Earthquake clusters in southwest Australia in 2013-14

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Abstract

Approximately 290 earthquakes were located by Geoscience Australia (GA) in the southwest Australia (SWA) seismic region in the 12 months June 2013-May 2014. Most of these events were located within 12 cluster sources, 9 of which have been previously identified, and many of the remainder are also probably cluster-related. The SWA region has been divided into 8 zones, and the seismicity of each zone examined. Cluster locations have been identified as accurately as possible, sometimes aided by relocations which have taken advantage of phase data from the relatively new "Public Seismic Network" (PSN). The occurrence of many of the 2013-14 events at the locations of previously identified cluster activity suggests that the majority of seismic events in SWA occur at the locations of historically active sites, some of which appear to have been persistently active over the last 50 years at least.

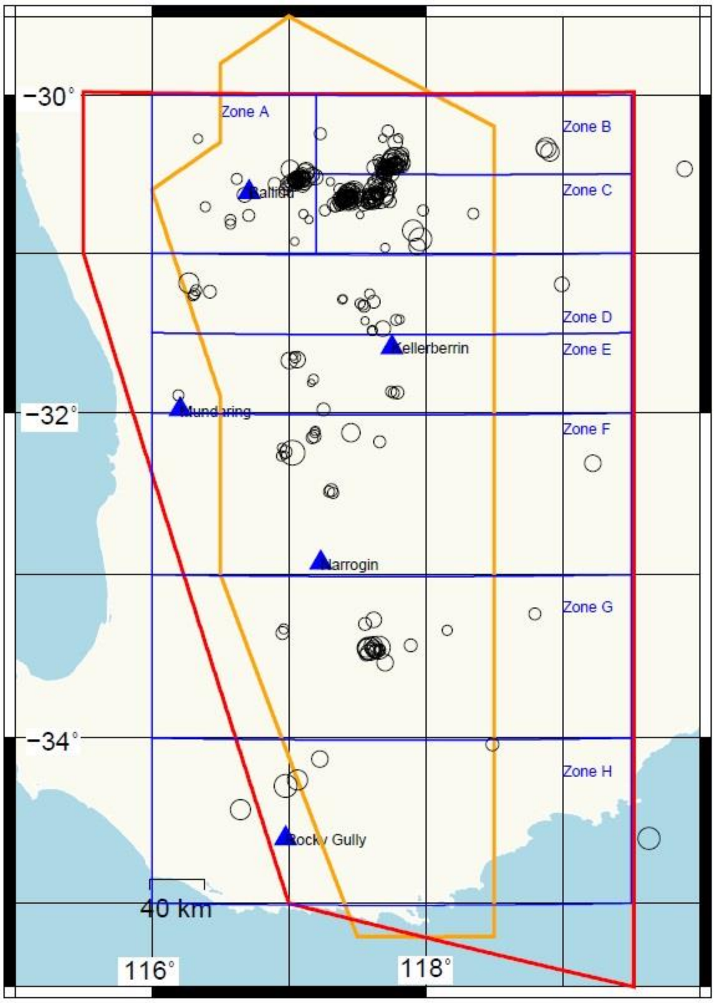
Keywords Southwest seismic zone, seismic clusters, earthquake relocations

1 Introduction

Southwest Australia (SWA) is an important site for intra-plate seismicity, and has experienced some of Australia's largest and most damaging earthquakes. Its seismic hazard has been closely studied (e.g. Burbidge, 2012; Brown & Gibson 2004). At least three surface rupturing earthquakes have occurred in the last 50 years – most notably the 40 km long Meckering scarp of 1968. In southwest Australia, earthquakes are frequently clustered, and this activity may be the normal mode of seismic expression in the region.

SWA is here defined as the area enclosed by 30S to -35S, 116.0E to 119.5E (Figure 1). This approximates the SWA region as defined by Leonard (2008). Within the SWA seismic region there is a region which has been commonly called "the southwest seismic zone" or SWSZ (Doyle, 1971; Gaull & Leiba, 1987). It does not include the periodic seismicity west of the Darling Fault, e.g. that in the Margaret River area, which belongs to a different seismo-tectonic region (the Perth Basin Zone, Brown & Gibson, 2004). The SWSZ has poorly defined boundaries, which is why the larger SWA region, as defined above, is probably a better unit to study.

Figure 1 Seismicity in SWA June 2013-May 2014



Legend: Circles= GA locations of epicentres June13-May14 (diameter proportional to magnitude). Triangles= ANSN seismograph. Red box - SWA as defined by Leonard (2008). Orange box - SWSZ of Gaull & Leiba (1987). Blue box –SWA as used in this study.

Earthquake activity in SWA is typically clustered – i.e., the events are grouped in space and/or time. Furthermore, the clusters can also often be described as "swarms". These are clusters where there is typically no clear "main" shock – there are at least two events of relatively similar magnitudes, and often occurring well after the cluster has commenced.

One of the problems in describing cluster activity is poor earthquake locations. Dent (2013) has shown that on occasions, events in SWA which are probably within 5 km of each other have been located up to 40 km apart.

