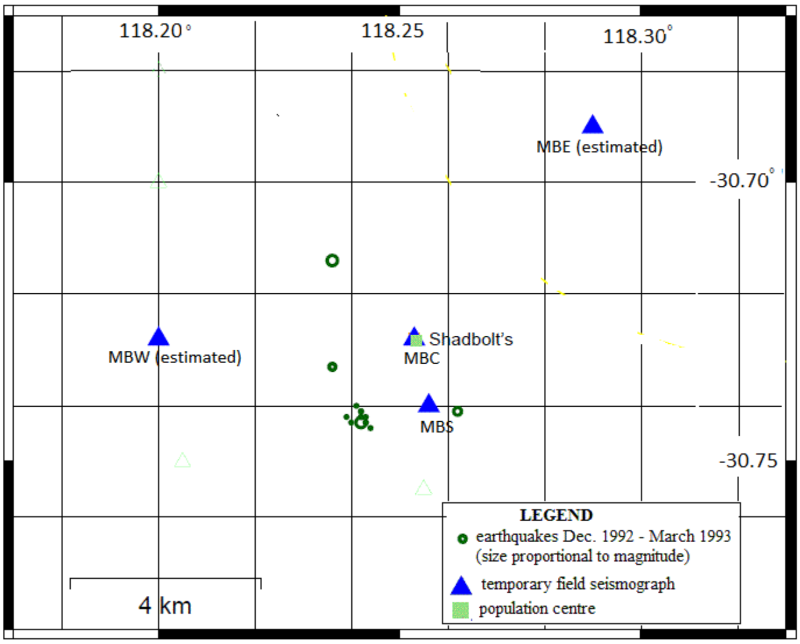
Because of the uncertainty in earthquake locations, the following question remains open - are "clustered" events scattered, as the catalogue suggests, or do they originate from a single location, or perhaps there may be several closely spaced centres of activity. Events in the MBR region between 1990 and 2017 are re-examined here, in order to try and answer these questions.

2 Review of Period A (1990 – 2013)

Events in this period are plotted on Figure 2. The significant events/clusters will be discussed, but first, the results of two periods of field recording which occurred in this period will be reviewed.

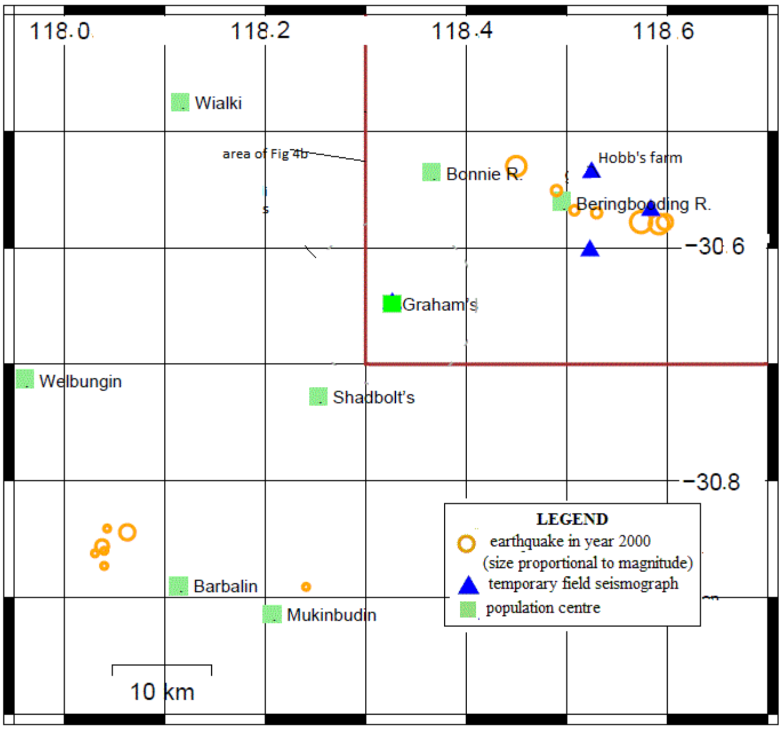
2.1.1 Field recording (1) – Cluster north of Mukinbudin, December 1992 to March 1993

Figure 3 – Events north of Mukinbudin Dec 1992 – Mar 1993



This survey is mentioned briefly in Leiba & Dent (1994). It was prompted by a group of many small felt events north of Mukinbudin, of which 16 were located by the MGO. The cluster was not noted in the review by Dent (2016) as none of the events were above the magnitude threshold of ML 2.1. Field seismographs were deployed by the MGO at four different locations between December 1992 and March 1993 (Figure 3). Thirteen of the locations are within 0.5 km of 30.743°S, 118.242°E (Figure 3). This location is saved as location A in Table 1. The other three more remote events probably did not have field data to assist in the locations, but they probably also originated from location A.

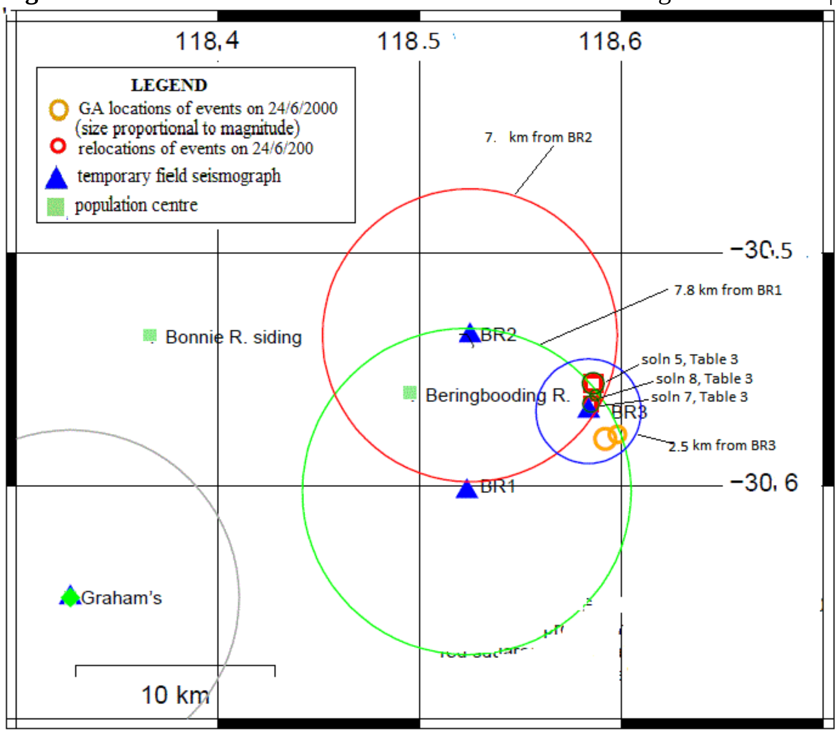
Figure 4a Events near Bonnie Rock, January – December 2000



2.1.2 Field recording (2) – Cluster east of Bonnie Rock, June – September 2000

This cluster of 7 events between June and Sept 2000 is shown as group C in Table 1. All located events in the year 2000 in the MBR region are shown in Figure 4a and relocated events in Figure 4b. Three recorders were deployed by GA near Beringbooding Rock in June 2000 (BR1, BR2 & BR3, blue triangles, Figure 4). No archival information has been found about this survey, other than the station coordinates, and that the data were used in locations for two earthquakes, both on 24th June 2000 (0242, ML 2.5, and 0243, ML 2.8). The event(s) which prompted this field survey are uncertain, but it was probably the ML 2.9 event east of Bonnie Rock on 5th June 2000.

