Clustered seismicity in southwest Australia, June 2012 – May 2013

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Abstract

This report continues a series that examines the seismicity of southwest Australia in 12-month periods, with a view to highlighting the clustered nature of the seismicity of the region. As with previous reports, the region is divided into 10 zones based on a latitudinal grid. There were 272 Geoscience Australia-located events in the region in the 12-month period June 2012 – May 2013, and about 80 of them have been relocated for this study, generally with the addition of new data from the "PSN" seismic network. It is suggested that the relocated events have about half the epicentral uncertainties that the Geoscience Australia locations have. Two cluster locations in the north of the region account for 45% of the located earthquakes, and overall, nearly 250 of the 272 events can be allocated to 21 cluster locations. Many of the remaining, mostly small events, may belong to a cluster location, but the association is less definite. Over 50 such cluster locations have now been identified in the region, mostly from the period June 2012 – May 2017, which has been studied in more detail. Sixteen of the cluster locations active in June 2012 – May 2013 have been identified as being active in other periods, and another five have been noted for the first time. The most significant newly defined cluster was one northeast of Hyden, where the largest event was ML 3.3. It is suggested that cluster locations can show periodic activity over many years, and it is probable that the locations called "new" in this report have had active periods in years not yet examined in detail. The faults which are presumed to exist at the cluster locations are not readily identified from the currently available geological maps. Seismicity in late 2017 near Ravensthorpe, about 50 km east of the southeast boundary of the SWA seismic zone suggests the zone boundaries used should be extended eastwards.

1 Introduction

The region studied here is an area of elevated seismicity, and uses the boundaries defined as "The southwest Australia seismic zone" (SWA) by Leonard (2008). However, the general region of seismicity is often generally referred to as "The southwest seismic zone", a term introduced by Doyle (1971) to describe an area recognised by Everingham (1968). The lead author has been summarising seismicity in the zone for 12 month periods over the last 5 years – the series beginning with the period June 2012-May 2013 in Dent (2013). These papers attempt to identify and provide some detail about the frequent earthquake clusters that occur in the region. Approximately 15 – 20 clusters have been identified in each year, and a total of 44 cluster locations have been defined in previous reports by Dent (2014a, 2015, 2016 & 2017). These cluster locations are shown in Figure 1. Some of these clusters appear to show recurring periods of activity over the five years so far studied.

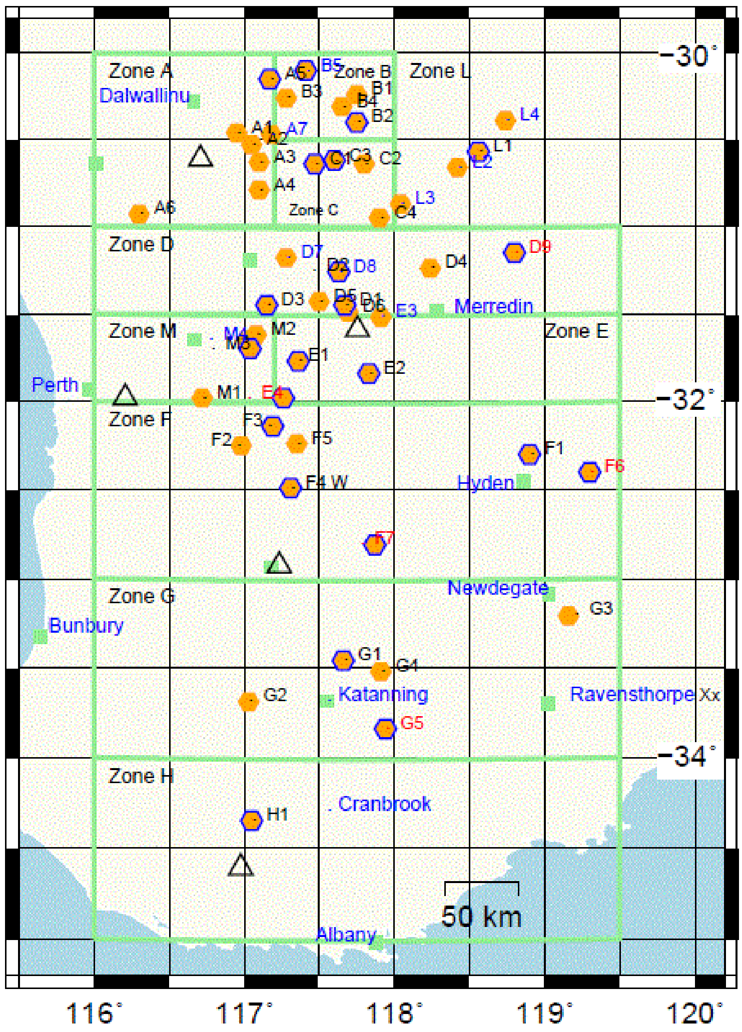
This paper covers much of what was studied in Dent (2013), but that paper did not review the entire SWA region – just the larger, more interesting clusters. This paper re-evaluates the seismicity in the light of the "cluster" concept, and uses the zonal structure, which has been developed since 2013. Data from the "Public Seismic Network" (PSN) (Dent et al., 2010**)** have been used to improve some earthquake locations, which is useful if events are to be assigned to discrete cluster locations.

Earthquake Locations and Relocations

The 272 events in the region (Table 1) were located by Geoscience Australia (GA) using the Antelope earthquake analysis program. The earth model used was the WA2 model (Dent, 1989) though some solutions used the IASPEI91 model (Kennett & Engdahl, 1991). The WA2 model was used exclusively until 2012, and the IASPEI model has been used since 2014. The WA2 model has generally faster P and S velocities than the IASPEI model. For this report, about 50 of the 200 events were relocated using the WA2 model and the EQLOCL location program. Metadata from the GA database indicates that this model and location program were used by GA for its WA locations until 2009. The relocations made in this report include data from the PSN network, where available, to reduce the uncertainties in the epicentral parameters.

The GA seismic stations are concentrated towards the centre of the SWA zone. Events in the centre of the zone can generally be well located, but events at the margins, or outside the seismic network, will necessarily have larger uncertainties in their locations, unless temporary stations were deployed in the epicentral region to provide extra data.

Figure 1 Map of defined clusters, and zonal divisions



Legend (all figures) **Hexagon** = cluster centre: yellow if defined in earlier work: with blue rim if active this period: filled blue if defined this period : **Circle** = epicentre (size proportional to magnitude). Black = current period, orange = previous 12 months : **Squares** = population centre (size varies by population) : **Triangle** = seismograph (Blue = GA, green = PSN). Map shows pre-defined zones (A-G, L & M).

