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Clustered seismicity in the Southwest Australia Seismic Zone, 2014-2015

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Abstract: One hundred and sixty eight earthquakes were located by Geoscience Australia (GA) in the Southwest Australia seismic zone (SWA) in the 12 months from June 2014 to May 2015. This was lower than in the previous 12 months, which was itself a period of relatively low seismicity. As with the previous year, much of the seismicity in the period originated from earthquake clusters, and approximately matches a suggested pattern of about 12 clusters per year, about half of which represent carry-over activity from the previous year. In many cases, these clusters could also be described as earthquake swarms. Spatial definition of cluster centres has been assisted by the relocation of about 40 of the 168 events. The relocations are believed to be more accurate than the original locations because extra data have been added from seismographs not used by Geoscience Australia, and the RMS of the residuals of phase arrival times is also lower. The most appropriate local velocity model to use in the location programs is a topic needing further investigation. Definition of cluster centres now active may help with interpretation of past and future seismicity in the region.

1 Introduction

1.1 Background to this study

Everingham (1968), and Everingham and Tilbury (1972) defined a relatively small region east of Perth as the “southwest seismic zone” (SWSZ), based on the limited amount of seismic data available at the time. With successive studies of the region since 1972, the zone has expanded, and Leonard (2008) defined a larger area that he termed the South West Australia Seismic Zone (SWA). Interestingly, Clark et al. (2011), in an examination of neotectonic seismic zones of Australia, did not consider the region to be one of elevated seismicity. They considered the high levels of activity since ~ 1968 to be “migratory”, because of the lack of earthquake-generated topographic relief in the region.

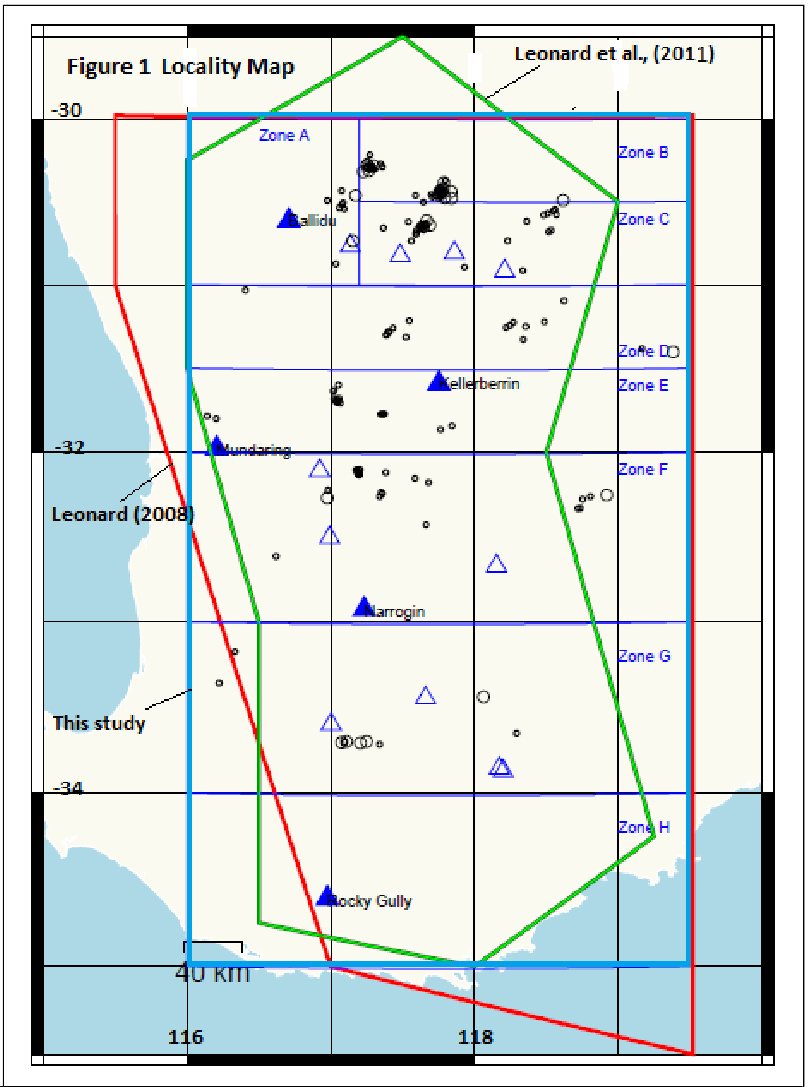


Figure 1. circles: GA located events June 2014-May 2015, size reflects magnitude, Closed triangles: ANSN seismographs, Open triangle: PSN seismographs

Leonard et al. (2011) modified the boundaries of the SWA zone again, as shown in Figure 1.In a recent study of the region, Dent (2014a) made minor modifications to Leonard's 2008 boundaries, and divided the region into 8 subzones, for the purpose of summarising the seismicity of the region for the period June 2013 to May 2014. The clustered nature of the seismicity of the region was emphasised in this report. These subzones are used again in this report.

2013-14 was considered to be a year of relatively low seismicity, with 288 located events, and most of the seismicity emanated from 4 major cluster centres in the north of the SWA zone. The largest event of the year, ML 3.4, came from a cluster to the north-east of Koorda, in subzone 3.