Figure 4b Locations/relocations of events 24 June 2000 using field data



The RMS of seismograph residuals for these two locations, including the close stations, are relatively large (> ~ 0.5 secs.), suggesting non-optimal locations (see Table 3). The author has reviewed the GA solutions for the 24th June events. The S-P times at each of the field stations is constant (ie, 0.9 for BR1, 0.8 for BR2, and 0.3 for BR3) which suggests the two events came from the same location. The events have been relocated, using the same data and methods as GA used, but with heavy weighting given to the field stations, and with most of the more distant arrivals removed from the regression. The solutions are shown in the appendix and summarized as solutions 5 and 7 in Table 3. The focal depths are less than 1 km. The results also suggest a 1 second clock error at BR2. The relocations move the events about 3 km northwards, and with focal depths of 0.2 and 0.9 km (solutions 3 and 5 in Appendix 1). A suggested location for both events is 30.57^{o}S, 118.59^{o}E, and this is saved as location C in Table 1.

It is possible that the best solution may be found by using only data from the three field stations. This has been done, and suggests a focal depth of 2.1 km (solution 8 in Table 3).

It is suggested that all seven events near Bonnie Rock in 2000 emanated from the location determined for the 24th June 2000 events (ie, Location C).

Table 3 Parameters of significant earthquake solutions (GA data, except where indicated)

Date	Time UTC	Latitude	Longitude	Dep (km)	Mag (ML)	r.m.s resid	# of stns.	# of Phases	**Comment**	
19-Jan-1993	0439	-30.743	118.242	2	2.0	-	-	-	"Shadbolts"; good location	1
26-Apr-1994	1549	-30.6	118.48	5G	4.1	.49	8	10		2
5-Jun-2000	0349	-30.58	118.57	2	2.9	.71	7	12		3
24Jun-2000	0242	-30.578	118.598	0.3	2.5	.38	7	13	Free depth; see appendix	4
	0242	-30.548	118.583	0.2		.09	5	9	See note 1; see appendix	5
24 Jun-2000	0243	-30.580	118.592	0G	2.8	.43	7	13	See appendix	6
	0243	-30.565	118.585	0.9		.08	5	9	See note 1; see appendix	7
	0243	-30.561	118.587	2.1					See note 3	8
03-Jan-2001	1509	-30.87	118.04	5	2.8	.44	7	12	Barbalin	9
27-May-2001	2048	-30.61	118.59	1	2.3	.82	7	12		10
17-Oct-2002	2034	-30.51	118.32	0	2.5	.81	6	9		11
20-Apr-2007	0510	-30.53	118.51	5	2.3	.82	5	8		12
18-Jan-2008	1040	-30.53	118.59	14	2.8	.47	7	14	Free depth	13
24-Mar-2008	1731	-30.67	118.38	13	3.0	.31	6	12	Free depth	14
3-Nov-2010	0737	-30.73	118.38	10	2.2	.08	4	6		15
30 Jan 2011	0857	-30.53	118.11	0	2.5	-	-	-	Wialki, poor location	16
10 Sep 2013	2348	-30.34	118.88	13	2.7	.74	8	14	Mt Jackson	17
03 Jan 2017	1530	-30.455	118.609	10	4.2	3.2	18	23	"Graham's"	18
	1530	-30.698	118.385	0	4.0	.39	-	-	See note 2; SRC solution	19
	1530	-30.635	118.431	2N	4.2	.26			See note 1	20
05 Jun 2017	0911	-30.752	118.050	10	2.9	2.3	9	13	Welbungin	21

All focal depths are believed to be constrained by the analyst, except as indicated in the comments column
Note 1 - PSN location using WA2 model and EQLOCL program
Note 2 - SRC location using WA2 model and EQFOCUS program
Note 3 – PSN location using only field station phase data

2.2 Other seismicity during Period A

2.2.1 The Magnitude 4.1 event, 26 April 1994

The hypocentral parameters for this event (including RMS of residuals, number of stations and phases used), are listed in Table 3. The GA location puts it near Beringbooding Rock. There was only one GA located aftershock, ML 2.4, about 40 mins later, which GA locates about 3 km northeast of the main event. The station residuals for the main event are relatively high (Table 3), suggesting an uncertainty of ~ +/- 10 km. It seems probable there were other aftershocks, but with magnitudes below the locatability threshold, estimated to be at about ML 2.0.

2.2.2 Northwest of Barbalin, December 2000 – January 2001

There were 8 events in this group in the southwest of the MBR region, in December 2000 and January 2001, largest ML 2.8 (Figure 4a). It is suggested they have originated from a common point, 30.87°S, 118.04°E, the approximate median position of the two largest events. This location is saved as location D in Table 1.

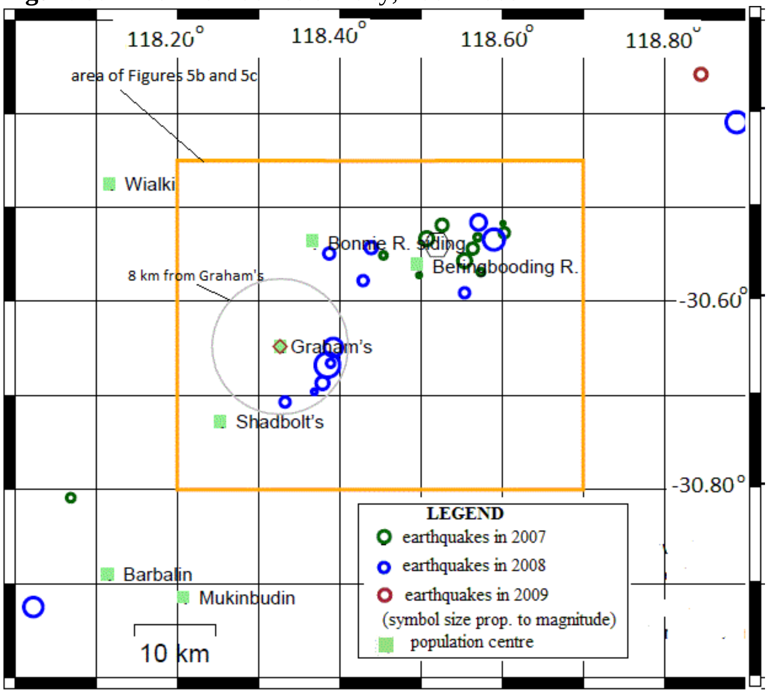
2.2.3 Cluster near Beringbooding Rock in May, 2001.