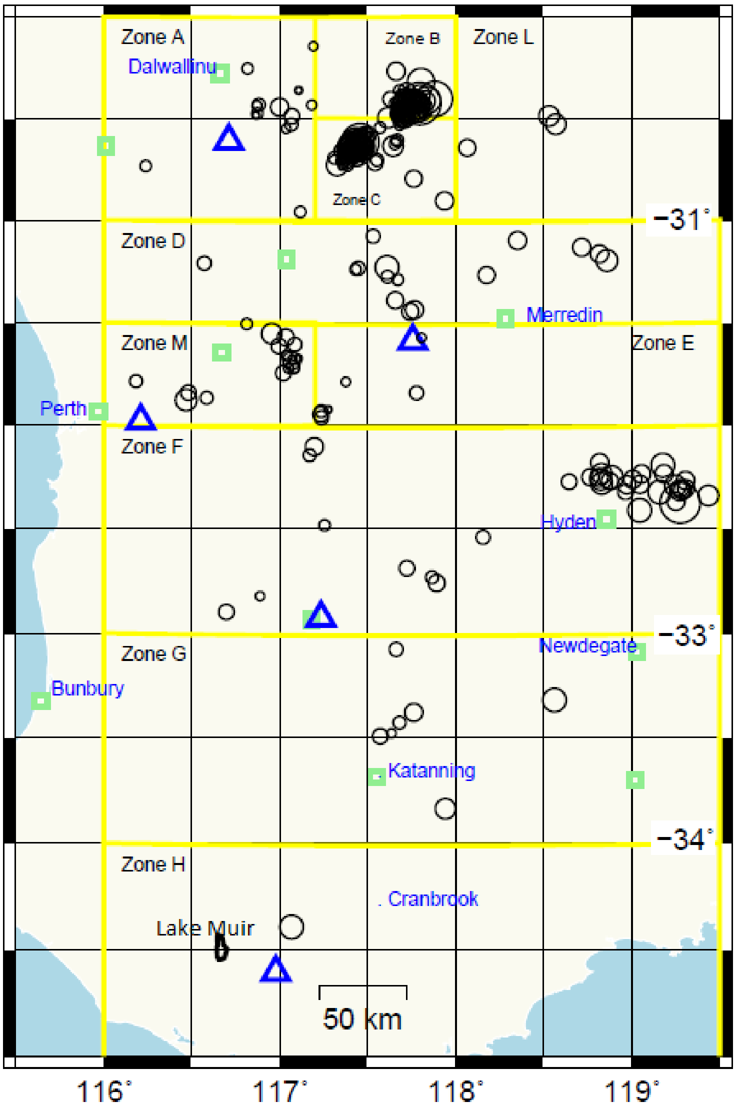
Many of the relocations correlate well with the GA locations, particularly for those near the centre of the zone, and where the same earth model was used. Comparing solutions which were derived using the WA2 model vs IASPEI suggests the slower velocities of the IASPEI model may cause a shift in location of about 5 km relative to the WA2 solution, depending of the location of the stations relative to the epicentre.

Cluster Definitions

A cluster is defined where there are two or more similar events (i.e. less than ~ 1.0 magnitude unit difference) within ~5 km of each other. They may be several months apart. If the smaller event is much smaller (difference in magnitudes > 1) , it may be treated as an “isolated” main-shock/aftershock event, and not considered a cluster event. However, most of the events studied here fall into the former category. Clustering implies some kind of dependency between the events, the causes of which are outside the scope of this report.

Many of the seismic clusters in the SWA seismic zone contain a high proportion of events with magnitudes close to the maximum magnitude of the sequence. These larger events may be distributed throughout the course of the episode, and not concentrated at the beginning. Such seismic episodes are often referred to as "swarms". Much time could be spent arguing about the definitions used, but the object of this paper is to summarise the activity in 2012-2013, and refinements of the definitions is probably best left to future work.

Figure 2 Seismicity June 2012 – May 2013



Overview of seismicity, June 2012 – May 2013

The seismicity for the year is plotted in Figure 2. Table 1 summarises the annual seismicity from 2012 to 2018, using data extracted from the GA on-line data base. The table suggests that 2012-2013 was a relatively average year, with 272 events recorded in total, of which 169 above ML 2.0. The largest event was ML 3.5 (near Beacon on 18 July 2012). As has been noted before, the seismicity was highly clustered, and most of the seismicity came from two locations about 50 km apart – i.e., west of Beacon (about 66 events), and north of Koorda (about 120 events). One other location, north of Hyden, had significant activity with about 32 events, the largest being ML 3.3.

Table 1 Summary of seismicity in southwest Australia, June 2012 – May 2018

	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18
Total number events	272	289	167	73	209	245
ML 2.0 and above	169	195	115	45	163	154
ML 3.0 and above	5	3	1	2	8	4
Largest event (ML)	3.5	3.4	3.3	3.2	4.2	3.9
Largest cluster & number of events	C1 (120)	B2 (54)	B2 (26)	B3 (13)	L2 (65)	

2 A review of events June 2012- May 2013 by zone

In this section, each of the 10 zones identified above are individually reviewed. As clusters are identified in a zone, they are added to Table 2. Significant events (ie, ML > 2.3) which are not part of a cluster, or events which may be part of an ill-defined cluster, are listed in Table 3.

Table 2 Properties of clusters active in the SWA zone, June 2012 – May 2013

Location	Label	# of events	Max mag	Most active period	Comments
N of Kalannie	A5	1	1.6	9 Aug 2012	
West of Beacon	B2	66	3.5 (July)	Aug 2012	Periods of activity before and after 2012-13 period. Many smaller events detected by a short-term field survey
North of Koorda	C1	~120	3.3 (May)	Active all year	Periods of activity before and after 2012-13 period
NE of Koorda	C3	(6?)			Part of a swarm active 2012 until 2014
Bonnie Rock	L1	2	2.4	Aug 2012	Cluster location was active in 2001
Nungarin	D4	2		4 Aug 2012	
SE of Wyalkatchem	D8	3	2.6	Dec 2012	
N of Westonia	D9	3	2.5	Apr 2013	New, location poor, -31.15 118.80
N of Kellerberrin	D1	3	2.3	Sep 2012	Poor locations – not confident
S of Meckering	M3	2	1.7	17 Jun 2012	
NE of Youndegin	E1	1	1.6	23 Dec 2012	
W of Bruce Rock	E2	1	2.0	19 Jan 2013	
N of Dubelling	E4	4	2.1	Sep 2012	New. -31.98 117.25
North of Hyden	F1	12	2.6	Feb 2013	Periods of activity before and after 2012-13 period; also active in 2006?
N of Holt Rock	F6	~10	3.4	3-4 Mar	New Poorly defined; -32.30 119.27
Morbinning	F3	2	2.3	22 May 2013	
Pingelly	F4	1	1.8	27 May 2013	
SW of Kulin	F7	4	2.2	Jan-May 2013	New -32.81 117.87
N of Katanning	G1	4	2.3	4 Aug 2012	
Northwest of Gnowangerup	G5	1	2.4	19 Apr 2013	New -33.84 117.94 Correlates 2017-2018 activity
N of Rocky Gully	H1	1	2.6	22 May 2012	Continuation of larger cluster of March 2012

Zone A Burakin

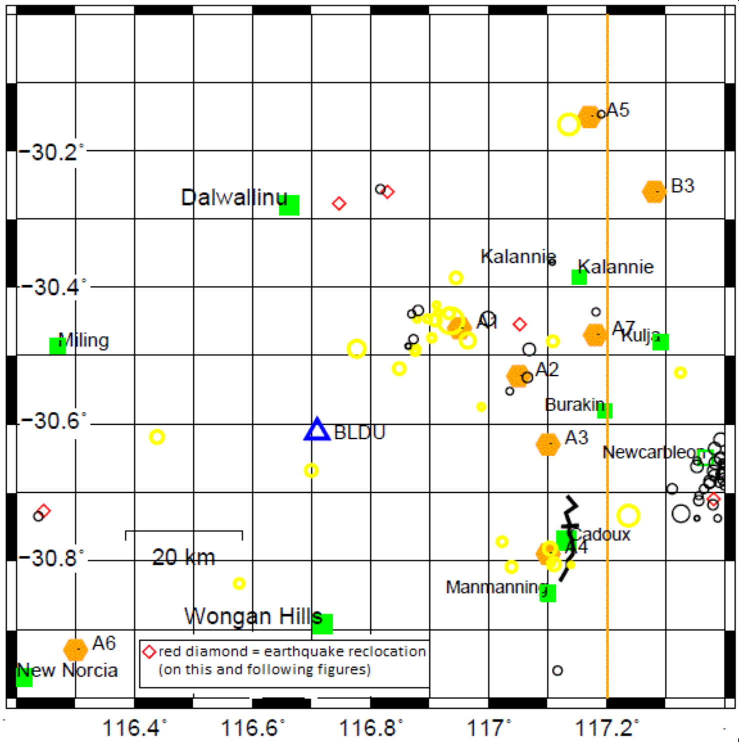
This zone was relatively quiet during the period, with 14 events, the largest being ML 2.3 on 14 September 2012 (Figure 3). Some of the events west of Burakin may be related to one of two cluster locations in the area (A1 & A2, Figure 3), but the closeness of the cluster locations, combined with epicentral uncertainties makes it hard to confidently assign events to a specific cluster location. Figure 3 shows about 15 events in the preceding 12-month period clustered around location A1.