Twenty three cluster centres in the SWA zone were discussed in Dent 2014a. They were labelled A to W in Table 1 of Dent, 2014a, and are indicated on Figures 2-6 of this report. 20 of the centres had been identified in two earlier studies (Dent 2012, 2013). Twelve of the centres displayed activity in the 2013-14 period. Dent (2014a) concluded that most (about 80%) of the seismicity in the SWA zone in 2013-14 originated from these 12 cluster centres.

The 2014 analysis was assisted by relocations of about 40 events which occurred during the year. Relocations used additional phase data supplied by the Public Seismic Network (PSN), which has been growing in the southwest Australia region since 2006.

Because of the difficulty in achieving accurate locations towards the north and east boundaries of the SWA zone, some of the cluster locations remain poorly defined spatially. Dent (2014a) suggested that it is probable that some, if not many, of these more remote cluster centres have been active in earlier years, but it is hard to prove this because of the poorer quality of earlier earthquake locations.

Earthquake clusters are often described as “swarms” when there are several events near the maximum magnitude of the cluster (Gibson et al., 1994). Many of the clusters described here could also be called earthquake swarms.

In this report, the seismicity in the 12 month period following that of Dent 2104a (ie June 2014-May 2015) is reviewed. Geoscience Australia's (GA) locations for events in the period are plotted on **Figure 1**. As in Dent (2014a), the review is assisted by the relocations of selected events, and the relocations are made with the benefit of extra data from the PSN net.

1.2 Seismographs operating in 2014-15 in SWA

There were two networks operating in SWA in 2014-15. GA operates five stations in the SWA zone, and two just outside of it (Figure 1). These stations are a part of the wider Australian National Seismograph Network (ANSN), and operate at 40 s/s. The ANSN is used by GA to routinely locate earthquakes in Australia, and they use the ANTELOPE earthquake location program to do this.

The other network is the “PSN/ACG” network, a private network, which operates with the assistance of the Australian Centre for Geomechanics (ACG) in Perth, WA. It has grown since the first stations were set up near Perth in 2006. It was described by Dent et al. (2006) and Dent (2010), and it has expanded to include stations in South Australia and along the east coast of Australia. The latest network configuration is described in the Australian Seismological report for 2014 (Glanville et al., in prep.) In 2014-15, data were collected from 10 sites in SWA (Figure 1) although some had long periods of unserviceability during the year. Although the stations are not as well calibrated as GA stations (relevant to magnitude calculations) they operate at a much higher sampling rate (200 s/s) which improves the precision of picking phase arrivals.

GA does not use PSN data in its earthquake locations.

1.3 An overview of seismicity in the SWA zone in 2014-15.

Activity in 2014-15 was even lower than in 2013-14, with 168 events (Figure 1), only two of which were of ML ≥ 3.0. In 2013-14 there were 299 events, of which four were of ML ≥ 3.0. Most of the activity in 2014-15 occurred in the first half of the period. As in 2013-14, most of the seismicity can be attributed to cluster centres in the top degree the SWA zone (between 30^{o} and 31^{o} south, subzones 1, 2 and 3), and mostly these cluster centres were even more active in the previous 12 month period. The largest event of the period, ML 3.3 came from a cluster northeast of Koorda (July 2014). The same cluster provided the largest event of the previous 12 months (ML 3.4). A short but intense period of cluster activity occurred about 20 km east of Kalannie between 3 and 6 March, 2015 (largest event ML 3.0).

Of the activity in the rest of the SWA zone, there was a minor renewal of activity at two cluster centres which had been quite active several years earlier – ie. north of Hyden (point R), and south east of Wyalkatchem (point I). Activity in the Meckering area was higher than in the previous 12 months. A cluster of six events occurred north of Kojonup between September and November 2015, and it may have occurred at the same location as a cluster of ~ 40 events in September-October 2011.

There was one relatively large event which appears to be non-clustered event – near Cadoux in December 2014, ML 2.8. There are other events which appear to be non-clustered, but they are relatively small.

2 Earthquake relocations

Selected earthquakes have been relocated using the same techniques as described in Dent (2014a) ie., they were located using the EQLOCL program and the WA2 velocity-depth model (Dent, 1990). The relocations, as well as the distances between the original locations and the relocations are shown in Table 1. Earthquakes for relocation were selected on the basis of remoteness from other events, the fact that they were well recorded by PSN stations, or they were large events and significant in defining a cluster. Note that GA used the ANTELOPE location program, and the IASPEI91 velocity-depth model to compute their solutions. Locations in Table 1 are given to two decimal places only, as the third decimal place implies a degree of precision that does not exist (Bondár et al., 2004).

The differences in distance between the GA locations and the EQLOCL relocations range between 0 km and 22 km (Table 1), the average difference 10 km, and the median difference 9 km. These values are very similar to the differences found in the relocations presented in Dent (2014a). In general, the solutions are more in agreement towards the centre of the zone, and larger towards the extremities. The new solutions all have lower RMS residuals than the original GA solutions. The focal depths are always significantly less than the GA solutions, and this is probably due to the fact that GA switched from using the WA2 earth model to the IASPEI91 earth model for its West Australian earthquake locations after May 2014. This is discussed in more detail below.