In this discussion, a cluster may contain as few as two events. This is because it is often the case that there are other events which have not been located because they are below Geoscience Australia's (GA's) locatability "threshold".

Since 2006, a new "independent" seismic network, the "PSN" network (Dent, 2008; Dent et al., 2010), has been expanding in the SWA region, and data from this network have the potential to allow earthquake re-locations which are significantly better than the original GA locations.

Previous studies of SWA clusters

Useful historical information on felt earthquakes in WA (1904-1959) is contained in Everingham (1968). Localities only are given in this report, as earthquakes occurring before 1959 could not be instrumentally located

In a review of seismic swarms in Australia between 1983 and 2007 (Dent 2009), 26 out of 42 clusters identified were from SWA – although some of the cluster centres were represented more than once.

In a 2012 study, Dent (2012) prepared a list of 15 relatively well defined cluster centres in SWA (Points A to O, Table 1). The uncertainty in these locations is estimated to be about +/- 3 km.

In a review of 2012-2013 activity (considering only events of ML 2.5 or more), Dent (2013) identified five more cluster locations. These new locations have also been added to Table 1 (Points P to T). The cluster centres in Table 1 are plotted on Figure 2.

The 2013 study suggested that GA locations are often about 10 km from the actual earthquake location, and sometimes much more. This can make identification of cluster centres, and the earthquakes belonging to them, difficult.

Table 1 – Proposed cluster centres

Location	**Lat**	**long**	**Reference**	Loc
NW of Burakin	-30.46	116.95	Leonard & Boldra	A
W of Burakin	-30.53	117.05	Leonard & Boldra	B
NW of Cadoux	-30.63	117.10	Leonard & Boldra	C
W of Cadoux	-30.79	117.10	Leonard & Boldra	D
N of Kalannie	-30.15	117.17	Dawson et al	E
N of Koorda	-30.64	117.47	Dent 2010	F
N of Beacon	-30.24	117.75	Dent 2009	G
Yorkrakine	-31.45	117.67	Dent 2011	H
Wyalkatchem	-31.25	117.45	Dent 2012	I
N of Bencubbin	-30.64	117.80	Dent 2012	J
Lake Mollerin	-30.62	117.60	Dent 2012	K
SW of York	-31.98	116.72	Dent 2012	L
Cunderdin	-31.45	117.15	Dent 2012	M
Meckering	-31.62	117.08	Dent 2012	N
S of Meckering	-31.70	117.04	Dent 2012	O
W of Beacon	-30.4	117.75	Dent 2013	P
S of Bencubbin	-30.95	117.9	Dent 2013	Q
N of Hyden	-32.3	118.9	Dent 2013	R
Woodanilling	-33.46	117.66	Dent 2013	S
N of RKGY	-34.35	117.05	Dent 2013	T
N of Brookton	-32.25	116.98	This study	U
E of Beverley	-32.14	117.19	This study	V
E of Pingelly	-32.49	117.31	This study	W

Previous studies (e.g. Dent, 2012; Dawson et al., 2008; Robinson, 2010) have supported the conclusions that the clusters are denser than GA locations suggest – i.e., the epicentral zone may be only 2 km wide, or less) and the events are shallow (perhaps 0 to 3 km deep).

Object of this study

The object of this study is to identify cluster locations active in 2013-14, and determine their locations as accurately as possible. These locations have then been examined to see if they were the location of significant seismic activity prior to 2013-14.

For ease of analysis, the SWA region has been divided into eight rectangular zones, as defined in Table 2, and then seismicity in each zone for the 12 months June 2013-May 2014 has been examined. The GA solutions for some of the events which appear to be either isolated or anomalous have been relocated. Where residuals suggest possibly poor locations, relocations have been attempted, and PSN data have frequently been added to the GA data to improve the data set. PSN data are collected at a much higher sampling rate (200 s/s), and also the stations are frequently closer to the epicentres. Relocations are shown in the appendix. Some of the events in Appendix 1 (i.e. June – August 2013) were previously presented (Dent 2013).

As clusters are identified, they are summarised in Table 3.

Table 2 Zone boundaries

Zone	Zone name	Lat North	Lat South	Long West	Long East	Historical seismicity	Points from Table1
Zone A	Burakin	-30	-31	116.0	117.2	Burakin 2001	A,B,C,D,E
Zone B	Beacon	-30	-30.5	117.2	119.5	Beacon 2009	F, G, P
Zone C	Koorda	-30.5	-31	117.2	119.5	Cadoux 1979	F, J, K
Zone D	Wyalkatchem	-31	-31.5	116.0	119.5	Calingiri 1970	H, I, M
Zone E	Meckering	-31.5	-32	116.0	119.5	Meckering 1968	L, N, O
Zone F	Brookton	-32	-33	116.0	118.0	Nourning Spring 1963	R,U,V,W
Zone G	Katanning	-33	-34	116.0	117.5	Broome Hill 2007	S
Zone H	Cranbrook	-34	-35	116.0	119.5		T

2 An overview of Seismicity in southwest Western Australia, 2000 - 2014

Some of the more notable seismicity in SWA since 2000 includes significant swarm-like activity at the following locations – Cadoux, late 2000 (Leonard, 2001), west of Burakin 2001 – 2003 (Leonard 2002, 2003), the Kalannie swarm of September 2005 (Dawson et al. (2008), north of Koorda, November 2004 onwards (Dent 2010), and northwest of Beacon, January-March 2009 (Dent 2009).