There are four events in this suggested cluster - two in May 2001 (group E in Table 1), and two in July 2001 (Figure 4a). The locations are relatively scattered, to the east and south of Beringbooding Rock, but examination of the GA solutions suggests that the accuracy is not high. A “preferred location” is not proposed in Table 1. They could be at the same location as the June-Sept 2000 events. (Location C, Table 1)

2.2.4 Cluster near Bonnie Rock siding in September and October, 2002.

This cluster of only two events is shown as group F in Table 1. They are about 8 km apart, and are apparently near the Bonnie Rock siding. The locations probably have relatively large uncertainties. Again, no “preferred location” is suggested here.

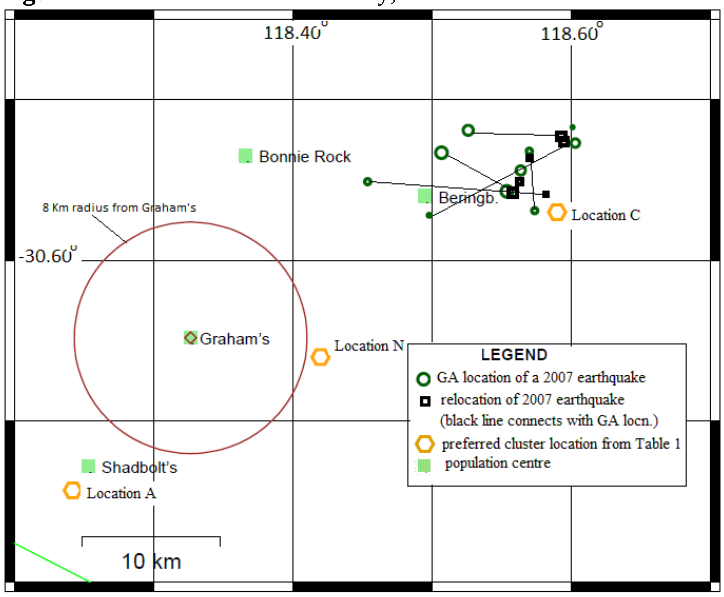
Figure 5a Bonnie Rock seismicity, 2007-2009



2.2.5 Events in 2007, 2008 and 2009

Events between 2007 and 2009 are plotted on Figure 5a. There is one cluster noted in Table 1 in April 2007 (group G). All 2007 events are plotted in more detail on Figure 5b. Good relocations have been made for some of these events. Archival data from the temporary station KOO3, which was part of a network of three stations deployed in 2005 to monitor seismic clusters near Koorda and Kalannie (Figure 1), have been used in some of these relocations. The relocations suggest that the rather scattered events could

Figure 5b Bonnie Rock seismicity, 2007



all be relocated close to Location C (shown as a yellow circle on Figure 5b).

All GA locations for 2008 are plotted on Fig 5c. Table 1 shows two cluster groups in 2008 (in January and March), and good relocations were achieved for some of the events. The new plot suggests that some of the events are continuing activity from the 2007 cluster location (location C in Table 1), and some represent activity at a location about 9 km southeast of Graham's farm. This location is close to a well-constrained cluster location (location N) defined later in this report. It is suggested that this group of 2008 events comes from location N.

Figure 5c Bonnie Rock seismicity, 2008

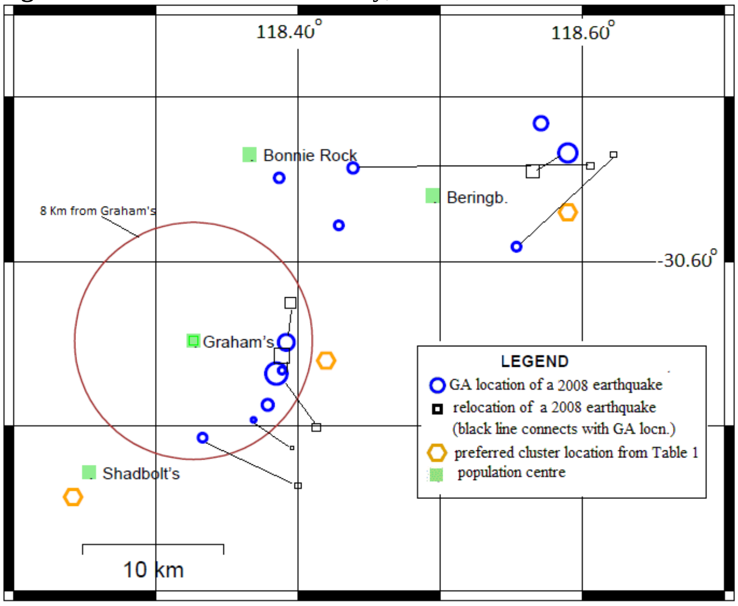


Figure 5a shows one event northwest of Barbalin in December 2007, which may correlate with the December 2000 activity (location D in Table 1) and two events in the far northeast of the zone, (December 2008 and November 2009), which may correlate with later activity "southwest of Mt. Jackson" in 2013, which is discussed below.

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2.2.6 Events from 2010 to 2013

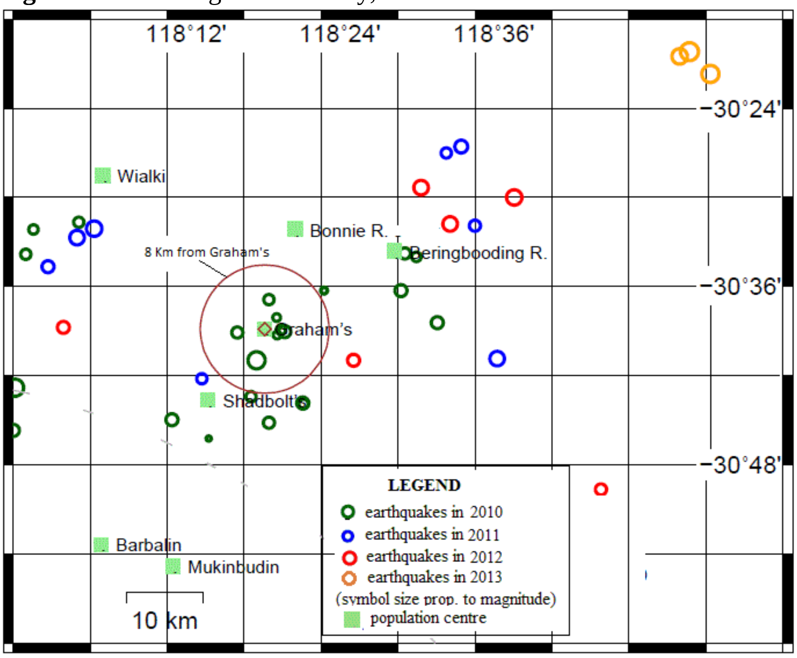
GA solutions for events in this period are plotted on Figure 6, but as noted earlier these solutions may have large uncertainties. Table 1 notes clusters in November 2010, January 2011, and September 2013.

