A preliminary map of cluster locations in southwest Western Australia, 1990 – 2016

Vic Dent

University Associate, Department of Exploration Geophysics, Curtin University, Bentley, Perth, W.A. Email: vic_dent@yahoo.com

Abstract

Earthquake clusters in southwestern Western Australia between 1990 and 2016 have been mapped using a visual perusal of the Geoscience Australia earthquake catalogue. Also plotted are 36 relatively well-determined clusters (Dent 2014, 2015, 2016), from re-evaluation of epicentres mostly between 2014 and 2016. Approximately 100 centres have been identified, but further examination may show that some closely-spaced centres are actually coincident; a cluster of apparent clusters. Many smaller cluster groups may also be present in the data-set. Significant non-clustered activity in the period is also discussed. The majority of the seismicity in the area over the 26-year period examined occurs in clusters, and this pattern may also reflect the distribution of seismicity over a much longer term. The presence of cluster groups in a presentation of historical WA activity by Everingham (1966) is noted.

A preamble on clustered seismicity

As stated by Gibson & Brown (1999), Australia has an unusually high proportion of earthquakes within clusters, and in some areas clustered events may represent more than 90% of the earthquake catalogue. Gibson (2004) identified southwest Australia (SWA) as the region where earthquake clustering was the most significant. Denham et al. (1987) noted that in SWA, earthquakes formed spatial clusters which seemed to bear no relation to either rock type or geology. Gibson & Brown (1999) further state that **"**Seismicity studies should consider the recurrence of sequences rather than individual events" and this paper intends to review the recent seismicity of SWA from that perspective. Dent (2008a) included 8 earthquake clusters from the SWA region out of a total of about 40 clusters Australia-wide in an examination of cluster activity between 1983 and 2005.

Table 1 The most important clusters between 1990 and 2016 in SWA

Place	When	Max	Locn ID	Comment	Reference
Burakin	30 Sep 2001 (-2003)	5.1	Locn B	Three ML 5 events	Leonard 2003
Yorkrakine	Mar 1996 (-1998)	4.6	Locn H	Largest Aug. 97 ~200 events	Dent 2011
Beacon	Jan-Feb 2009	4.6	Locn G	Approx. 300 events	Dent 2009
Koorda	Nov 2004	4.4	Locn F	Approx 100 but continues	
Kalannie	Sept. 2005	4.1	Locn E	Approx 50 events	Dent 2010

Comparing the "size" of one cluster with another is not trivial. Does it depend on the maximum magnitude, the number of significant events it contains, the number of events in the cluster, or its duration? With these factors in mind we list in Table 1, in possible order, the five most significant clusters in SWA between 1990 and 2016. Without question, the Burakin swarm of 2001-2003 (Leonard 2002, 2003) is by far the most significant, with three events of magnitude 5 or above, and perhaps over 18,000 events recorded (the majority small and not located) in that interval (Leonard, 2003).

Dent (2012, 2014, 2015, 2016) has identified a total of 36 cluster locations in the region, most of which reflect activity from 2013-2016.

It is important to understand clustering, as event catalogues are "declustered" (i.e."dependent events" are removed from a catalogue), in the procedures used to determine earthquake hazard or risk. To quote from

Gibson & Brown (1999):

"Declustering an earthquake catalogue means removing dependent events, including foreshocks, aftershocks, and swarm events (except for the largest event in each swarm). The number of events removed is affected by the definition of dependent event.
"Typically, events that are within a given time interval and a given distance of a larger event are regarded as dependent. This time interval and distance may vary with magnitude. The chosen values are arbitrary. For example, a dependent event may be defined as being within three weeks and 20 kilometres of a larger event."

Gibson & Brown (1999) do not consider the situation where a cluster centre appears to become dormant for a period which may vary from months to years, before resuming activity, as appears to be common in SWA. For example, Location R, north of Hyden (Dent,2013), had a burst of clustered activity in September 2006, and then longer clustered period between late 2013 and early 2013.It can be argued that all events over what may be quite a long time span are "dependent" to some degree. Therefore, should the entire sequence be replaced by a single "non-dependent" event?

Methodology of map preparation

The preparation of this map of cluster activity has required a simplification of the Geoscience Australia (GA) database, but it should reflect to some degree the activity between 1990 and 2016. It has been prepared by visually perusing an extract of the GA catalogue (ML $\geq$ 2.1), and noting the largest event where groups of events occur at similar locations and at similar times. These largest events in the cluster groups are listed in Appendix 1 and plotted on Figure 1.