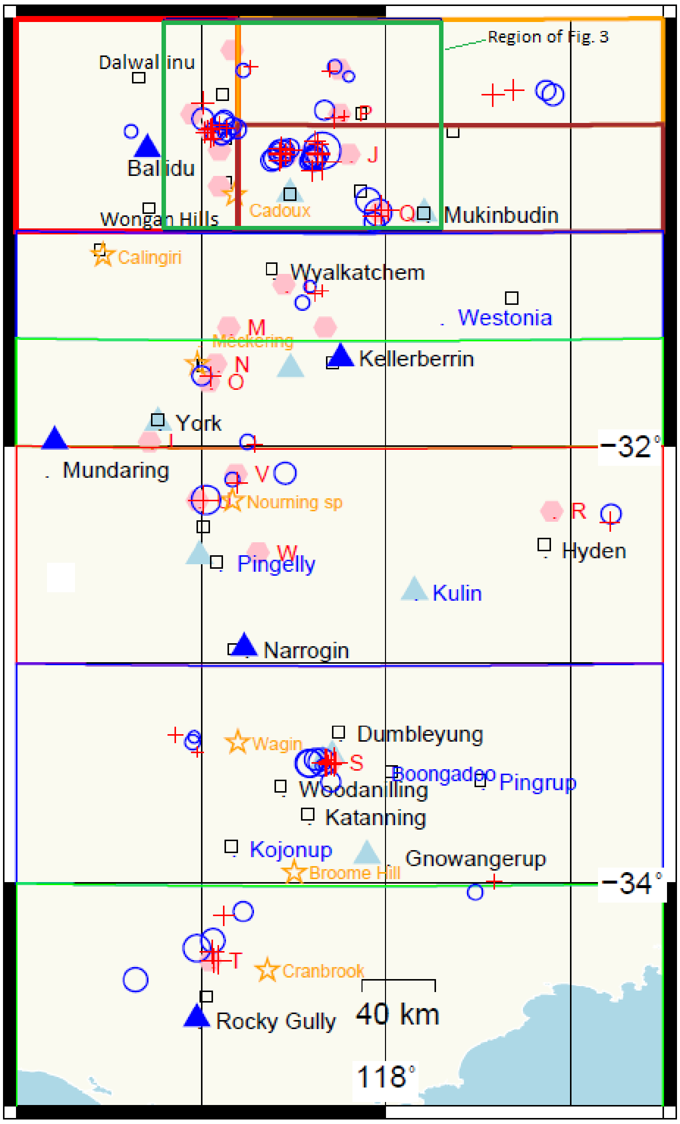
A relatively large event (mag 4.8) occurred south of Katanning in October 2007. This event caused measurable surface deformation, and has been relatively well studied (Dent, 2008; Dawson et al., 2008). While it apparently had many small and unlocated foreshocks, as well as two located aftershocks, it is dissimilar from the events above in that it was not swarm-like. The maximum aftershock magnitude was only 2.2.

In the period 2013-14 there were 290 GA-located events, of which 214 were ML 2.0 or above, and four were ML 3.0 or above. 217 of the 290 (i.e. 75%) events were between 30^{o}S and 31^{o}S, almost all of which originated from cluster activity near Burakin, Beacon and Koorda.

With a maximum magnitude of only 3.4, seismic activity in the time period is considered relatively low, and this has been the case since 2009. The last magnitude 4 event in the SWA region was in June 2009, and the 5 years between then and June 2014 is the longest period in SWA without a magnitude 4 event since modern seismic monitoring was introduced to Western Australia in 1959. (The longest previous period in SWA without a magnitude 4 event was that between September 1997 and September 2001).

Earthquake relocations

Figure 2 Cluster centres and Relocated events



Legend: Circles = GA locations, red crosses = their relocations: Stars = significant historical events referred to in text, pink hexagons = cluster centres listed in Table 1, blue triangle = seismograph.

Identification of cluster centres in this report is supported by the relocation of about 60 selected events (out of the 290 GA located events in 2013-14). GA location methodologies, as well as the program used here (EQLOCL) are summarised in Dent (2013). Events were selected because of their importance in defining a cluster location, or because the phase residuals indicated a probably mediocre solution. Ideally, all 290 events would have been relocated. The relocations were made using a combination of GA and PSN data, using the EQLOCL location program. The SD of the residuals suggests the relocations have smaller uncertainties than the GA originals.

An earthquake location (or relocation) will vary according to the phase data selected for use, and/or the weighting assigned to these phases. Choosing the preferred location is a fairly subjective process, and the locations presented here may still be varied at some future time if the data from contributing stations is reanalysed.

Details of relocated events are summarised in Appendix 1.