There were 13 events in November 2010, with 9 events on 3rd November (largest, ML 2.2). These events hovered around Graham's farm, and it is here suggested that this cluster emanated from location N, east of Graham's farm.

Three events occurred south of Wialki in January 2011, the largest being ML 2.5. The suggested cluster centre, shown as Location K in Table 1, is the approximate centre of the two largest events. This 2011 activity is probably at the same location as three smaller events in January 2010.

Three events occurred in the NE of the MBR region (ie, near Mt. Jackson) in August and September, 2013, the

Figure 6 MBR region seismicity, 2010 – 2013.



largest being ML 2.7. Location L in Table 1 is the approximate centre of this cluster. This group of events was noted in a review of 2013 seismicity in Dent (2014), and has been labelled as cluster location L3 in Dent (2017)

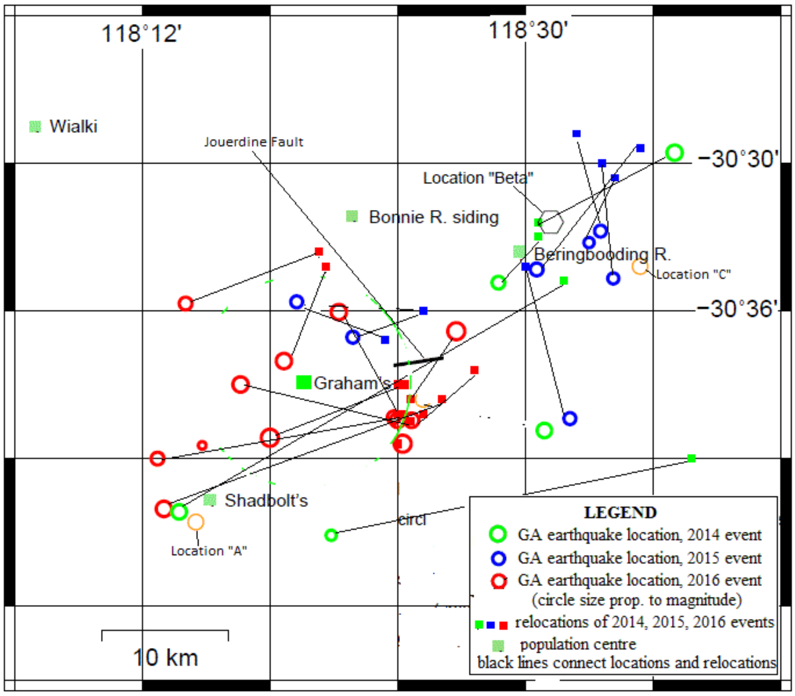
3 Review of Period B (2014 – 2016)

Events in this period are plotted on Figure 7. They will be discussed in two groups, events in 2014-2015, and events in 2016

3.1 Events in 2014 and 2015

The 12 month period June 2014- May 2015 was discussed in Dent (2015). There were 11 events in the area over this period, mostly in July 2014 and April 2015. As with previous events, they are quite scattered, which is attributed to uncertainty in the locations. Four of those events were relocated, and a cluster centre was roughly defined at location “Beta” (Figure 7 and Table 1). A number of the other events in 2014 and 2015 are here relocated, and are also shown on Figure 5. Two of the events have been moved about 40 km in the relocation, and most seem to congregate in the vicinity of the well-defined location “C”, about 8 km southeast of “Beta”. It is suggested that location Beta, which was not well constrained, be moved about 5 km east, to coincide with location C.

Figure 7 Relocations of Bonnie Rock events, 2014, 2015, 2016



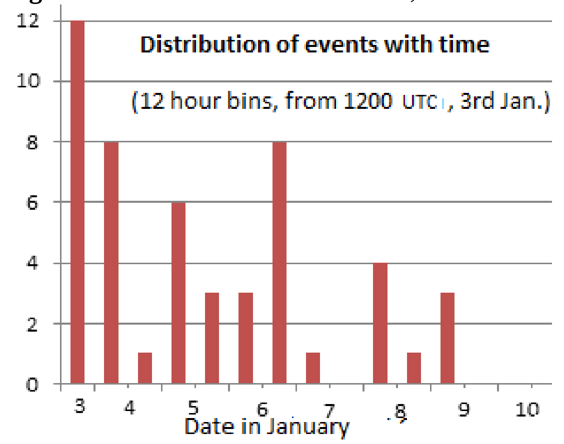
3.2 2016 events

The 13 events in the MBR region in 2016 (Figure 7) fall into two groups – September 2016 (3 events) and November 2016 (10 events). The first event of the September 2016 group (1st September, 2050 UT) plots well to the northeast of Bonnie Rock, and seems to be in a similar location to the group “SW of Mt. Jackson” of August 2013, ie, location “L”. The other two events (both on 2nd September 2016) are each moved about 10 km by relocation, and now plot close to each other, about 5 km southwest of Bonnie Rock.

The 10 events in November 2016 occurred between 14th and 16th November. These events have been relocated and suggest a quite tight grouping close to -30.67°S , 118.41°E, which will be shown to be the preferred location for the major cluster in January 2017 (location N).

4 Period C -- January to June, 2017

Figure 8 Time distribution of events, 1-10 Jan.