A single small event (9th August 2012, ML 1.6) is noted very close to location A5, north of Kalannie, and is assigned to that location in Table 2.

One small event is noted south of Miling (20th June, ML 1.8). Examination of seismogram data from Beacon shows a second event of similar size at this location 8 minutes earlier. This is therefore a potential cluster location, and has been added to Table 3 for future reference.

A small event south of Manmanning (ML 1.8, 29 July 2012) when relocated, moves about 30 km east to join the cluster of events north of Koorda, in zone C.

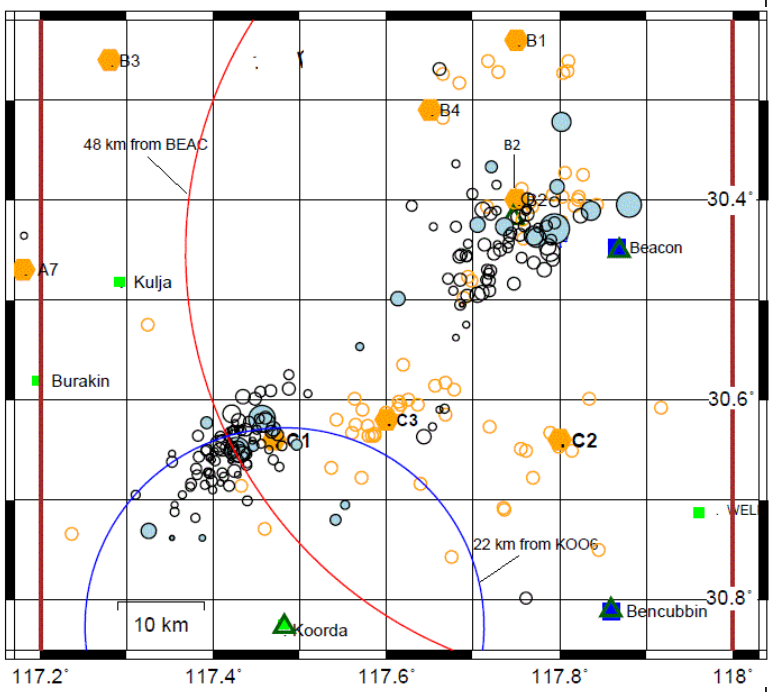
Figure 3 seismicity of Zone A, June 2012 – May 2013



Zone B Beacon

Although they are the smallest subdivisions of the SWA seismic zone, zones B and C are usually well represente in numbers of events. Zone B was quite active again in this period, with 66 events which are distributed over a zone about 12 km wide, about 12 km west of Beacon (Figure 4).Many of the events were accompanied by loud “bangs”. It is suggested that almost all these events have emanated from cluster location B2. This location was originally defined in Dent (2014a), on the basis of relocations of about four events in the time period studied here. Support for the above definition, and a possible refinement of it, will be sought from three approaches, as given below.

Figure 4 Seismicity of zones B and C, Jun 2012 – May 2013



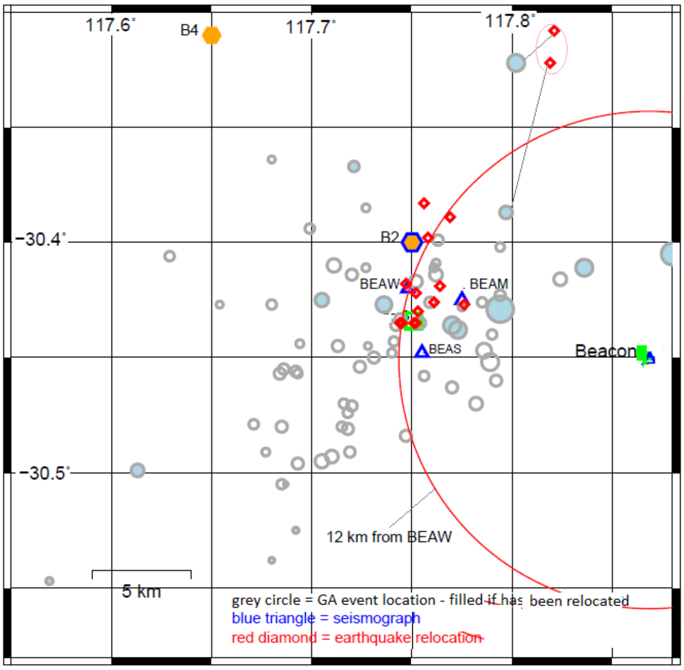
Legend: filled circles indicate event that have been relocated

1) Relocations of some events including phase data from stations not previously used - principally BEAC)

Eleven events have been relocated, incorporating data from the PSN network, and the relocations are shown in Table 4, and Figures 5 and 6. Most of these relocations plot about 2 km to the southeast of location B2.

2) Locations using temporary field station data

Figure 5 seismicity near Beacon, Jun 2012 – May 2013



Field stations (BEAW, BEAM and BEAS) were deployed at the locations shown in Figure 5 between 12 and 22 September 2012, although only the station BEAW operated for more than a few days. In this period, two events (12/9 @ 0608, ML 1.8 and 21/9 @ 0853, ML 2.5) were located by GA in the region, but the field stations also detected many smaller events. All had S-P times very close to 0.35 secs at the BEAW station (Table 5). The GA solution for the ML 2.5 event on 21 Sep.2012 is about 4 km west of the BEAW station. In the relocation (solution 1 in Appendix 1) the data from the BEAC and BEAW stations are given maximum weight, and a solution about 3 km deep, and about 0.2 km west of BEAW is obtained, and it is suggested that this is the better location. The difference is probably caused by discrepancies between the WA2 model and the true (unknown) earth model. The WA2 model has higher velocities than most earth models used in Australia, as might be expected, as it attempts to model the high velocity Australian shield (Bowman & Kennett (1993). More research is needed in order to define the best velocity model and thus obtain the best solutions for these events.

Table 3 Undefined events, June 2012 – May 2013

Location	Zone	Num-ber	Max Mag	Most active Period	Comments
S of Miling	A	1	1.8	20 Jun 2012	-30.73 116.24 Extra event not GA-located
N of Beacon	B	2	2.8	Nov 2012	-30.31, 117.81
Bolgart	D	1	2.0	18 Jun 2012	Correlates with events earlier in 2012
W of York	M	2		14 Aug 2012	Main shock and aftershock?
N of Pingrup	H	1	2.6	6 Sep 2012	May correlate with Lake Grace events?