3 Discussion of seismicity in declared zones

Zone A "Burakin", 59 events

Table 1 shows 5 cluster centres (A-E) in this zone. Centres A to D were originally defined by Leonard (2002) in a discussion of cluster activity near Cadoux in October 2000. Point B, about 12 km west of Burakin, was the subsequent centre of major seismicity in 2001 – 2002 and lesser activity near this location has continued since then. The activity at the location in 2005 was discussed in Dent (2010).

The magnitude 6.2 Cadoux earthquake of June 1979 (Lewis et al., 1981) also occurred in this zone, about 10 km southeast of point D.

Of the 59 events in zone A in 2013-14, the majority (about 50) form an elliptical zone near Point B. The majority of the events occurred in November and December 2013, (the largest being magnitude 2.6). Many events are poorly located however, as BLDU, a close station critical for good locations, was unserviceable for much of this period.

About 10 events in this zone have been relocated (Figure 3, Appendix 1), and the relocations in general are much closer to Point B.

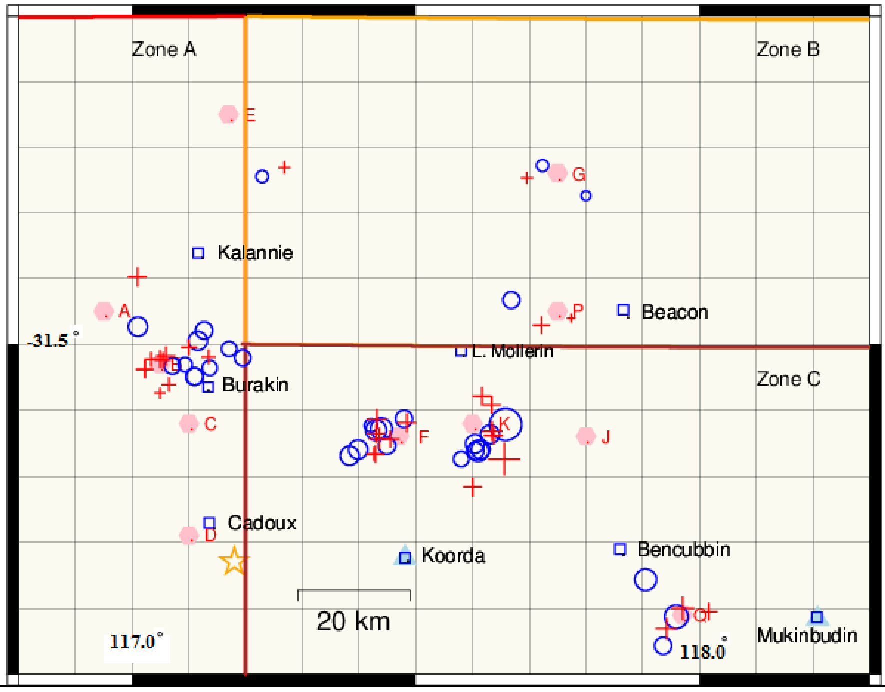
Zone B “Beacon”, 52 events

Of the 52 events in this zone in 2013-14, all but 4 were close to Beacon. Two cluster locations have previously been suggested to exist in this zone (points G and P in Table 1), and 48 of the 52 events can be assigned to these two clusters, with most belonging to point P (“west of Beacon”). A third cluster, of only 3 events, can be seen in the far east of the zone, near Bonnie Rock.

The activity at point P, with about 44 events, is a continuation of the high seismicity seen at this location during 2012. The maximum magnitude during 2012 was magnitude 3.5, and, in the current period being examined, magnitude 3.1 (April, 2014).

The second grouping, with only 4 events, is about 10 km north of the point P, and is probably related to the centre of intense seismicity at point G in January – March 2009 (Dent 2009). This location has been periodically active since then.

Figure 3 Cluster centres near Burakin, Beacon and Koorda



Legend: Circles = GA locations, red crosses = their relocations: Stars = significant historical events referred to in text: Pink hexagons = cluster centres listed in Table 1. Blue triangle = seismograph.

The third grouping consists of three events to the northeast of Bonnie Rock (Aug – Dec 2013, max ML 2.7). The region east of Bonnie Rock has seen significant cluster activity in previous years, but good locations have been difficult to obtain because temporary stations were not deployed. Two of the above events were relocated (Appendix 1) and the relocations are about 15 km to the west of the GA locations (Figure 3). However, as the events are outside of the network, the locations are still not considered reliable, and this location has not been added to Table 3.

A single, small event to the northwest of the zone is close to point E, representing the centre of a significant cluster of events north of Kalannie in 2005. This cluster has had periods of minor activity since then, and this event may have originated from this cluster centre.

Zone C “Koorda-Bencubbin”, 106 events

Three cluster centres were previously identified in this zone (Points F, J and K in Table 1), and points F and K were quite active during 2013-14, with all but six of the 106 events in the zone occurring close to these two points.

Because of location errors, discrimination of these two points, based on GA solutions is relatively difficult. The relocated events however (Figure 3) define point F quite well. However, point K is still not well constrained.