3 Focal depths and earth models

Earthquake focal depths are hard to determine, unless close seismographs are present and the local earth velocity/depth model is well known. The relocations shown in Table 2 have all been derived using the WA2 velocity model, and most have been constrained to a “normal” focal depth of 2 km. This is because inadequacies in the WA2 model causes the lowest computed RMS of residuals to occur slightly above ground level for many of the events. From May 2014, GA has used the IASPEI 91 velocity-depth model when locating WA events, because they considered that model to give more accurate locations (Glanville, pers. comm. 2015). However, the RMS of residuals for all their locations in the SWA zone are much higher than has been achieved in the relocations given here. For the data used here, the WA2 model gave lower RMS of residuals than did the IASPEI 91 model. Note also that the GA locations did not use available S phase arrival data, which can assist greatly with earthquake locations when there are few recording stations available.

The focal depths computed by GA for the events in the region vary widely between 0 and 15 km., and sometimes greater. The deeper depths (≥ 9 km) are contrary to locations determined by limited, but relatively accurate, temporary field surveys around active areas – eg. Burakin in 2001-02 (Leonard 2002), Yorkrakine 1996 (Dent 2011) and Woodanilling (Dent 2014b). These surveys have all suggested that focal depths are usually less than 5 km. Determining an earth model appropriate to the local conditions is a fairly pressing need in Western Australia.

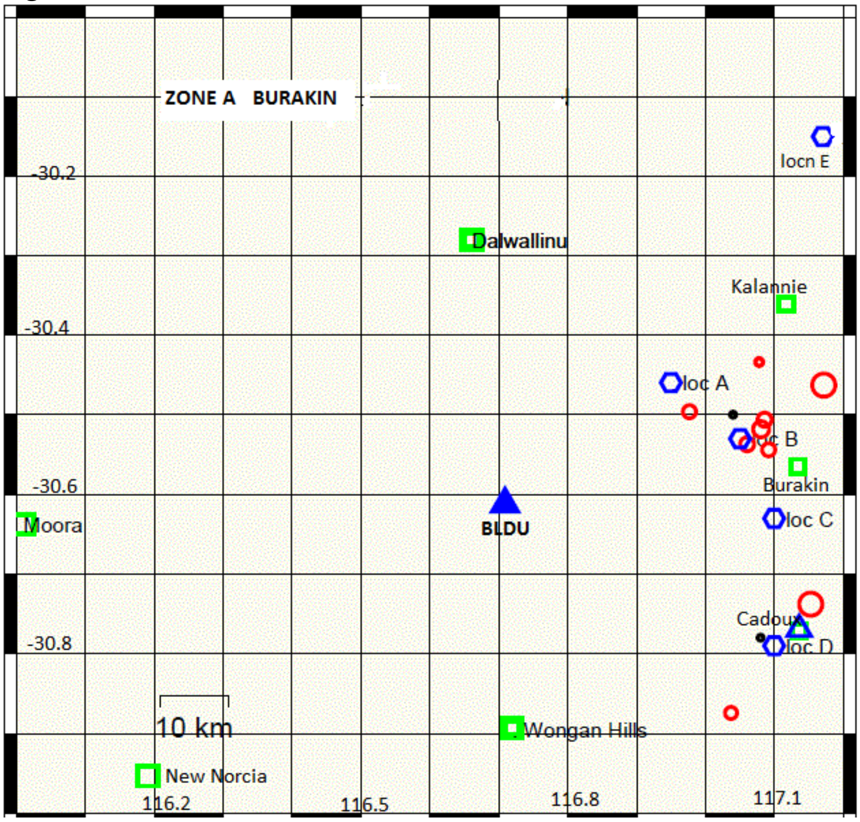
Table 1 Earthquakes relocated using EQLOCL for June 2014 – May 2015 (plotted in zone order)