3 Reviewing S-P times of events at BEAC

Although S-P times from a single station cannot give an earthquake location, they can, if clearly recorded, give an accurate estimate of the hypocentral distance of a station from an earthquake. The cluster events from the B2 location all had very similar S-P times at BEAC, as shown in Table 6. The times averaged 1.42 secs, and were within 0.1 secs either side of this. This

Table 4 Beacon area relocations

Date/time	New Lon.	New Lat.	GA Lon	GA Lat	Move (km)
8 Jul 0920	117.751	-30.435	117.793	-30.429	4.7
9 Aug 0420	117.764	-30.419	117.770	-30.436	2.0
9 Aug 0433	117.773	-30.410	117.836	-30.411	7.0
28 Aug 0432	117.76	-30.415	117.735	-30.427	3.1
28 Aug 1942	117.769	-30.417	117.773	-30.438	2.4
12 Sep 0608	117.745	-30.422	117.569	-30.547	24
21 Sep 0853	117.747	-30.418	117.707	-30.425	4.5
18 Jul 1635	117.756	-30.383	117.880	-30.405	14
18 Jul 0920	117.751	-30.435	117.794	-30.429	2.0
08 Sep 0836	117.754	-30.432	117.797	-30.387	6.9
10 Nov 1711	117.792	-30.323	117.721	-30.367	9.0
14 Nov 2023	117.821	-30.308	117.802	-30.322	2.6

indicates a hypocentral distance of 12 km, +/- 2 km, according to tables presented in Dent (2012), which used the same earth model as has been used here. The GA locations for events noted in **Table 4** are indicated as filled circles on Figure 5, and many are relatively remote (>5km) from location B2. This discrepancy is interpreted as representing the uncertainties in the GA locations. The relocations of several events are plotted on Figure 5. They have mostly been assigned a shallow focal depth (2 km), and they fall very close to the expected 12 km distance from BEAC.

Table 5 Coordinates of temporary field stations and S-P times

Code	Latitude	Longitude	comment	Opened - closed
BEAW	-30.4181	117.746	S-P 0.35s. to B2	Sep 08 Sep 23 2012
BEAM	-30.425	117.775		
BEAS	-30.448	117.755		
BEAC	-30.4511	117.869	S-P 1.45s to B2	Mar 2009 – Dec 2012
KOO4	-30.6303	117.604	S-P 0.2s. to C3	Nov – Dec 2011
KOO5	-30.664	117.541	S-P 1.2s. to C1	29 Sep 2012 – 03 Oct 2012
KOO7	-30.701	117.416	S-P 1.0s. to C1	24 Sep 2012

Other events in Zone B

There is one apparent outlying event, about 15 km NNW of Beacon, on 14 November (ML 2.8), and relocation confirms this position. Relocation of a smaller event (ML 2.2) on 10 November brings it close to the location of the ML 2.8 event. Both have S-P values close to 1.9 secs, and a third, small event on 10 November (estimated ML 1.3, detected only on the BEAC station) has a similar S-P value. This group of events is listed in Table 3 as a potential cluster location.

Zone C Koorda

There were ~ 120 events in this zone. **Figure 4** shows a distinct NE trending cluster about 20 km north of Koorda, in the vicinity of cluster location C1. There were events originating from this location throughout the year; the largest was ML 3.3 in May 2013. As with location B2 discussed above, C1 was defined in Dent (2014a) on the basis of several relocations of events from the 2012-2013 period. Since its installation in February 2013, the PSN station at Koorda has been very useful in adding extra precision to epicentres in this region. The relocations (Table 7 & Figure 4) suggest the events are less scattered than they appear to be from the GA locations. The apparent northeast trend is reduced but is still evident. If real, the trend may indicate the orientation of a causative fault. This location is thought to be the same as a cluster of events between March and May 2005 (largest, ML 4.2).

Table 6 A sample of S-P times recorded at BEAC station

Date-time	ML	S-P	Comment
2012		**sec**	
Jun 23@2133	2.2	1.42	
Jun 28@1122	2.3	1.39	
Aug 08@2222	2.1	1.46	
Aug 09@0117	2.3	1.48	
Aug09@0136	2.3	1.47	
Aug09@0138		1.43	not located by GA
Aug09@0738	2.6	1.45	
Nov 10@1711	2.2	1.89	different group
Nov 14@2023	2.8	1.90	different group

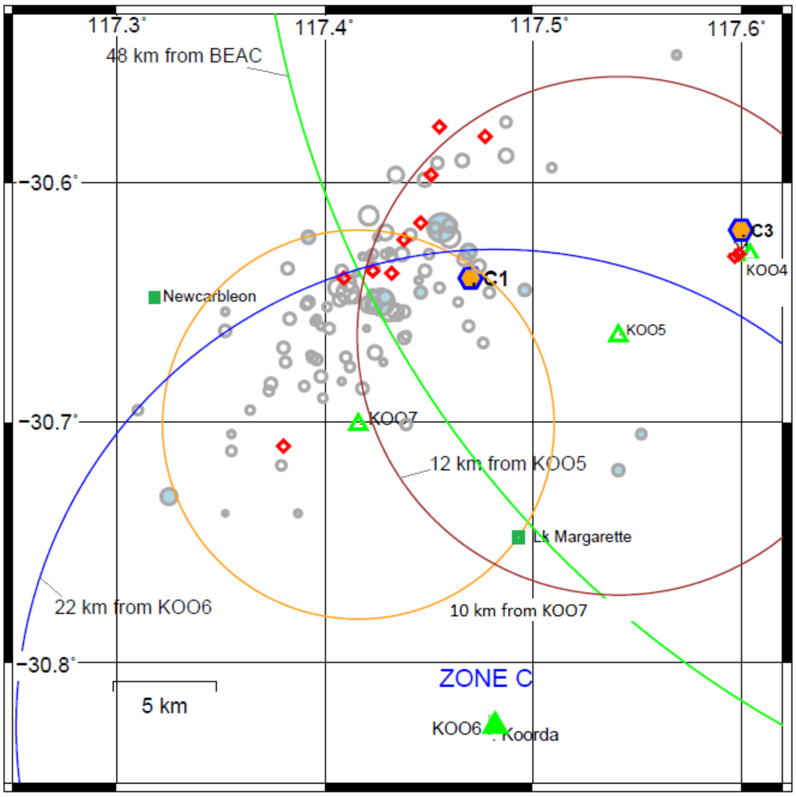
Many of the events north of Koorda were recorded on the BEAC station and, also, during September 2012, on the temporary field station BEAW. They had consistent S-P times of about 5.4 secs at BEAC, which correlates with an epicentral distance of about 48 km (Figure 4), and 4.8 secs at BEAW.

Table 7 Koorda area relocations

Date & Time	New Lon	New Lat	GA Lon	GA Lat	Mag
17 July 2251	117.438	-30.624	117.469	-30.629	ML 2.4
27 Aug 0456	117.446	-30.613	117.325	-30.731	ML 2.5
11 Sep 0804	117.423	-30.634	117.352	-30.738	ML 1.4
30 Jan 1535	117.468	-30.622	117.387	-30.738	ML 1.6
01 Feb 0949	117.451	-30.597	117.427	-30.65	ML 3.2
21 Feb 0607	117.409	-30.64	117.392	-30.623	ML 2.2
24 Mar 1411	117.432	-30.638	117.446	-30.646	ML 2.1
17 May 1511	117.423	-30.637	117.456	-30.619	ML 3.3
31 May 1921	117.624	-30.634	117.552	-30.705	ML 1.9
16 Sep 2047	117.599	-30.63	117.541	-30.72	ML = ?
18 Mar 0505	117.631	-30.629	117.667	-30.609	ML 1.7

Data from temporary field sites north of Koorda occupied in October 2012 can be used to estimate the correct location for cluster C3. Data were recorded at the sites indicated in Figure 5 and listed in Table 5. Several small events were recorded, but none of them was large enough to be located by the GA network. However, the S-P times can be used to estimate epicentral distances (Table 5) which leads to a good estimate of the probable epicentre, shown in Figure 4, and this estimate is notionally applied to the entire sequence of events.