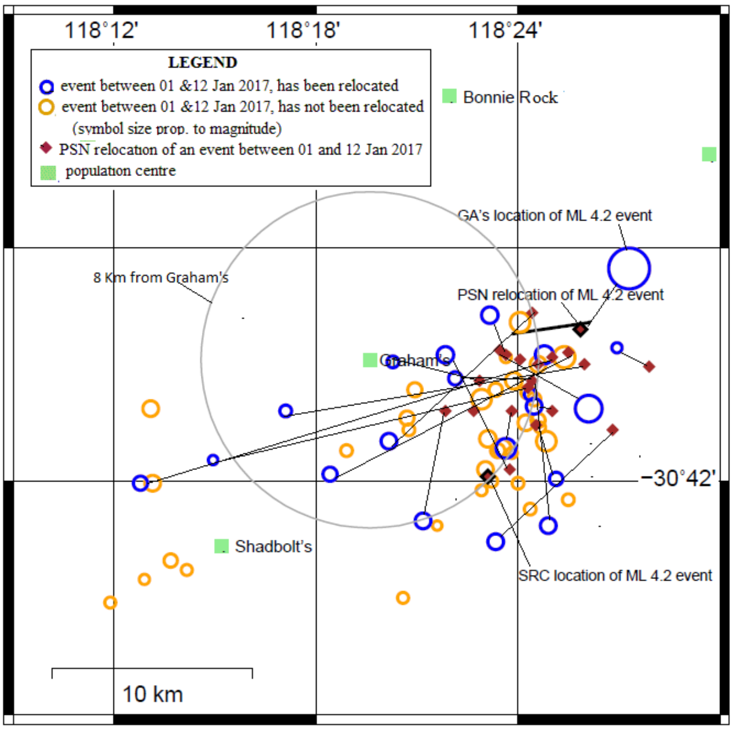


This period is divided into two sub-periods. Sub-period 1 is 1st – 12th January, which includes the ML 4.2 event and most of the aftershocks, and Period 2 is after 13th January, when a new (PSN) seismograph (code BR4) was installed at Graham's farm, the closest available location to the ML 4.2 event. Relocations of events after the installation of BR4 can be expected to be relatively more accurate. The BR4 station became more reliable, as well as more sensitive, on 9th May 2017, when the the recording computer was upgraded, and the initial sensor (a 4.5 Hz geophone) was replaced by a Willmore Mk II seismometer, and moved to a quieter location.

4.1 Sub-period 1, 01-12 January 2017

The ML 4.2 event on 3rd January 2017 was the first magnitude 4 event in the SWA region for over 7 years. It was felt widely in the area (estimated MM III at Mukinbudin), and 49 aftershocks were located by GA over the next 6 days (Figure 8). Their magnitudes ranged between ML 1.9 to 3.4, and 18 of them have been relocated. PSN data indicates the presence of at least 18 other aftershocks not located by GA. About half of these were in the first 6 hours after the main event, and their estimated magnitudes are up to ML 2.0.

Figure 9 Relocations of Bonnie Rock events, 01-12 Jan 2017



The GA solution for the ML 4.2 event (Figure 9 and Table 3) appears to be separate from most of the aftershocks, being about 10 km to the northeast of them. All events in the cluster were assigned focal depths of 10 km by GA, and the locations plot over a region about 20 km wide. However there is a concentration of aftershocks at about 30.6°S, 118.4°E, coinciding with the relocated events of November 2016 (Figure 7). The uncertainty of the coordinates for the main event is indicated by GA to be about 7 km. However, the large RMS of residuals (3.18 secs) suggests the uncertainty could be larger than this. The earth model used by GA was IASPEI91 (Kennett & Engdahl, 1991). It would be expected that the main shock would be better located than the aftershocks, as it was recorded by more stations, and the phase arrivals would also be clearer.

However, this may not be the case, as phase data from distant stations (> ~ 500 km) does not necessarily help to improve an earthquake location.

The main event was also located by the Seismology Research Centre (SRC) in Melbourne, using the WA2 earth model (Dent, 1990), and this solution is about 9 km southwest of the GA location, with a focal depth of 0 km (Table 3). This solution is closer to the plot of the aftershocks. The SRC solution used fewer stations (10), but the RMS is much lower (Table 3). The relocation by the author, incorporating PSN data, is between the GA and SRC solutions (Figure 9). Twenty of the 49 aftershocks before 13th January have been relocated, with PSN data added to the data mix. These relocations bring all events closer to the author's relocation of the main event. Some of the GA solutions have been moved ~ 20 km.

The GSWA 1:250,000 geological map of the region shows a group of three faults on Jouerdine Hill, in the vicinity of the epicentres. The largest of these faults is about 2.5 km long, strikes approximately to the east-northeast, and is clearly visible on aerial photography. This fault is shown on Figure 9, and the proximity of the fault to the epicentres may suggest an association with the seismicity.

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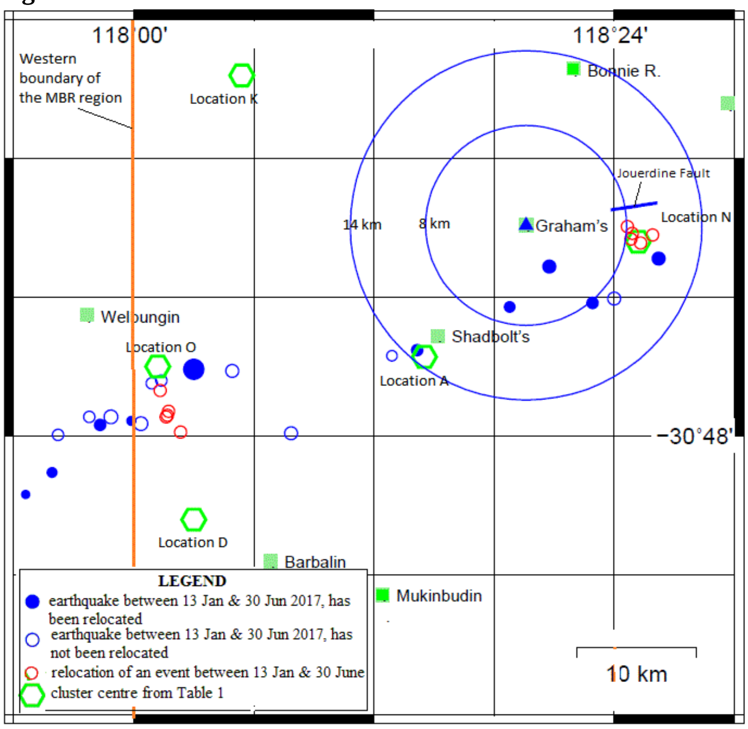
4.2 Sub-period 2, 13 January 2017 – 30 June 2017

During sub-period 2, from 13 January – 30 June 2017, there were 13 GA-located events in the MBR region, most of which were recorded at BR4. Seven of these events (up to 5th March 2017) appear to be aftershocks of the 3rd January 2017 event. The high sample rate used by PSN seismographs (200 s/s) allows for accurate timing, and the important feature of the seismograms recorded is the well-determined S-P times. These are consistently close to 1.0 seconds (Table 4), which suggests a tight source zone, contrasting with the diffuse pattern suggested by the GA locations. The five EQLOCL relocations (Table 4, Figure 9) suggest the source zone is about 2 km south of the Jouerdine Fault. These relocations have been used to define Location N, at 30.66°S, 118.42°E. It is suggested that this is the location of the January 2017 ML 4.2 event.