Date & Time	Place	Z	Magn	new lat	new long	DEP	move	RMS	GA dep, RMS	
UTC			(ML)			(km)	(km)	(secs)	Km	secs
2014-07-08_0649	Burakin	A	2.8	-30.50	117.04	0.98	15	0.16	10	0.97
2014-12-05_0358	Cadoux	A	2.8	-30.78	117.08	1C	9	0.07	5	1.54
2014-07-10_2156	Bonnie rock	B	2.5	-30.54	118.51	1.4	13	0.16	10	0.91
2014-07-11_1007	Bonnie rock	B	2.3	-30.55	118.51	9.03	5	0.08	0	0.5
2014-10-30_1734	Beacon	B	2.9	-30.41	117.78	1C	1	15	8	3.8
2014-11-08_2204	West of Beacon	B	2.2	-30.42	117.74	2N	17	0.11	0	4.99
2015-03-04_0900	Kalannie	B	2.4	-30.26	117.30	2N	7	0.32	10	1.77
2015-03-05_2054	Kalannie	B	2.2	-30.26	117.28	1C	6	0.17	10	0.91
2015-03-06_0139	Kalannie	B	2.5	-30.22	117.29	1C	13	0.13	18	0.52
2015-03-06_0343	Kalannie	B	2.3	-30.26	117.28	2N	5	0.14	0	6.66
2014-07-22_0612	Koorda	C	2.4	-30.64	117.63	1.4	13	0.02	3	1.54
2014-07-22_1949	NE of Koorda	C	3.3	-30.64	117.67	1.9	2	0.07	10	0.93
2014-09-02_1202	Koorda	C	2.2	-30.65	117.46	3	9	0.06	10	1.47
2014-11-08_2355	Due N of Koorda	C	1.9	-30.64	117.45	1C	9	0.05	0	1.43
2014-11-11_0538	SE of Bencubbin	C	2.1	-30.90	117.90	2N	3	0.14	0	0.81
2015-04-03_1143	Mukinbudin	C	2.0	-30.51	118.57	2N	5	0.2	1	1.42
2015-04-12_1504	Merredin	C	2.3	-30.49	118.59	1.8	1	0.09	13	0.43
2014-08-17_0057	NE of Merredin	D	2.0	-31.24	118.39	2N	13	0.14	12	0.53
2014-08-18_1642	NE of Merredin	D	2.3	-31.25	118.44	11.2	6	0.66	6	0.83
2014-08-28_1336	Wyalkatchem	D	1.9	-31.28	117.61	2.01	10	0.06	6	0.48
2014-09-10_1844	Wyalkatchem	D	2.4	-31.27	117.47	4.8	10	0.11	14	1.44
2015-01-04_0032	Mukinbudin	D	2.2	-31.10	118.51	3.1	12	0.15	0	1.62
2015-05-09_1553	N of Merredin	D	2.0	-31.27	118.21	2N	5	0.24	14	0.86
2015-05-10_1752	Merredin	D	2.0	-31.31	118.51	5.7	19	0.13	16	0.61
2014-09-03_0226	Meckering	E	1.7	-31.64	117.02	6.6	0	0.08	13	1.33
2014-09-10_0717	Meckering	E	1.9	-31.69	117.04	1C	0	0.11	14	0.68
2014-09-13_1104	Youndegin	E	1.9	-31.76	117.37	2N	2	0.3	0	0.75
2015-04-25_1142	Meckering	E	2.4	-31.70	117.00	2N	6	0.16	14	0.59
2014-08-03_1459	Hyden	F	2.1	-32.30	118.88	2N	18	0.14	3	1.08
2014-08-07_2028	Hyden	F	2.6	-32.32	118.91	2N	8	0.28	10	1.71
2014-09-11_0933	Corrigin	F	2.3	-32.19	117.79	2N	22	0.19	3	2.36
2014-10-07_2356	Corrigin	F	2.0	-32.48	117.76	2N	12	0.11	6	0.2
2015-05-10_1641	SW of Quairading	F	2.0	-32.12	117.20	2N	0	0.11	4	0.62
2014-09-15_1427	SW of Quairading	F	1.9	-32.15	117.21	2N	4	0.12	2	0.76
2014-10-11_1706	Kojonup	G	2.3	-33.69	117.02	7.4	9	0.14	3	0.46
2014-07-23_1804	Katanning	G	2.6	-33.50	117.97	1.3	12	0.12	0	0.53
2014-10-18_1952	Kojonup	G	2.3	-33.69	117.04	2N	33	0.18	13	1.82
2014-11-05_0345	N of Kojonup	G	2.7	-33.61	117.09	6.4	10	0.12	6	0.59
2014-11-05_1213	Kojonup	G	2.6	-33.69	116.99	2N	29	0.28	13	1.72

4 A detailed examination of the seismicity within the subzones in 2014-15.

Fourteen cluster centres have been noted in Table 2 - two more than in the 2013-14 period, and 8 of these are "pre-defined". The six previously undefined cluster centres are labeled Alpha to Theta in Table 2. Most of the clusters are minor. As with the previous period, the most active region is between 30° and 31° South. Two of the new clusters may be considered significant – the cluster east of Kalannie (location alpha) has approximately 20 events (largest ML 3.0) and the cluster north of Kojonup (location theta), which, while only having 6 events, is in the approximate location of a significant cluster in 2011.

Figure 2 Events in the Burakin Zone



Legend for figures 2-6: Green square = town. Closed triangle = ANSN seismograph; Open triangle = PSN seismograph. Red circle = GA event location (size according to magnitude). Black circles = PSN relocation (Table 1). Blue hexagon = pre-defined seismic locality. Orange hexagon = newly

<u>Zone A **Burakin** 9 events, largest ML 2.8 (59 previous year, largest ML 2.6)</u>

There are 5 defined cluster centres in this zone (A-E) defined by Dent (2013). Centres A to D are based on centres identified by Leonard & Boldra (2001) during the September 2000 seismic cluster northwest of Cadoux. Location B was subsequently the locus of most of the activity for the major Burakin swarm a year later, and was quite active during 2013-14. This location has seen continuing seismicity for most of the years since the 2001-02 period of intense activity.