Figure 6 seismicity near Koorda, Jun 2012 – May 2013



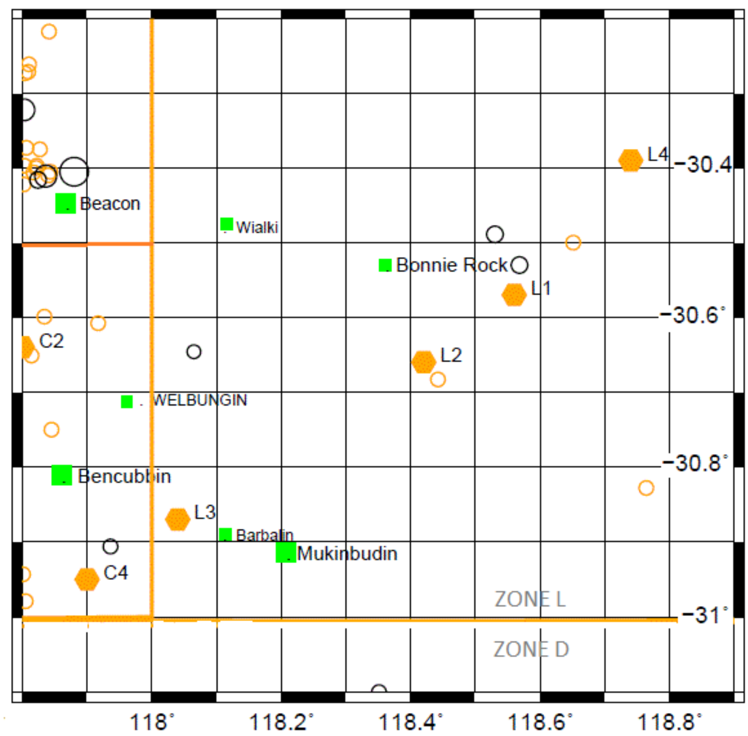
Again, consistent S-P times of about 2.1 secs. were recorded, correlating with an epicentral distance of about 21 km (Figure 6), assuming a shallow focal depth. Using these derived epicentral distances, the intersection of the circles (Figure 6) suggests a common epicentre at 30.64°S, 117.43°E, which is about 3 km WNW of the location assigned to the events which occurred in 2013-2014 (location F in Dent (2014a), or C1 in Dent (2017). This may represent a better location for the C1 cluster.

Other events in Zone C

Figure 6 shows that several events plot near location C3 “NE of Koorda”. Relocations of these events bring the events closer to C3, and these events have been assigned to that location. C3 was defined in Dent (2014a) on the basis of a relatively large number of events, many of which were felt, in late 2011 (Dent, 2012). Figure 6 indicates some of these earlier earthquakes (yellow circles in the vicinity of C3 on Figure 4),

Zone L Bonnie Rock

Figure 7 seismicity of Zone L (Bonnie Rock)



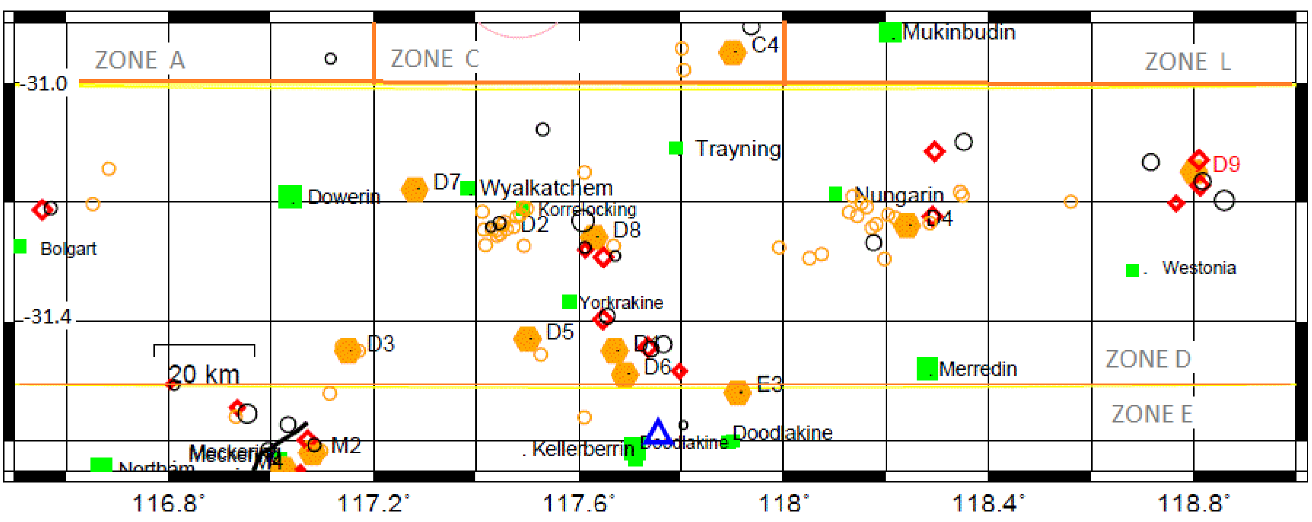
There are only three events in this zone. Two events in August 2012, both ML 2.4, were near Location L1. Relocations bring them closer together, and also closer to L1 (Figure 7). Location L1 was active in 2001, and was well-constrained because of a temporary deployment of seismographs by GA (Dent & Collins, 2017). The August 2012 events are shown in Table 2 as belonging to that cluster location. The third event (2 December, ML 2.2) is poorly located, but could belong to a cluster (L3) near Welbungin, noted by Dent & Collins (2017).

Zone D   Wyalkatchem

Two events occurred near Nungarin on 4th August 2012, near cluster D4 noted in the 2016-17 report. Figure 8 shows events that occurred near there in the previous 12 months. The GA database shows an ML 3.0 on 21 April 2012. The August events are assigned to D4 in Table 2.

Three events occurred southeast of Wyalkatchem between September and December 2012 (largest ML 2.6 on 9 December). They have been assigned to cluster D8, defined in Dent (2017).

Figure 8 seismicity of Wyalkatchem Zone (Zone D)



Three events occurred north of Kellerberrin in September 2012 (largest ML 2.3). They are grouped in time, but relocations (using limited extra data) only bring them partly together. They are close to (< ~ 5 km) two cluster locations, D1 and D6, and are tentatively assigned to location D1. This uncertainty demonstrates the need for quality locations to assist in seismic interpretation.