Figure 10 Events from 13 Jan. 2017 to 30 June 2017



Of the other six events in period 2, most can be attributed to a cluster of events south of Welbungin, (northwest of Mukinbudin), largest event ML 2.9, which occurred between the 3rd and 5th June 2017. This cluster also contains another 6 events which GA has located just west of 118°E, ie, just to the west of the MBR region defined here. The events in the Welbungin cluster appear to show a strong northeast trend, but relocations of some of these events (Figure 10) show that they cluster near to -30.82°S, 118.05°E, ie very close to Location O of Table 1. The apparent northeast trend is due to biases introduced by poor station distribution, as discussed by Dent (2010).

When the BR4 station was upgraded on 9th May 2017, as mentioned above, many more small events became apparent because of the lower background noise. A group of three small events (magnitudes ~ 1.0), was noted on 17th June 2017, and they had well-defined S-P times of close to 1.6 seconds. This indicates they were probably 14 km from the BR4 station. Whether they were in the vicinity of the Jouerdine Fault remains unknown.

Table 4 S-P times of events recorded close to the BR4 seismograph, January 2017 – June 2017

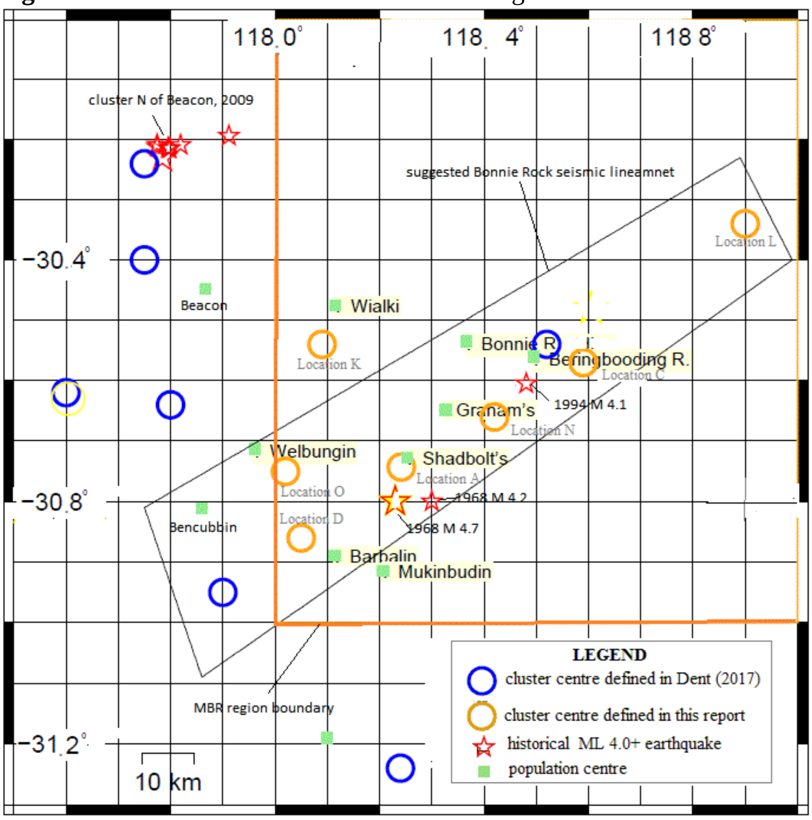
Date 2017	Time UTC	S-P (secs)	ML GA	ML BR4	Comment or suggested location
14/1	2358		2.3		
15/1	1155	0.85	2.2	1.7	30.654 118.415
15/1	2005		2.1		
15/1	2231	0.85	2.2	1.9	30.649 118.411
12/2	0811	0.92	2.3	1.6	30.658 118.414
12/2	0925	0.85			
12/2	0926	0.91		1.6	
18/2	0429	0.57		2.0	Felt at Graham's
22/2	1318	0.96	2.3	2.3	30.655 118.432
05/3	1803	0.98	2.1	1.8	30.661 118.422
17/6	1141	1.59		1.9	13.8 km from BR4
17/6	1205	1.53		2.1	13.6 km from BR4
17/6	1356	1.61		1.5	13.9 km from BR4

5 Discussion

Relocations using PSN data, particularly phase arrivals from the new Bonnie Rock station, has resulted in a significant refining of the epicentre of the January 2017 event and its aftershocks. Looking at the reviews of data from the earlier years, it is suggested that the location of the 2017 events (ie location N, ~ 8 km east of Graham's) may also have been the source of seismicity in 2008, 2010 & 2016. The source of the year 2000 activity, Location C (east of Beringbooding Rock), also seems to have produced seismicity in 2001, 2007, 2012 and 2014 -2015. The ML 4.2 event of 1994 is about midway between locations C and N (Figure 11), but is relatively poorly constrained. It is conceivable, or even likely, that its true location is at one of these two cluster locations.

Overall, the majority of events in the MBR region appear to have come from the above two cluster locations C and N. Five other lesser cluster centres are noted in Table 1, four of which (locations A, Shadbolt's, D, Barbalin L, Mt Jackson and O, Welbungin) are close to being co-linear with locations C and N, forming a northeast trend. When a larger area is considered (Figure 11), a 6th point south of Bencubbin, (location L2, defined in Dent, 2017) also seems to belong to this lineament. It is suggested that this lineament be called the "Bonnie Rock Seismic Lineament".

Figure 11 Plot of cluster centres in the MBR region and surrounds



The proximity of Location N to the fault on Jouerdine Hill (i.e., about 2 km to the south), suggests that Location N may be associated with this fault, particularly if the fault is found to dip to the south.

Conclusions

Using relocations where possible, we have attempted to demonstrate that most of the ~400 earthquakes located by GA in the MBR region since 1990 can be assigned to a limited number of locations, and seven have been identified here. In the course of this study, a possible northeast alignment of cluster locations has become evident. The events of 2017 cluster near the Jouerdine Fault, and may be related to it. Relocations which use data from near-event recorders suggest events in the region are of shallow depth (< 5 km). Computed focal depths are to some extent model dependent, and future relocations using an improved earth model may increase the average focal depth, but probably not significantly. The large (ML 4+) events of 1968 and 1994 are within the zone defined by the active cluster centres, but may not be well located. Given the location uncertainties, they could have originated from one of the cluster centres identified here.

GA epicentres in the region appear to commonly have errors of ~10 km, and sometimes greater than 20 km. These errors have masked patterns in the true distribution of epicentres in the region. In particular, the interpretation that most of the seismicity in SWA has come from recurring activity at numerous, relatively small (< ~2km diameter), but possibly long-lived source zones, has escaped the attention of previous researchers.