Table 2 Summary of properties of clusters in 2014-15

#	Label	Cluster locality	Zone	Max	Events	Lat	Long	Most active time	Comment
1	B	W of Burakin	Zone A	2.8	8	-30.53	117.05	July- Sept 2015	Major
2	P	W of Beacon	Zone B	2.9	26	-30.40	117.75	Sept 14 – Jan 15	Major
3	alpha	E of Kalannie	Zone B	3.0	17	**-30.26**	**117.28**	4th – 6th March	Major
4	K	NE of Koorda	Zone C	3.3	24	-30.62	117.60	July 2014	Major
5	beta	Bonnie rock	Zone C	2.4	8	-30.54	118.52	July2014 & Apr	Poorly defined
6	I	Wyalkatchem	Zone D	2.1	5	-31.25	117.45	Sept 14 & Jan 15	Major
7	gamma	N of Merredin	Zone D	2.2	6	-31.24	118.24	August 2014	Poorly defined
8	O	S of Meckering	Zone E	2.4	13	-31.70	117.04	Not clustered	
9	delta	Youndegin	Zone E	1.9	4	**-31.77**	**117.36**	Aug-Sep 14	New minor
10	R	Nth of Hyden	Zone F	2.6	5	-32.3	118.9	Aug 2014	Major
11	U	Nth of Brookton	Zone F	2.5	2	-32.25	116.98	July 2014	
12	V	East of Beverely	Zone F	2.2	12	-32.14	117.19	Sept 2014	
13	epsilon	Sth of Quairading	Zone F	2.2	3	**-32.24**	**117.35**	July 2014	New minor
14	theta	Nth of Kojonup	Zone G	2.7	6	**-33.69**	**117.03**	Sept 2014 ??	Poorly defined

In 2014-15 there are four GA-located events close to point B. Relocation of the event (ML 2.8) northeast of the centre (Table 2) brings that event close to the other events, and very close to location B.

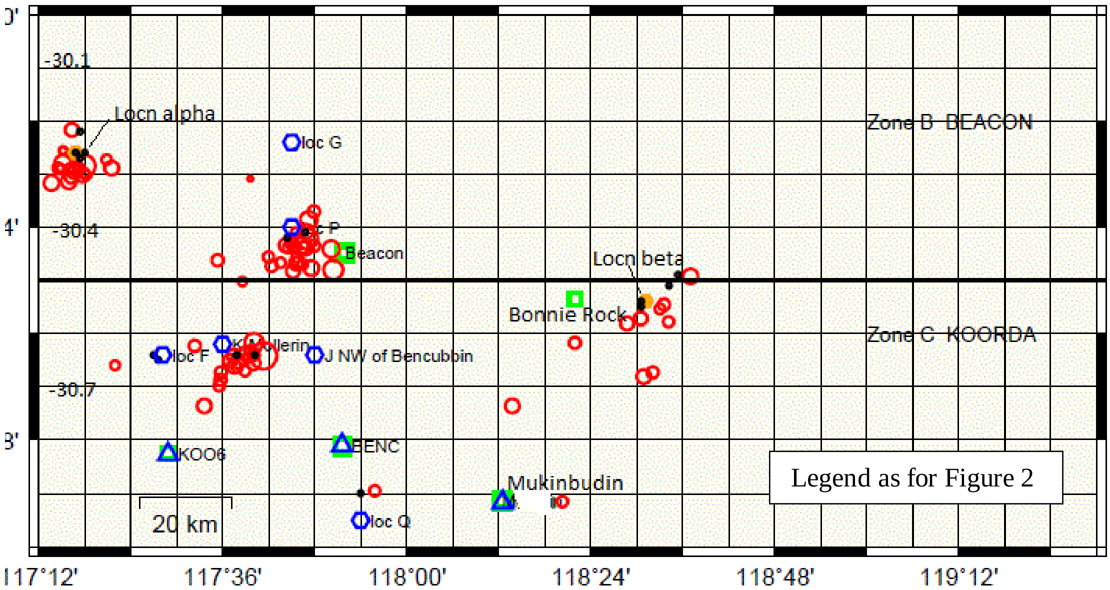
The relocation of the other significant event in the zone, (ML 2.8 event northeast of Cadoux), moves it by about 9 km to a location ~ 5km southeast of Cadoux. This event is relatively large, but there are no events close to it, in time or spatially. It is therefore termed here "solitary". It is however very close to location D, which was noted by Leonard & Boldra (2001) as a location of lesser activity, close to a major cluster at location C in Sept. 2000.

Zone B Beacon 47 events, largest ML 3.0 (52 previous year, largest ML 3.1)

There are two defined cluster centres in this zone. Location G, northeast of Beacon, was the site of a significant swarm in early 2009 (Dent 2009). Location P, about 10 km ENE of Beacon, had significant activity during 2011-12, and has continued on at a lesser level through to 2015. Most of the 2014-15 GA locations are slightly south and east of location P, and this may be due to errors in locations, or possibly the earlier definition of location P was slightly wrong. Relocations of some of the "outer" events near location P brings them towards the main grouping of events.

The other significant cluster in this zone in 2014-15 is east of Kalannie. 20 events belong to this cluster, 15 of which occurred between 3rd and 6th of March, 2015. This is a "new" location, identified here as location "alpha" on Figure 3. There was no significant activity from near this location in the previous 30 years. It is separate from location E "North of Kalannie" which was mainly active in late 2005. Relocation of some of the "peripheral" events around location alpha brings them back within the main grouping.

Figure 3 A and Figure 3 B Events in the Beacon and Koorda zones



Zone C **Koorda** 34 events, largest ML 3.3 (106 previous year, largest ML 3.4)

There are three defined cluster centres in this zone (points F, J and K). About half of the events in zone C in 2014-15 are assigned to location K, ie, northeast of Koorda, and represent continuing activity from the previous 12 months. The plot of GA locations (Figure 3b) shows a northeast trend in the epicentres, but this trend can be attributed to a bias introduced by the distribution of seismograph stations (Bondár et al. 2004; Dent 2010). Relocations of some of the events (Table 2) brings the events closer to location K. Relocation of a solitary event to the west of the group moves it about 7 km east – close to location J ("north of Koorda"), which was the locus of a significant swarm in 2004, and again in 2011.