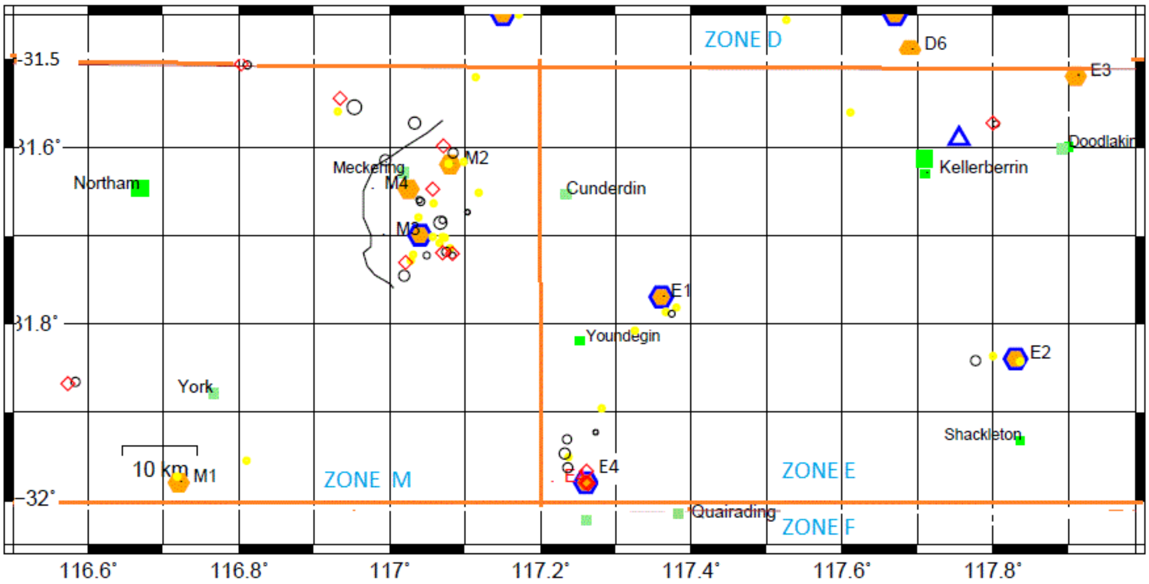
A group of three events north and northeast of Westonia, between 25th April and 4th May 2013 (largest Ml 2.5), has been assigned to a new cluster location, D9.

In the west of the zone, a small event (ML 2.0) near Bolgart in June 2012 appears isolated, but Figure 8 indicates there were two other small (largest ML 2.0) events near that earthquake in the preceding period. This, like the "Miling" event in Zone A, is called a "potential" cluster, and added to Table 3. Note that there was a large but poorly located event near Bolgart (ML 5.1) in 1952.

Zone E Kellerberrin

There are seven small events in this zone (largest ML 2.1). Two are quite isolated, but plot close to cluster locations E1 and E2 (Figure 9), and are here assigned to those locations. Another small, isolated event plots about 10 km NE of Kellerberrin. The remaining four events form a group northwest of Quairading, three of which were relocated. The relocation of one of them (07 Feb 2013@0216 U.T.) is shown in Appendix 1. These relocations move the events about 4 km southwards, and a (new) cluster location is suggested at 31.98°S, 117.25°E, called E4. This location is only about 4 km distant from the centre of an earthquake cluster in January1992, reviewed in Dent & Collins, (2018) It was suggested in that report that all seismicity near this location may be related to a period of stronger activity between July and October 1967, when five (poorly located) magnitude 4 events were recorded southwest of Quairading.

Figure 9 seismicity of Zones E (Kellerberrin) and M (Meckering)



Zone M Meckering

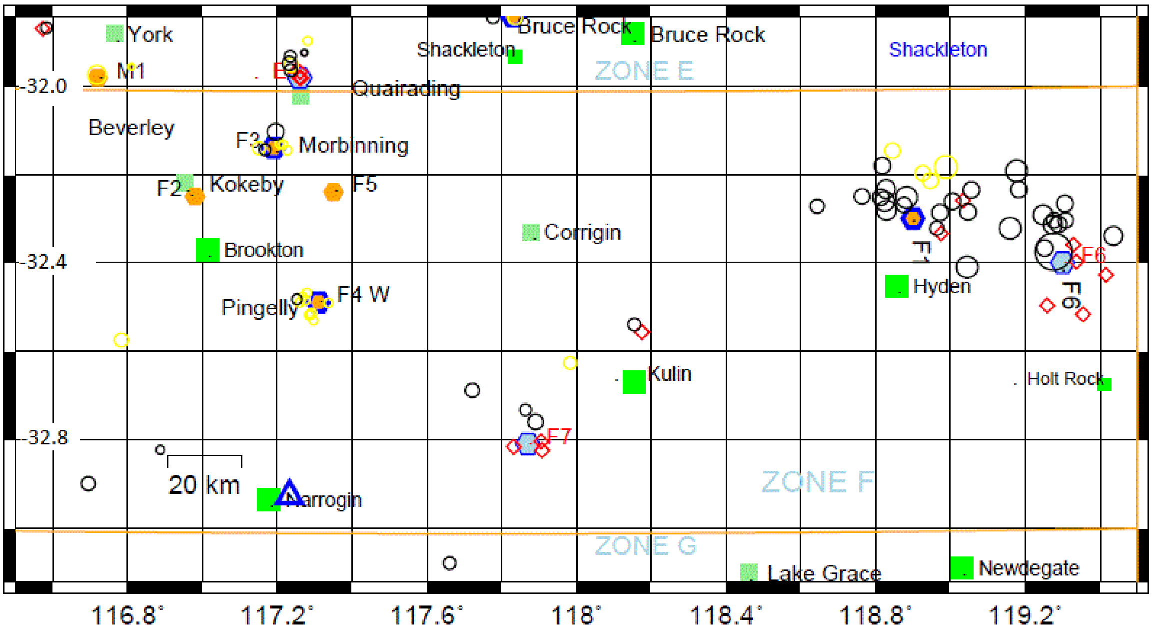
Events near Meckering are not particularly clustered in time, except for two small events (ML 1.6 & 1.7) which were 20 minutes apart on 17th June 2012. They plot close to cluster location M3 (Figure 9), to the east of the Meckering fault, and are assigned to that location in Table 2. The remaining events are not assigned to a cluster location, although some of them are close to locations M2 and M4. Being close to a known large seismogenic fault, different mechanisms may apply in this region. It might be expected that earthquakes could originate along the length of the fault, and the region needs closer investigation when the collection of good epicentres is larger.

There were two events an hour apart on 14th August 2012 (ML 2.5, 2.1) in the far west of the zone, about 20 km west of York. These two events may be categorised as a simple mainshock/aftershock sequence, rather than a cluster, and are noted in Table 3.

Zone F Brookton-Hyden

There was a group of 32 earthquakes north of Hyden, between December 2012 and May 2013. Ten of these events occurred on 3rd March, including the largest event of the year, ML 3.4. Earthquakes near Hyden are difficult to locate, because they are outside of the SWA network. In addition, the station at Kambalda seems to have been unserviceable for much of 2012 and 2013. Fortunately, some of the events were recorded at the PSN stations Kulin, Pingelly, and Gnowangerup, and the S-P times of many events have been measured and noted in Appendix 2. The Pingelly S-P times suggest the events can be put into two groups: those with S-P times about 21 secs, and those with S-P times about 26 s.

Figure 10 seismicity of the Brookton-Hyden zone (Zone F)



The first group, of 12 events, (December 2012 – February 2013, largest ML 2.6), plot near cluster F1, 20 km north of Hyden. The events of March 2013, and later, fall into the second group, and plot about 45 km northwest of Holt Rock, or 40 km northeast of Hyden. A new cluster centre has therefore been defined as F6 in Table 2, north of Holt Rock. This is the most significant of the newly defined clusters in the 2012-2013 period.