Of the remaining events, three events about 20 km south of Bencubbin, belong to a new cluster, identified in Dent (2013), and here added to Table 1 as cluster location Q. This cluster is similar to that mentioned above near Bonnie rock, in that it contains three relatively large events (magnitudes of 2.9, 2.8 and 2.5) and apparently no smaller events.

Table 3 Cluster properties

Cluster code	Cluster locality	Zone	Max. magn.	# events 2013-14	Lat.	Long.	Most active period	Comment
B	W of Burakin	Zone A	2.6	49	-30.53	117.05	All year	
P	W of Beacon	Zone B	3.1	~54	-30.40	117.75	Feb-Apr 2014	
G	N of Beacon	Zone B	2.3	4	-30.24	117.75	Dec 2013-Jan 2014	
F	NW of Koorda	Zone C	2.8	49	-30.64	117.47	All year	
K	Lake Mollerin	Zone C	3.4	~43	-30.62	117.60	Sep-Oct 2013	
Q	S of Bencubbin	Zone C	2.9	3	-30.95	117.90	July-Sep 2013	
U	N of Brookton	Zone F	3.0	5	-32.25	116.98	Dec 2013	
V	E of Beverley	Zone F	2.6	5	-32.14	117.19	July 2013	
W	E of Pingelly	Zone F	2.2	3	-32.49	117.31	May 2014	
R	N of Hyden	Zone F	2.5	1	-32.3	118.9	March-June 2013	poor location
S	Woodanilling	Zone G	2.9	~ 20	-33.46	117.66	June-July 2013	good location
T	N of Rocky Gully	Zone H	2.9	2	-34.35	117.05	May-June 2013	poor location

Zone D "Calingiri-Wyalkatchem", 19 events

The significant Calingiri earthquake (magnitude 5.9) occurred in the west of this zone in March 1970. This event caused a ground rupture about 3 km long (Gordon & Lewis, 1980*)*. Table 1 shows three clusters in zone D (Yorkrakine – H, Wyalkatchem – I, and Cunderdin – M)

Of the 19 events in this zone, five were near Calingiri, but the locations are not good as the area is on the edge of the seismic network. The event locations in the vicinity of Calingiri are not sufficiently close in space or time to suggest they represent one or more cluster events, and will not be analysed further at this time.

There are 12 events in the region between Kellerberrin and Wyalkatchem. Five of these appear to form a single cluster about 30 km north of Kellerberrin, which may be best described as a mainshock (ML 2.4) with four aftershocks. Although this sequence is relatively close to cluster locations H and I of Table 1, it cannot be definitively linked with either.

A single event occurred in the east of the zone, north of Westonia, in October 2013. When examining a longer time period, two other events are found near this point, about six months earlier, and this event is probably from a poorly defined cluster location.

Zone E, "Meckering", 11 events

The magnitude 6.7 Meckering earthquake occurred in this zone in October 1968, and the region experienced high seismicity levels for several years after that event. A magnitude 5.5 event occurred in January 1990 about 10 km south of the 1968 epicentre, close to point O of Table 1. Continuing seismicity near Meckering is probably related to the October 1968 event.

Everingham (1968) noted a period of activity near Meckering between October and December 1916. However the precise location cannot be determined as the activity was well before the modern seismograph network in SWA was established.

There are three clusters in this zone from Table 1, i.e. York (L), Meckering (N) and S of Meckering (O).

In the vicinity of Meckering, the relatively small and scattered events in 2013-14 cannot be clearly associated with any cluster centre yet defined. The whole of the Meckering area seems to have experienced seismic activity since the 1968 event, and perhaps no clear centres of repeating seismicity will emerge from this area.

To the east of Meckering, a group of three events to the south of Kellerberrin are relatively tightly grouped in space and time, but again are relatively small (max ML 2.2), and the location is poorly defined. It has not been added to the cluster list.

Zone F, "Brookton-Hyden", 15 events

A significant historical event in this zone was the magnitude 5.4 "Nourning Spring" event of 18th January 1963 (Everingham et al., 1982). This event was the largest of a cluster of about 50 events between late December 1962 and April 1963. The 2nd largest event in the cluster, Mag 4.7, occurred in April 1963. Most of the events were assigned to a location of -32.3°S, 117.2°E, although the main event was given a location of -32.25°S 117.17°E. Some of the events were given a location of -32.3°S, 117.2°E, probably reflecting the inaccuracies of the epicentres at that time. Activity in this cluster appears to have been present at least as far back as March 1958, when a magnitude 4.8 event occurred. The presence of smaller events in 1958 is not confirmed, as this was just before the installation of the first seismograph in the region, at Mundaring, in 1959.

The cluster location was also apparently active between May and August 1961 (maximum magnitude 4.4), and February-March 1974 (maximum magnitude 3.3). Again, earthquake locations during this period were not good.

In the 2013-14 period, 15 events occurred in zone F. One of these, magnitude 2.5 on 29th June 2013, was a late event in the Hyden cluster, which occurred in the first half of 2013 (maximum magnitude 3.4, point R in Table 1). Most of the remaining events belong to three new proposed cluster centres (U, V and W) as described below.