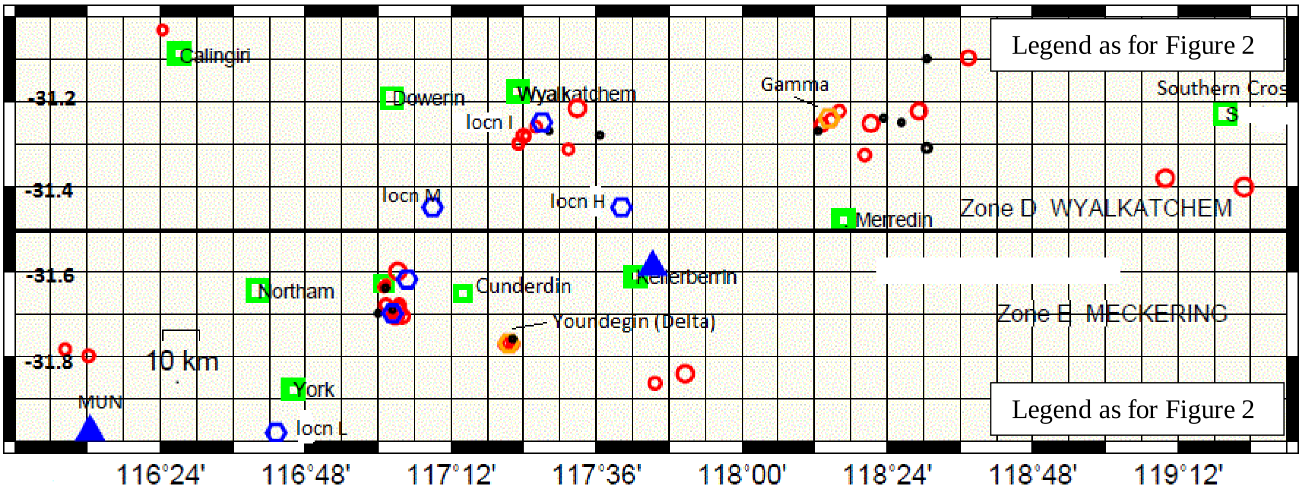
To the east of the above events, near Bonnie Rock, are a number of broadly distributed events. The Bonnie Rock region has been the locus of significant swarm activity over the last 30 years and beyond, but good locations in this region have been difficult to obtain. Events in this region are moving out of the region within which events can be relatively reliably located by the existing seismic network. Some of these events are obviously clustered by time, and by inference, also in location. Relocation has not brought the epicentres to a tight grouping, but an approximate location, identified as location beta (Table 2) is proposed.

<u>Zone D **Wyalkatchem** 17 events largest ML 2.5 (19 previous year, largest ML 2.7)</u>

There are 3 defined cluster centres in this zone (Figure 4A). Location I (SE of Wyalkatchem, Location M (NNW of Cunderdin) and location H (Yorkrakine - active between 1996 and 1998). 2014-15 saw renewed activity at location I, southeast of Wyalkatchem. The GA location of the largest event (~ 12 km east of Wyalkatchem) moves it closer to location I.

Another group of events is broadly distributed about a region north of Merredin. It is suspected that these events may come from a single location, and that the scattered nature of the locations is due to poor locations, which are to be expected near the extremities of the seismic network. Relocations have suggested a location "gamma" in Table 2, but the location remains poorly defined.

Figure 4 A and B Events in the Wyalkatchem and Meckering zones



<u>Zone E **Meckering** 24 events, largest ML 2.4 (11 previous year, largest ML 2.5)</u>

Zone E has roughly double the number of events to the previous 12 months, due largely to an increase of activity in the Meckering region. Thirteen of these events occurred very close to point O, about 10 km SSE of Meckering, and were spread out over the 2014-15 period. The largest was ML 2.4. Three events occurred close to Meckering itself, and close to point N. A well-defined cluster of four small events (largest ML 1.9) occurred near Youndegin, southeast of Meckering, in August and September of 2014 – location delta in Table 2.

Zone F **Brookton** 27 events, largest ML 2.6 (15 previous year, largest ML 3.0)

There are 4 cluster centres in this zone U, V, W and R (Figure 5). There were nearly twice as many events in this zone during 2014-15 as against the previous year. The largest event was ML 2.4, and was part of a resurgence in activity at location R, north of Hyden. This zone was quite active in early 2013. Relocation of two of the events in this 2014-15 cluster brings them closer location R.

Twelve small events (largest ML 2.2) were recorded at location V, about 20 km east of Beverley. This location was suggested by Dent (2014a) to be the site of a very significant earthquake cluster in 1963, of which the ML 5.4 Nourning Spring event (January 1963) was the largest.

Two events were recorded at location U, north of Brookton. This location also showed minor activity in the previous 12 months.

Three small events are tightly grouped at a "new" locality southwest of Quairading, identified as location epsilon in Table 2.