In the Bonnie Rock region, magnitude 4 events have occurred in 1968, 1994 and 2017, suggesting a cycle period of about 24 years. The earlier history is uncertain because of the lack of instrumentation. One could speculate that a magnitude 4 event or larger could occur at this location in about another 24 years.

Acknowledgements

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Appendix EQLOCL solutions for selected events

Solution 1 - original GA location for first event on 24/06/2000 (0242 39.5 UTC)

```
Date            2000-06-24
Origin Time     0242 32.39   +   1.06
Zone                    50
Easting             653.24   +   6.99             Longitude     118.598
Northing           6616.07   +   3.29             Latitude      -30.578
Depth                 0.28   +   4.49

Arrival times    = 13            S.D. = 0.383        Seismographs =  7
Nearest recorder =    1.8 km     Gap  = 266.4 deg    Accuracy = A
Effects Code     =               Imax =  0           Fault =

   1 km SE (128 deg) of  BR3   WESTERN AUSTRALIA
 303 km NE ( 61 deg) of PERTH
  23 km  E (104 deg) of Bonnie Rock

MAGNITUDES
Code      R       ML       MD       MB       MS       MW       MN
FORT     905     2.9
BAL      181     2.9
KLB      137     2.0
MRWA     292     2.1

Mean             2.5                                       Assign ML  2.5

DATA USED
Code  Wave       AT    +    WT      CT     DT     Dist  Azim    Ad    Ae
BR3  i         32.50  0.10  1.65   32.70  -0.20     1.8   308   19.9  19.9
BR3  i S       32.80  0.10  1.48   32.91  -0.11     1.8   308   19.9  19.9
BR1  i-P       33.40  0.10  1.53   33.65  -0.25     7.7   249    4.6   4.6
BR1  e S       34.30  0.10  0.96   34.52  -0.22     7.7   249    4.6   4.6
BR2  i-P       34.30  0.10  1.52   33.78   0.52     8.5   303    4.5   4.5
BR2  e S       35.10  0.10  0.96   34.74   0.36     8.5   303    4.5   4.5
KLB  i       55.00  0.10  1.23   54.89   0.11   137.9   215  -30.8  30.8
KLB  e S       71.10  0.10  0.77   70.49   0.61   137.9   215    0.2   0.2
BAL  e P       60.20  0.10  0.84   60.96  -0.76   181.4   268  -42.2  42.2
BAL  e S       82.20  0.10  0.75   82.26  -0.06   181.4   268  -40.3  40.3
MUN  e P       72.70  0.10  0.81   72.32   0.38   275.4   234  -42.2  42.2
MRWA e P       73.90  0.10  0.80   74.45  -0.55   293.0   300  -42.2  42.2
MRWA e S      106.00  0.10  0.72  105.75   0.25   293.0   300  -40.3  40.3
                        13 times used, S = 0.383
Deferred Data
KLG  e P       75.90  0.10  0.81   72.28   3.62   275.2    95  -42.2  42.2
KLG  e S      107.20  0.10  0.73  101.97   5.23   275.2    95  -40.3  40.3
MUN  e S      105.80  0.10  0.73  102.04   3.76   275.4   234  -40.3  40.3
MEEK e P       93.30  0.10  0.77   91.85   1.45   436.6     0  -42.2  42.2
FORT e P      150.20  0.10  0.72  149.18   1.02   911.1    93  -42.2  42.2
FORT e S      238.70  0.10  0.64  235.85   2.85   911.1    93  -40.3  40.3
```

Solution 2 Relocation of 0242 event

```
Date            2000-06-24
Origin Time     0242 32.13   +   1.88
Zone                    50
Easting             651.85   +   3.29             Longitude     118.583
Northing           6619.42   +  15.24             Latitude      -30.548
Depth                 0.21   +  36.02

Arrival times    =  9            S.D. = 0.087        Seismographs =  5
Nearest recorder =    2.2 km     Gap  = 238.5 deg    Accuracy = A
```

```
   2 km  N (358 deg) of  BR3   WESTERN AUSTRALIA
 303 km NE ( 60 deg) of PERTH
  21 km  E ( 96 deg) of Bonnie Rock
MAGNITUDES
Code      R       ML      MD      MB      MS      MW      MN
FORT     907     2.9
BAL      180     2.9
KLB      139     2.0
MRWA     290     2.1

Mean             2.5                                         Assign ML  2.5

DATA USED
Code  Wave       AT     +    WT      CT      DT     Dist  Azim    Ad     Ae
BR3    S-P      0.30  0.05  1.85    0.26    0.04     2.2   178    0.0    0.0
BR3  i         32.50  0.10  1.61   32.50   -0.00     2.2   178   14.6   14.6
BR3  i S       32.80  0.10  1.45   32.76    0.04     2.2   178   14.6   14.6
BR2    S-P      0.80  0.10  1.56    0.66    0.14     5.8   284    0.0    0.0
BR1    S-P      0.90  0.10  1.51    0.94   -0.04     8.3   223    0.0    0.0
BR1  i-P       33.40  0.10  1.51   33.49   -0.09     8.3   223    3.8    3.8
BR1  e S       34.30  0.10  0.95   34.43   -0.13     8.3   223    3.8    3.8
KLB  ip        55.00  0.10  1.22   54.90    0.10   139.8   213  -30.8   30.8
MRWA e P       73.90  0.10  0.80   73.84    0.06   290.0   300  -42.2   42.2
                        9 times used, S = 0.087
Deferred Data
BR2  i-P       34.30  0.10  1.55   33.07    1.23     5.8   284    6.0    6.0
BR2  e S       35.10  0.10  0.98   33.73    1.37     5.8   284    6.0    6.0
KLB  e S       71.10  0.10  0.77   70.75    0.35   139.8   213    0.2    0.2
BAL  e P       60.20  0.10  0.84   60.53   -0.33   180.0   267  -30.8   30.8
BAL  e S       82.20  0.10  0.75   81.72    0.48   180.0   267  -40.3   40.3
MUN  e P       72.70  0.10  0.81   72.16    0.54   276.1   234  -42.2   42.2
MUN  e S      105.80  0.10  0.73  101.94    3.86   276.1   234  -40.3   40.3
KLG  e P       75.90  0.10  0.81   72.24    3.66   277.0    96  -42.2   42.2
KLG  e S      107.20  0.10  0.72  102.09    5.11   277.0    96  -40.3   40.3
MRWA e S      106.00  0.10  0.72  104.88    1.12   290.0   300  -40.3   40.3
MEEK e P       93.30  0.10  0.77   91.19    2.11   433.3     0  -42.2   42.2
FORT e P      150.20  0.10  0.71  149.12    1.08   912.7    94  -42.2   42.2
FORT e S      238.70  0.10  0.64  235.95    2.75   912.7    94  -40.3   40.3
```