Examination of the seismograms indicates that the large event in the F6 group (ML 3.4, 3rd March, at 2136 UTC) is actually a double event. The first event of the doublet has an origin time the same as the GA located event and is probably smaller, ML ~ 2.3. The larger event cannot be located accurately because its trace overprints the earlier event, and appears to have an origin time about 20 secs later than the first event.

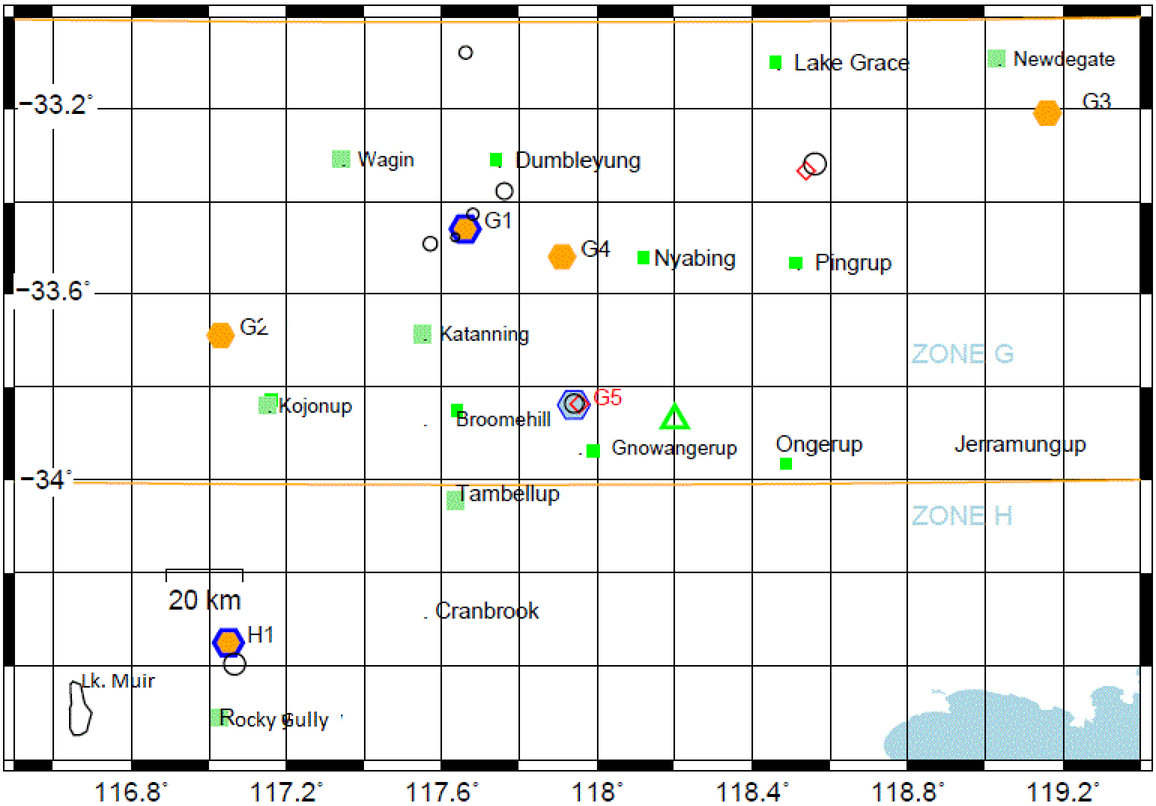
A group of four events between January and May 2013 (largest ML 2.2) is observed southwest of Kulin. They have been relocated and three plot close to each other, and a new cluster location (F7**)** is defined in Table 2 at the approximate centre of these events. The fourth event was recorded by only three stations, and its location is therefore unreliable but it could belong with the others in F7.

Two events in the northwest of the zone (largest ML 2.3 on 22nd May 2013) correlate well with cluster centre F3 (“Morbinning”), discussed in more detail in Dent (2018). A small event on 27 May 2013, east of Pingelly, is very close to cluster centre F4.

Zone G Katanning

There were seven events in this zone. The largest event was ML 2.6, north of Pingrup, on 6th September 2012. This event appears isolated, although there are many other (poorly located) events near it in other years. The event has been added to Table 3 as future work may indicate a cluster centre in its vicinity.

Figure 11 seismicity of Zones G & H



The next largest was ML 2.4 northwest of Gnowangerup, on 19 April 2013. This event also appears isolated, but, as noted in Dent (2017), its location correlates with a cluster of small events in 2016 (none located by GA). It also correlates with a cluster of three events in November 2017 (largest ML 2.4), and is close to GA’s location of an ML 3.7 event in October 1996 (-33.9, 117.909). It is here defined as a new cluster location, G5 (Table 2).

The remaining four relatively small events (largest ML 2.2) in the Katanning zone are grouped southwest of Dumbleyung. The location uncertainties leave open the possibility that they come from location G1, which was quite active in July 2013, and partially monitored by a field instrument (Dent, 2014b).

Zone H Cranbrook

This zone achieved prominence when a magnitude 5.7 event occurred east of Rocky Gully in September 2018. However, in the time period June 2012 to May2013, there is only one event in the zone, an ML 2.6 event on 22 May 2013, north of Rocky Gully, or about 40 km east of the September 2018 event. Although the ML 2.6 appears isolated, a review of the GA catalogue suggests it was part of a cluster of eight located events, which commenced in March 2012 with an ML 2.9 event, and continued until November 2013. The group was defined as cluster location T in Dent (2014a), later renamed to H1. Over the six years between 2012 and 2018, this is the only cluster to be defined in zone H. However, the GA earthquake catalogue shows earlier clusters in zone H, eg ~40 km SW of Kojonup in May 1996 (largest event ML 3.0) and ~ 10 km east of Tambellup in October 1999 (largest event ML 2.5).

Lake Muir area seismicity

Note that an ML 2.7 event which occurred three days after the interval studied here (ie, on 3 June 2013) was only about 10 km west of the location of the September 2018 ML 5.7 Lake Muir event. Considering location uncertainties, they could be co-located. However, a search back to 1980 shows it is the only previous event in the close proximity to Lake Muir. It can be stated that, unlike the Meckering region, which experienced many small cluster episodes in the decades prior to the magnitude 6.5 1968 event (Everingham, 1968, Gordon & Lewis, 1980), the 2018 Lake Muir event did not have any significant prior seismic activity.

3 Discussion

The analysis above has assigned ~253 events, or over 90% of the located seismicity between June 2012 and May 2013, to 21 cluster locations. Only six of these locations have not been defined before, and the other 15 are found within a group of 44 cluster centres as listed in Dent (2017). Another five locations are noted as “provisional” cluster locations, and it is intended to watch for future activity at these locations.

The most active centres of the year, C1 near Koorda and B2 near Beacon, belong to relatively long-lived cluster centres which have been defined previously. The most significant “new” cluster centre is that north of Holt Rock (east of Hyden), and it is relatively close to another previously defined centre, F1. Difficulties in location in this region at the edge of the zone means that the possibility remains that they represent just one cluster location. This demonstrates the high degree of clustering in the region, and the possibility of repeating seismicity raises the prospect of some degree of prediction for seismicity in the region.

Many of the clusters which are closely spaced also seem to demonstrate contemporaneous activity, examples being the “north of Hyden” location (F1) and the “north of Holt Rock” location (F6) (active between February and March 2013, and about 25 km apart), and also the locations west of Beacon

(B2) and "north of Koorda" (C1), both active throughout much of the 12 month period, and about 40 km apart.