"North of Brookton" (Point U) – this cluster contains 5 events, and occurred between 11th and 15th December 2013. The largest event, near the end of the cluster, had a magnitude of 3.0, was the farthest east of the group, but its relocation (Figure 2) brings it closer to the smaller events in the cluster

A second cluster "East of Beverley" (five events, maximum magnitude 2.6) is apparent on Figure 1. Note that the first and largest event was located by GA as "south of Quairading", but its relocation moves it about 25 km to the west, bringing it close to the other events. A cluster centre (Point V) of -32.14°S 117.19°E is proposed.

Other relatively minor activity occurred near this location in July 2011. More significantly, it is only about 10 km north of the assumed location of the 1963 Nourning Spring event, and may be connected to that event – and may even represent the true location of that event.

The third cluster, of three events, occurred east of Pingelly on 11th and 12th May 2014. The maximum magnitude was magnitude 2.2. A location of -32.49°S 117.31°E is suggested (Point W). Other activity occurred near this location in April 2012.

Zone G "Katanning", 23 events

The most notable recent earthquake in this zone was the magnitude 4.8 event west of Broome Hill in 2007. This event had only two minor located aftershocks.

Table 1 shows only one cluster in this zone – Point S, north of Katanning. The cluster is renamed here the "Woodanilling" cluster, as other clusters are known to have occurred near Katanning. The Woodanilling cluster was most active in July and August 2013, with a resurgence in late January 2014. Fifteen GA-located events occurred in this reporting period, with a maximum magnitude of 2.9. This cluster has been studied in some detail by Dent (2014), and an accurate location was established by using S-P times recorded by close field stations. A possible causative fault was also identified. The cluster was approximately 30 km west of a significant earthquake cluster near Boongadoo, during March – May 1937, which was reported in "The West Australian" newspaper at the time.

Data from two close temporary stations (Dent, 2014.) suggest a cluster location at -33.45^{o}S, 117.70^{o}E. The closest temporary station (WDN1) had very low S-P times (< 0.3 secs) indicating a maximum hypocentral distance of ~ 3 km. This means that the focal depths are also < 3 km, and this shallow depth is consistent with that for other well-monitored clusters in SWA, e.g. Lake Mollerin (Dent, 2012).

Two smaller clusters also appear to be present in Zone G, but are minor in terms of magnitudes and numbers of events, and as with other similar clusters in zones previously discussed, they have not been added to the cluster table (Table1). The first is in the western part of the zone, near Arthur River, and the other is to the north of the Woodanilling cluster. Each of these contains only two located events, but it is quite likely that other small events were present, but have passed undetected by the seismograph network.

Everingham (1968) also noted the occurrence of felt earthquakes northeast of Katanning in 1930, 1936 and 1937. Since the exact locations are unknown, it is not possible to correlate the events with recent activity.

Zone H "Cranbrook", 5 events

Table 1 shows one cluster in this zone, approximately 40 km north of Rocky Gully (point T). It was mainly active in late May and early June 2013, with a maximum magnitude of ML 2.9. The cluster was discussed in Dent (2013). Events in this cluster appear to be very scattered because, being on the periphery of the seismograph network, they are quite poorly located. As a consequence of this, Point T is also poorly constrained, with a probable uncertainty of +/- 10 km.

4 Discussion

Most of the 2013-14 seismic activity appears to be cluster related, and historically, most of the large events in SWA appear to be within clusters. There are exceptions, and in recent times, some events such as Broome Hill (2007, magnitude 4.8), Wagin (1986, magnitude 4.0) and Cranbrook, (1991, magnitude 4.4) do not appear to be clustered. Interestingly, these non-clustered events are from the more southerly parts of the SWA seismic zone, and this possible regional variation needs to be further investigated.

At least six of the 15 cluster centres defined in Dent (2012) appear to have been active during 2013-14, as well as another five which were identified in Dent (2013). In addition, another three cluster locations, active during 2013-14, are proposed here. The most active cluster, NNW of Koorda (point F), appears to have started with a magnitude 4.4 event in 2004. This event could be considered a "main shock", but the intermittent activity since 2004 has been more "swarm" like in behaviour. Another important cluster was that west of Burakin, and this cluster centre has been periodically active since the 2001-02 activity, which included 3 magnitude 5+ events.

The cluster nor-north east of Koorda (point K) is only about 15 km from the cluster at point F, and the two are relatively hard to distinguish because of errors in locations. The two cluster locations were contemporaneously active at times, but the causal relationship between the two is unclear.

It is suggested that the small cluster east of Beverley (location V) may be related to the large Nourning Spring event of January 1963.

When looked at in the context of longer term activity, some of these clusters, particularly that east of Beverley (location V) suggest long term activity can originate from these cluster sources. Cluster centres which may appear to be “minor” now may have been the location of large events before the advent of modern seismic monitoring.

Some clusters contain large numbers of smaller events, and appear to at least approximately follow the Gutenberg-Richter law – ie. a logarithmic increase in earthquake frequency with decreasing magnitude. However, some clusters do not seem to contain these small events – e.g. the south of Bencubbin cluster (location Q), and also the cluster north of Bonnie Rock. It is possible that smaller events occurred in these clusters, but were below the detection capability of the GA network. However, the new PSN network is relatively close to some of these centres, and has not detected such small events in these clusters.