Solution 3 Original GA location for 2nd event on 24/6/2000 (0243 53.3 secs)

```
Date            2000-06-24
Origin Time     0243 53.30   +   0.71
Zone                    50
Easting             652.65   +   4.43            Longitude     118.592
Northing           6615.86   +   3.39            Latitude      -30.580
Depth                 0.00   +   4.25  G

Arrival times    = 13          S.D. = 0.428        Seismographs =  7
Nearest recorder =    1.5 km   Gap  = 124.7 deg    Accuracy = A
Effects Code     =             Imax =  0           Fault =

   1 km SE (149 deg) of  BR3 WESTERN AUSTRALIA
 302 km NE ( 61 deg) of PERTH
  22 km  E (105 deg) of Bonnie Rock
MAGNITUDES
Code      R       ML      MD      MB      MS      MW      MN
FORT     906     2.9
MEEK     436     3.0
BAL      180     3.1
KLB      137     2.2
MRWA     292     2.6
```

Mean 2.8 Assign ML 2.8

DATA USED

Code	Wave	AT	+	WT	CT	DT	Dist	Azim	Ad	Ae
BR3	ip	53.20	0.10	1.66	53.56	-0.36	1.5	329	13.3	13.3
BR3	e S	53.50	0.10	1.04	53.74	-0.24	1.5	329	13.3	13.3
BR1	i-P	54.10	0.10	1.53	54.45	-0.35	7.0	249	2.8	2.8
BR1	e S	55.00	0.10	0.97	55.25	-0.25	7.0	249	2.8	2.8
BR2	i-P	55.00	0.10	1.52	54.63	0.37	8.1	307	2.8	2.8
BR2	i S	55.80	0.10	1.37	55.54	0.26	8.1	307	2.8	2.8
KLB	e P	75.70	0.10	0.86	75.71	-0.01	137.4	214	0.1	0.1
KLB	e S	91.80	0.10	0.77	91.25	0.55	137.4	214	0.1	0.1
BAL	e P	82.20	0.10	0.84	81.82	0.38	180.8	268	-30.8	30.8
BAL	e S	102.90	0.10	0.75	103.09	-0.19	180.8	268	-40.3	40.3
MRWA	e P	94.80	0.10	0.80	95.34	-0.54	292.6	300	-42.2	42.2
MRWA	e S	127.60	0.10	0.72	126.62	0.98	292.6	300	-40.3	40.3
FORT	e P	170.80	0.10	0.71	170.19	0.61	911.6	93	-42.2	42.2

13 times used, S = 0.428

Deferred Data

Code	Wave	AT	+	WT	CT	DT	Dist	Azim	Ad	Ae
MUN	e P	95.00	0.10	0.81	93.19	1.81	274.8	234	-42.2	42.2
MUN	e S	126.60	0.10	0.73	122.87	3.73	274.8	234	-40.3	40.3
KLG	e P	96.00	0.10	0.81	93.29	2.71	275.8	95	-42.2	42.2
KLG	e S	128.20	0.10	0.73	123.05	5.15	275.8	95	-40.3	40.3
MEEK	e P	115.20	0.10	0.77	112.82	2.38	436.8	0	-42.2	42.2
MEEK	e S	153.90	0.10	0.69	157.04	-3.14	436.8	0	-40.3	40.3
FORT	e S	258.60	0.10	0.64	256.93	1.67	911.6	93	-40.3	40.3

Solution 4 relocation of event at 0243 UTC, 24th June 2000 (excluding phases from most of the distant stations)

Date	2000-06-24				
Origin Time	0243 53.01	+-	0.38		
Zone	50				
Easting	652.01	+-	2.72	Longitude	118.585
Northing	6617.49	+-	5.16	Latitude	-30.565
Depth	**0.88**	+-	2.01		

Arrival times = 9 S.D. = 0.082 Seismographs = 5
Nearest recorder = 0.3 km Gap = 262.4 deg Accuracy = A

0 km NE (22 deg) of BR3 WESTERN AUSTRALIA
302 km NE (60 deg) of PERTH
21 km E (101 deg) of Bonnie Rock

DATA USED

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
BR3	S-P	0.10	0.05	1.98	0.15	-0.05	0.3	202	0.0	0.0
BR3	i+P	53.20	0.10	1.72	53.22	-0.02	0.3	202	75.3	75.3
BR3	e S	53.50	0.10	1.08	53.36	0.14	0.3	202	75.3	75.3
BR2	S-P	0.80	0.10	1.54	0.77	0.03	6.7	299	0.0	0.0
BR1	S-P	0.90	0.10	1.53	0.83	0.07	7.2	234	0.0	0.0
BR1	i-P	54.10	0.10	1.53	54.20	-0.10	7.2	234	9.6	9.6
BR1	e S	55.00	0.10	0.96	55.03	-0.03	7.2	234	9.6	9.6
KLB	e P	75.70	0.10	0.86	75.51	0.19	138.3	214	-30.8	30.8
MRWA	e P	94.80	0.10	0.80	94.78	0.02	291.2	300	-42.2	42.2

9 times used, S = 0.082

Deferred Data

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
BR2	i-P	55.00	0.10	1.54	54.11	0.89	6.7	299	10.8	10.8
BR2	i S	55.80	0.10	1.38	54.88	0.92	6.7	299	10.8	10.8
KLB	e S	91.80	0.10	0.77	91.22	0.58	138.3	214	0.5	0.5
BAL	e P	82.20	0.10	0.84	81.36	0.84	180.2	268	-42.2	42.2
BAL	e S	102.90	0.10	0.75	102.51	0.39	180.2	268	-40.3	40.3
MUN	e P	95.00	0.10	0.81	92.84	2.16	275.2	234	-42.2	42.2
MUN	e S	126.60	0.10	0.73	122.50	4.10	275.2	234	-40.3	40.3
KLG	e P	96.00	0.10	0.81	93.00	3.00	276.6	95	-42.2	42.2
KLG	e S	128.20	0.10	0.72	122.77	5.43	276.6	95	-40.3	40.3
MRWA	e S	127.60	0.10	0.72	125.88	1.72	291.2	300	-40.3	40.3
MEEK	e P	115.20	0.10	0.77	112.23	2.97	435.2	0	-42.2	42.2
MEEK	e S	153.90	0.10	0.69	156.25	-2.35	435.2	0	-40.3	40.3

FORT e P	170.80	0.10	0.71	169.89	0.91	912.4	94	-42.2	42.2
FORT e S	258.60	0.10	0.64	256.64	1.96	912.4	94	-40.3	40.3