Figure 5 Events in the Brookton zone

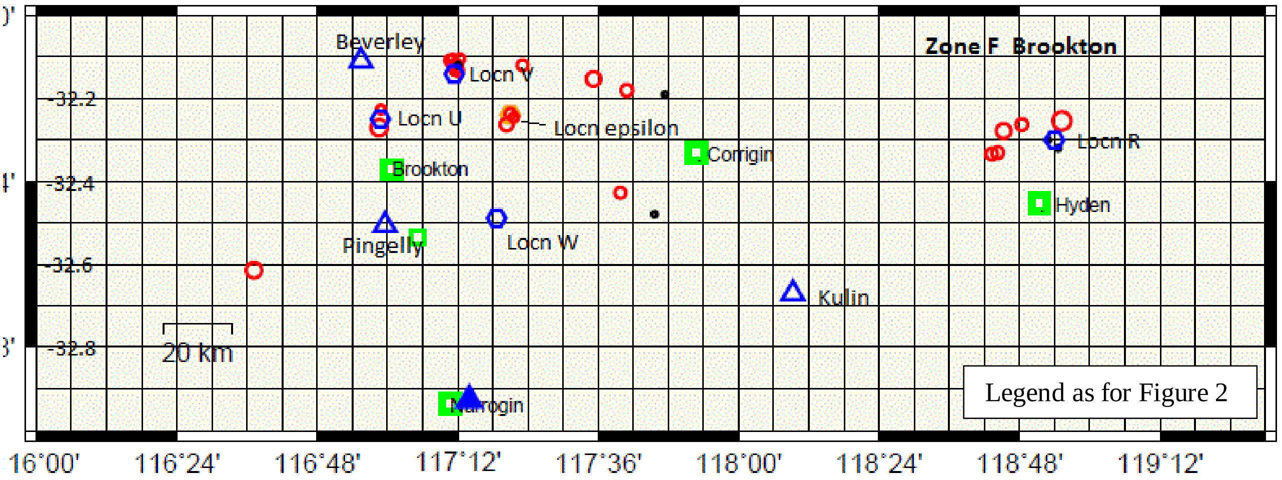
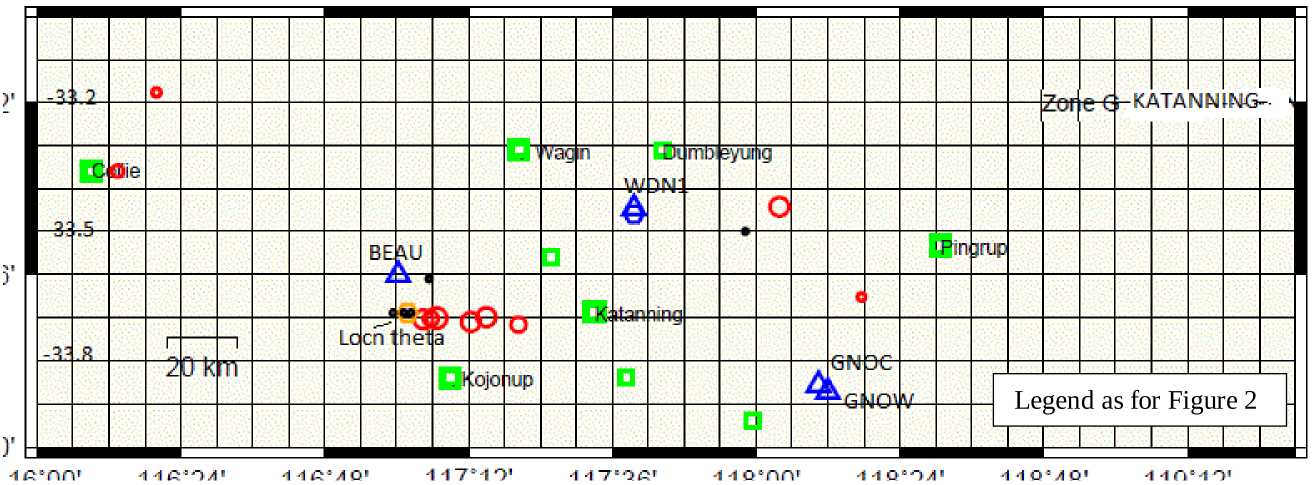


Figure 6 Events in the Katanning zone



Zone G **Katanning** 10 events largest ML 2.7 (22 previous year, largest ML 2.9)

Activity in zone G in 2014-15 is mainly from a location about 20 km north of Kojonup, where 6 events occurred, three of them on 5th November 2014. The events are not well located, and the relocations are not of high quality either, but the best relocations suggest the locus at location Theta (Table 2 and Figure 6). A significant swarm occurred near this locality in September and October of 2011, (max. magnitude ML 3.5), and it is suspected that both swarms emanated from the same location. A seismograph (BEAU) has subsequently been placed in the vicinity, to help improve future locations in the area.

Zone H (**Cranbrook) --** no events were located by GA in this zone in 2014-15.

4 Summary of 2014-15 activity

Fourteen cluster centres active in the SWA seismic zone in the 12 months June 2014 to May 2015, have been identified in this report, two more than were identified in the prior 12 months. Eight of these have been earlier identified as cluster centres, and 3 of these centres were significantly active in the previous 12 months. The most significant "new" centre was that east of Kalannie. The activity in the SWA zone in 2014-15 is consistent with observations by Dent (2014a), that activity broadly follows the principle of approximately a dozen "significant" active centres each year, with about a half of them represe continuing activity from the previous year, and the remainder mostly representing known centres of earlier activity.