These earlier seismic clusters, with a few exceptions, also occurred within the period June 2013 to May 2017. The exceptions are cluster centres A1 – A4, which are identified from activity northwest to southwest of Cadoux in 2001 (Leonard & Boldra, 2001), cluster centre D1, from activity north of Kellerberrin in 1996 and 1998 (Dent, 2011), and M1, from activity south of York in 1992.

These cluster centres in general have exhibited activity over periods of longer than a year. In the case of some of the more significant cluster centres (e.g. A2, Burakin, B1, Beacon) the largest event (or events) are near the start of the sequence, and in that sense they seem to be long aftershock sequences. In others, e.g. Bonnie Rock, it may be that significant seismicity occurred at the location more than 20 years ago. Seismicity near Meckering of course may be related to the M 6.5 event there in 1968, and this may also be true, but less definite, in the case of seismicity near Cadoux. Other early significant earthquakes in the region, e.g. Gabalong in the 1950s, Nourning Spring (1963) and Calingiri (1971) may also be related to modern day clustered seismicity. Some of these centres may yet be identified, as this study has been focussed around seismicity of the region between 2012 and 2018. It is also possible that some of the seismic clusters represent remnant activity from large earthquakes which occurred prior to records being kept. No clear correlation with neotectonic features in the region, as noted in the Neotectonic Features Database on the GA website, or fault scarps shown in Clark et al,. (2012) is yet apparent. It is possible that a review of geomorphological features in the vicinity of cluster centres identified by this research, will lead to the addition of new features.

It is important to note that even a single event can be considered a cluster event, if it coincides with a previously defined cluster location. However, if the locations are poor, the connection may not be apparent.

The monitoring capability in the south coast region of WA, east of the eastern boundary of the SWA zone (at 119.5^{o}E) is poor, and smaller events (ie < ~ ML 2.0) could easily go undetected. A recent (August-September 2017) earthquake cluster north of Ravensthorpe (about 30 events, largest ML 3.5) is about 50 km east of the eastern boundary of the SWA zone, but has all the characteristics of clusters inside the zone. An extension of the zone boundaries, in this area at least, seems warranted.

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Appendix 1 – sample EQLOCL solutions using PSN seismograph data

(a Solution for 21 Sept 2016 Beacon event, with maximum weight for close station arrivals (the suggested best location)

```
Date            2012-09-21
Origin Time     0853  8.41   +   4.14
Zone                    50
Easting             571.72   +  24.66            Longitude     117.747
Northing           6634.36   +  45.15            Latitude      -30.421
Depth                 2.99   +  69.45

Arrival times    =  8            S.D. = 0.049        Seismographs =  5
Nearest recorder =    0.2 km     Gap  = 120.3 deg    Accuracy = A
Effects Code     =               Imax =  0           Fault =

   0 km  W (252 deg) of  BEAW
WESTERN AUSTRALIA
 248 km NE ( 47 deg) of PERTH
  12 km  W (285 deg) of Beacon

No magnitudes known                               Assign ML  2.5

DATA USED
Code  Wave        AT     +     WT      CT      DT      Dist  Azim    Ad     Ae
BEAW   S-P      0.37  5.00  0.79    0.37   -0.00      0.2    72    0.0   0.0
BEAC   S-P      1.50  0.10  1.48    1.43    0.07     12.2   106    0.0   0.0
BEAC   P       10.45  0.10  1.48   10.47   -0.02     12.2   106   15.1  15.1
BLDU   P       25.02  0.10  1.26   25.03   -0.01    101.8   257    1.9   1.9
BLDU   S       36.60  1.00  0.71   36.55    0.05    101.8   257    1.9   1.9
KLBR   P       29.50  1.00  0.78   29.54   -0.04    129.8   179  -30.8  30.8
KLBR   S       44.30  1.00  0.70   44.27    0.03    129.8   179    1.5   1.5
MORW   P       42.12  0.20  1.02   42.08    0.04    223.0   311  -40.6  40.6
                        8 times used, S = 0.049
Deferred Data
MORW   S       67.40  1.00  0.67   66.56    0.84    223.0   311  -40.3  40.3
MUN    P       42.80  0.20  1.02   42.50    0.30    226.5   219  -40.6  40.6
MUN    S       68.10  1.00  0.67   67.28    0.82    226.5   219  -40.3  40.3
NWAO   P       49.50  0.20  1.00   49.38    0.12    282.0   189  -40.6  40.6
NWAO   S       78.84  1.00  0.65   78.97   -0.13    282.0   189  -40.3  40.3
MEEK   P       67.56  0.30  0.89   67.46    0.10    427.6    11  -40.6  40.6
MEEK   S      109.50  1.00  0.63  109.68   -0.18    427.6    11  -40.3  40.3
```

b) Solution for 07 Feb 2013 Quairading event

```
Date           2013-02-07
Origin Time    0216 10.03   +   1.22
Zone                   50
Easting            524.68   +  12.65          Longitude     117.261
Northing          6463.19   +   6.77          Latitude      -31.967
Depth                4.45   +  64.65

Arrival times    =  8           S.D. = 0.244       Seismographs =  5
Nearest recorder =   62.6 km    Gap  = 133.1 deg    Accuracy = B
Effects Code     =              Imax =  0          Fault =

  13 km  W (291 deg) of  QUAI
WESTERN AUSTRALIA
 133 km  E ( 91 deg) of PERTH
  35 km  S (175 deg) of Cunderdin


DATA USED
Code  Wave       AT    +     WT      CT      DT     Dist  Azim    Ad     Ae
KLBR   P       20.27  0.10  1.31   20.26   0.01    62.6    48    4.4   4.4
KLBR   S       27.40  1.00  0.74   27.36   0.04    62.6    48    4.4   4.4
PING   P       20.81  0.05  1.50   20.65   0.16    64.9   202    4.2   4.2
PING   S       28.36  0.50  0.85   28.01   0.35    64.9   202    4.2   4.2
MUN    P       25.96  0.20  1.10   26.28  -0.32    99.5   268    2.7   2.7
NWAO   P       27.12  0.10  1.25   27.40  -0.28   106.4   181    2.5   2.5
BLDU   P       35.22  1.00  0.76   35.15   0.07   159.1   340  -30.8  30.8
BLDU   S       54.30  1.00  0.69   54.00   0.30   159.1   340    1.7   1.7
                        8 times used, S = 0.244
Deferred Data
MUN    S       37.70  1.00  0.72   37.54   0.16    99.5   268    2.7   2.7
NWAO   S       39.00  1.00  0.71   39.45  -0.45   106.4   181    2.5   2.5
RKGY   P       53.15  0.30  0.92   51.78   1.37   294.2   185  -42.2  42.2
```

Appendix 2 S-P times of events near Hyden, March 2013, recorded at PSN stations

Date, 2013	Time	ML	S-P in secs at station				Assign to cluster
			KULI	PING	GNOW		F1 or F2
31 Jan	2024	2.5			20.8		F1
01 Feb	0450			21.7	20.1		F1
15Feb	1448	2.3		21.5			F1
16 Feb	1438	2.6		22.1			F1
16 Feb	1505	2.3		21.6			
03 Mar	0928	2.6		27	21.5		F6
03 Mar	1325		12.9	27.3	21.6		F6
03 Mar	1315	2.5		26.5			F6
03 Mar	1301	2.3	12.9	25.8			F6
03 Mar	2333	2.2	12.6	26.9	21.7		F6
04 Mar	1045	2.2		24.7	21.5		F6