Many of the relocations presented here have depths constrained to 2 km. The depths are constrained because, if not restricted, these events show “negative” depths – i.e. above the surface. This anomaly is probably due to deficiencies in the earth model used (WA2, Dent 1989). Test relocations with a model with a surface layer (ie. zero to ~ 2km deep) of lower velocity appears to give more realistic depths, generally in the order of 0.5 – 4 km deep. The introduction of such a layer is consistent with the observation of Somerville and Ni (2010) who found that a 1 km thick low velocity zone was needed to explain the strong dispersion observed in Raleigh (Rg) waves. In cases where GA has allocated depths of >10 km to earthquake solutions, the author believes that the depths, and probably the epicentres as well, are relatively erroneous.

Cluster behaviour can range between end members of main shock (with or without aftershocks) to swarm-like, with no clear main shock, and the clusters described here belong to the swarm-like end of the spectrum. The underlying reason for the differences in behaviour is unclear. Also it is unlikely that faulting mechanisms that apply to swarms in geo-tectonically active regions will apply to SWA, where the host rocks are Achaean shield.

Also it should be noted that there can be sizeable uncertainties in the magnitudes assigned to the events in SWA, although this is unlikely to significantly affect the position of a cluster on the main shock – swarm continuum.

Many other cluster locations have been known to be active at times in SWA. Because of relatively poor locations, the exact locations cannot as yet be well defined. Future close observations of clusters will help to define the density of cluster locations, and how frequently they may exhibit periods of activity.

Origin of seismicity

The cause of the seismicity in SWA, and in particular the cluster sources, is not clear. Faults related to the clusters have yet to be identified by terrestrial surveys, but work by Dawson et al., (2008) has provided inferred fault lengths, orientation and depth for the Kalannie cluster (point E) from satellite interferometry observations. Perhaps the present understanding is best summarised by the statement of Leonard (2008), repeated in Clark et al. (2014), that “contemporary seismicity in SWA is probably related to the earthquakes at Meckering, Calingiri and Cadoux.” This would imply that the active clusters in 2013-14, i.e. near Burakin, Beacon, Koorda and Mollerin, are related in some way to one or more of these events.

5 Conclusions

The majority of 2013-14 seismicity in SWA can be attributed to about a dozen cluster locations. This is also true of seismicity in the previous year, although there is some variation in the combination of active clusters. This seismic behaviour characteristic is probably extendable to previous years as well. The cluster events in 2014-13 are normally swarm-like in character, and only a few have main shock-aftershock characteristics.

Clearly, better locations need to be achieved in order to clarify cluster locations and the earthquakes belonging to them. This will involve the deploying of more seismographs, and the integration of data from different networks.

6 Acknowledgements

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Appendix 1 Table of earthquake relocations, June 2013 – May 2014