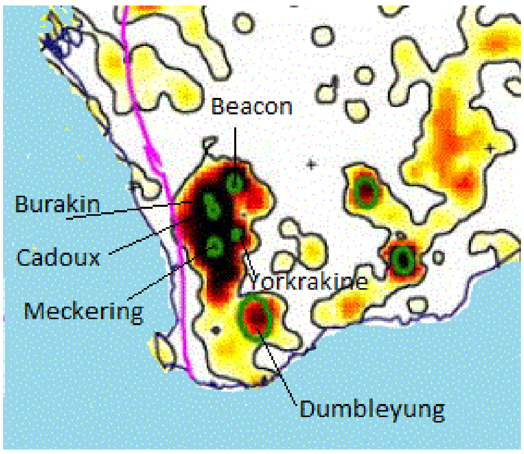
Legend as for Figure 2

As in previous years, clustered activity dominates the earthquake catalogue. Table 2 lists 139 events as part of a cluster, representing 83% of the 168 events located by GA in the SWA zone during the year. The only "non-clustered" event of note is the ML 2.8 event near Cadoux in December 2014. However, as noted earlier, that event occurred close to a known centre of cluster activity (location D).

5 Correlation of cluster centres with "hotspots" of Leonard et al., (2011)

In the process of constructing the 2012 seismic hazard map of Australia, Leonard et al., (2011) divided the continent into 4000 cells, each ½° x ½°, and looked at the seismicity in these cells since January1965. They used a declustered catalogue of events of ML ≥ 3.0. They identified 44 "hot spots", six of which were in the SWA zone (Figure 7). The hot spots were not named, but some can be readily associated with major events, and cluster localities named here (and some less so). These associations are shown in Table 3.

Figure 7 Hotspots of Leonard et al., (2011)



The Meckering and Cadoux events occurred before a suitable seismograph network was in place, and the precise location of the main events and their aftershocks are still not precisely known. It cannot be definitely said that the major activity at those locations correlates with the cluster centres identified here (D, near Cadoux, or N and O, near Meckering).

The broader, but lower level hot spot in the vicinity of Katanning in the south of the SWA zone is probably comprised of activity from a number of cluster centres. The centre of the hotspot appears to correlate with a known cluster location south of Dumbleyung (Dent 2014b). The largest event in the 2013-14 cluster was ML 2.9, but there was an ML 3.6 event near this location in 1977. Another cluster location, not yet named, which may have contributed to the hot-spot is found north of Nyabing, about 50 km east of Dumbleyung. Five events of magnitude 3.0 or more were recorded at this location in April 1995.

Table 3 Correlation of Hotspots of Leonard et al., (2012) with cluster centres

ZONE	MAIN EVENT		Correlation with locality	Approx duration of activity	Reference
	ML	DATE			
Meckering	6.7	14/10/1968	(N, O)	1968 - 1969	Gordon & Lewis (1980)
Cadoux	6.2	2/6/1979	(D)	1979 - 1980	Lewis et al. (1981)
Burakin	5.2	29/9/2001	B	2001, continues	Leonard (2002)
Beacon	4.6	31/01/2009	G	2009, Jan- Feb	Dent (2009)
Yorkrakine	4.6	31/08/1997	H	1996, 1998	Dent (2011)
Dumbleyung	3.6	1/3/1977	S	1977, 2013	Dent (2014b)

6 Discussion

If more phase data were available to allow good relocations of the remaining events, it is probable that at least some would join the cluster groups. It is almost certain that if more seismographs were deployed (ie. the detection limit was lowered), more minor cluster activity would be revealed. It may then also become possible to determine focal mechanisms and information about fault geometry – lengths, depths, dips, orientation etc.

The high degree of clustering exhibited in the southwest Australia seismic zone, also evident on the Eyre Peninsula of South Australia (Leonard et al., 2011) may be a property of Achaean shield environments. Because many of the cluster events are comprised of quite minor earthquakes, they may also be occurring in more remote parts of the Yilgarn and Pilbara cratons, but have escaped detection because the seismograph network is so sparse.

If clusters are closely spaced, such that they occur within a single “cell” or sample region, the statistical procedures analyzing the data may be more likely to identify the cell as a “hot spot”.

While the Gutenberg-Richter frequency/magnitude law was intended to apply to regional seismicity, it also appears to be valid for some of the larger earthquake clusters in SWA – eg, the Beacon cluster of 2009 (Dent, 2009). However, for other clusters it does not appear to be valid, as there is a fairly narrow range of magnitudes present. Note however that many of the clusters are comprised of events which are only just above the limit of detectability /locatability – ie. it is probable that events are occurring which are escaping detection.

7 Conclusions

Most events in the SWA seismic zone are clustered. The cluster centres often show recurring activity over successive years. The cluster centres become better defined when more seismographs are available. Over recent decades, the northern portion of the SWA seismic zone has been more active than the southern region. Locations such as “location B” west of Burakin have been active for about the last 15 years. Perhaps individual locations may have recurring activity over centuries. The nature of the seismicity seen in the SWA seismic zone may be unique to cratonic regions.

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