	Date	Time U.T.C.	Mag. (ML)	Lon. Deg E	Lat. Deg S	Dep Km	Move Km	SD	C*	Near Stn	Nearest Town
1	03/06/2013	1329 28.0	2.7	117.431	-30.614	1 C	2	0.134	F	KOO6	Koorda
2	03/06/2013	2009 16.2	2.7	117.069	-34.347	1 C	43	0.349	T	RKGY	Rocky Gully
3	03/06/2013	2025 26.2	2.9	117.093	-34.344	1 C	13	0.200	T	RKGY	Rocky Gully
4	09/06/2013	1640 10.2	2.1	117.617	-31.292	1.3	8	0.188			Wyalkatchem
5	10/06/2013	0755 12.0	2.5	117.721	-30.471	2 N	7	0.321	P	KOO6	Beacon
6	12/06/2013	2004 45.2	1.9	116.981	-33.402	3.2	7	0.158			Arthur River
7	13/06/2013	1530 21.5	2.8	117.436	-30.643	1 C	9	0.120	P	KOO6	Koorda
8	16/06/2013	1047 02.3	2.6	117.484	-30.619	5 N	10	0.233	P	KOO6	Koorda
9	29/06/2013	1511 02.3	2.5	119.212	-32.349	5 N	4	0.306	R	KULI	Hyden
10	05/07/2013	0153 32.9	2.9	117.676	-33.451	1.2	8	0.206	S	GNOW	Dumbleyung
11	05/07/2013	0319 20.1	2.6	117.664	-33.462	1.1	9	0.079	S	GNOW	Dumbleyung
12	09/07/2013	1609 47.1	2.5	117.051	-31.676	1.0	5	0.223		YORK	Meckering
13	19/07/2013	1842 08.8	2.6	117.208	-32.125	1.7	26	0.063		PING	Quairading
14	20/07/2013	1524 41.4	2.5	117.725	-33.452	2.9	9	0.212	S	GNOW	Dumbleyung
15	23/07/2013	0934 41.2	2.8	117.942	-30.931	1 C	8	0.573	Q	KOO6	Bencubbin
16	31/07/2013	1853 07.0	2.2	117.219	-32.140	2 N	4	0.048		PING	Beverley
17	01/08/2013	0416 51.8	2.9	117.973	-30.899	0.9	12	0.253	Q	KOO6	Bencubbin
18	04/08/2013	1452 22.7	2.2	117.701	-33.462	1 C	19	0.143	S	GNOW	Dumbleyung
19	15/08/2013	0529 38.3	2.6	118.612	-30.387	5 N	32	0.200		KLBR	Bonnie Rock
20	21/08/2013	1102 56.8	2.9	117.719	-33.450	5 N	6	0.071	S	GNOW	Dumbleyung
21	26/08/2013	2159 31.7	2.0	117.049	-30.574	2 N	42	0.277		BLDU	Ballidu
22	05/09/2013	1759 29.9	2.5	118.016	-30.905	2.0	10	0.049		MUKA	Mukinbudin
23	18/09/2013	1547 11.6	2.6	117.637	-30.638	2 N	3	0.136	L	KOO6	Koorda
24	18/09/2013	1731 08.0	2.7	117.635	-30.632	2 N	4	0.042	L	KOO6	Koorda
25	18/09/2013	1752 00.6	2.5	117.634	-30.592	2 N	8	0.246	L	KOO6	Koorda
26	18/09/2013	1836 19.7	2.6	117.638	-30.650	3.6	6	0.277	L	KOO6	Koorda
27	19/09/2013	0247 53.3	2.2	116.985	-33.352	2 N	10	0.126		NWAO	Wagin
28	28/09/2013	1702 51.1	2.7	117.060	-34.309	3.2	5	0.308	T	RKGY	Rocky Gully
29	30/09/2013	1431 30.2	2.2	117.426	-30.666	2 N	4	0.005	L	KOO6	Koorda
30	04/10/2013	2003 00.9	3.4	117.656	-30.674	0.2	5	0.177	L	KOO6	Koorda
31	10/10/2013	2057 21.2	2.6	117.009	-30.397	2 N	8	0.242		KOO6	Koorda
32	05/11/2013	1648 44.1	2.6	117.600	-30.717	2 N	7	0.175	L	KOO6	Koorda
33	11/11/2013	1213 17.2	2.2	117.291	-31.990	5.5	4	0.090		YORK	Quairdaing
34	21/11/2013	2028 41.3	2.4	117.100	-30.505	0.9	10	0.184	A	KOO6	Burakin
35	22/11/2013	0955 52.7	2.3	117.065	-30.561	5 N	8	0.117	A	KOO6	Burakin
36	24/11/2013	1456 46.4	2.3	117.146	-30.501	2 C	4	0.291	A	KOO6	Burakin
37	28/11/2013	1319 50.1	2.5	117.124	-34.145	1 C	11	0.213	T	RKGY	Rocky Gully
38	30/11/2013	2130 02.8	2.3	117.034	-30.523	1.2	6	0.084	A	BLDU	Burakin
39	01/12/2013	1248 17.7	2.5	117.429	-30.667	7.9	2	0.235	L	KOO6	Koorda
40	01/12/2013	1250 52.1	2.6	117.430	-30.635	0.3	6	0.190	L	KOO6	Koorda
41	01/12/2013	1921 35.2	2.5	118.693	-30.340	5 N	17	0.221		KOO6	Bonnie Rock
42	06/12/2013	1306 27.7	2.4	117.054	-30.524	1 C	2	0.212	A	BLDU	Burakin
43	06/12/2013	1414 45.9	2.5	117.049	-30.523	1 C	9	0.138	A	BLDU	Burakin
44	07/12/2013	0625 25.0	2.6	117.059	-30.518	1 C	6	0.270	A	BLDU	Burakin
45	14/12/2013	1432 37.0	3.0	117.015	-32.248	1.0	1	0.101		PING	Beverley
46	16/12/2013	0324 15.1	2.1	117.696	-30.247	2.2	3	0.261	G	KOO6	Beacon
47	16/12/2013	1702 20.2	2.5	117.455	-30.644	2 N	4	0.118	L	KOO6	Koorda
48	31/01/2014	0303 27.2	2.9	117.672	-33.451	2.2	9	0.110	S	GNOW	Dumbleyung
49	31/01/2014	0347 05.7	1.8	117.688	-33.443	1.8	5	0.094	S	GNOW	Dumbleyung
50	31/01/2014	0417 16.5	1.9	117.674	-33.447	0.9	1	0.315	S	GNOW	Dumbleyung
51	01/02/2014	1733 50.8	2.5	117.022	-30.538	2 N	9	0.323	A	BLDU	Burakin
52	14/03/2014	1940 54.7	2.1	117.268	-30.231	3.2	4	0.281		BLDU	Kalannie
53	08/04/2014	1326 31.8	1.8	117.774	-30.460	2 N	19	0.106	G	KOO6	Beacon
54	24/04/2014	2314 44.3	2.2	118.588	-33.992	2 N	11	0.249		GNOW	Gnowangerup
55	03/05/2014	1021 14.5	1.9	117.655	-31.278	3.4	7	0.122		KLBR	Wyalkatchem

C* -- cluster location (Table 1)in which this event occurred
Depth, C = "constrained" N = "normal"