Cluster locations defined by Dent in the publications between 2012 and 2016 are listed in Appendix 2, and also indicated on Figure 1. Usually these are the approximate average location of events in a cluster. There is some overlap between the "defined" cluster locations and the cluster locations in Appendix 1; these will be removed in a future edition. The most significant cluster locations, listed in Table 1, are also indicated on Figure 1.

Appendix 1 does not claim to list all the clusters which have occurred in the period, but only the most obvious ones. It is almost certain that new "unique" cluster sites are yet to be identified, requiring further close inspection of the catalogue.

Caveats regarding cluster identification

The identification of clusters for inclusion in Table 1 is complicated by various factors, which should be kept in mind when reviewing the clusters listed in Appendix 1. These factors include

1) Some event locations are quite poor, which means that two events that are actually clustered may be plotted in quite different locations. In cases like this, proximity in time may be considered more important than apparent dissimilarities in location.

2) It has been found that sometimes there can be clusters of perhaps hundreds of events, but only the largest of these events may have been located by GA – ie, where almost all events are of very low magnitude (ML 2.0 or less). Thus, in perusing the catalogue, an apparently single event may be passed over, but may actually represent the only located event of a cluster.

3) Some of the cluster locations in Figure 1 form groups of relatively closely-spaced cluster locations. In some cases, they may actually represent a single cluster location. However, independentt, but relatively closely spaced cluster locations (within ~ 15 km) have been identified, e.g. west of Burakin, north of Kellerberrin, and north of Koorda.

Discussion

Most of the clusters listed in Appendix 1 can also be described as earthquake "swarms". An earthquake

swarm is a group of events where the largest events have comparable magnitudes (within 0.5 of a magnitude unit). Also, the largest event in a swarm is quite often not the initial event, and can occur towards the middle of an earthquake sequence. In these two respects, earthquake swarms are different from mainshock/aftershock event sequences. In the groups of earthquakes plotted here and listed in the appendix, groups which may be conventional mainshock/aftershock sequences are noted.

The GA catalogue for the area of interest (29^oS – 36^oS, 115^oS – 120^oE), and the time of interest (1990 – 2016) contains about 2,100 events above magnitude 2.0 and about 5,000 events in total. About 600 of these are a part of the major activity west of Burakin, about 250 km NE of Perth. This activity began with a magnitude 5.1 event in September 2001, continued with periods of strong activity into 2003 (including two magnitude 5 events in March 2002), and with lesser activity continuing until at least 2016. A lesser swarm of events occurred 12 months before the first magnitude 5 event, about 10 km to the northwest of the 2002-2003 cluster, but any connection between the two, if one exists, has yet to be proven.

Perusal of the GA catalogue has resulted in a list of about 100 cluster groups in these 26 years (Appendix 1), and the locations of the main events in these groups are plotted on Figure 1. These event groups account for about 50 - 60% of these 5,000 events. When Leonard (2008) declustered his catalogue of SWA events, he removed about 63% of events. Gibson & Brown (1999) have suggested that the percentage of "dependent" events in SWA may be approximately 90%, and the recent detailed analyses by Dent (e.g. Dent 2014, 2015, 2016) supports this estimate.

Note that many of the groups listed in Appendix 1 may represent recurring activity at a single cluster location – for example "Burakin" is listed many times. If these event groups were removed from the catalogue and examined in detail, it is probable that the ~100 cluster groups would reduce to about 50 to 60 unique cluster locations. Note that Appendix 2 lists 36 unique locations that have so far been defined, and it is suggested there may be another 20 – 30 "undiscovered" cluster locations within Appendix 1.

Features on this map reveal possible avenues for future research. For instance, is the apparent north-westerly lineation in seismicity in the NW of the region real? Earlier work by Dent (2010) suggests it may be a factor of lack of recording instruments introducing biases to the locations. Also of interest is the apparent seismic "low" between about 32 and 33 degrees south, also noted by Dentith & Featherstone (2003, p 171) who called it the "Narrogin Seismic Gap". The Burakin cluster location continues to produce activity 15 years after its onset, and the data provided here may help to find similar long-lived activity from other cluster locations.

Large and isolated events

It is important to try and distinguish clustered from non-clustered, or "isolated" events. Appendix 3 lists all events of ML 4.0 and above in the region and time period, and these are plotted on Figure 1 as stars. Many of these are probably associated with one of the 40 named centres, and these are indicated in the Table. Some appear to indicate cluster centres not yet defined (e.g., Manmanning, 1982). Only a few appear to be genuinely "isolated" events and these are also indicated (as filled stars). The ground deforming ML 4.8 Katanning event (Dent, 2008b, Dawson et al., 2008) is called "isolated" because, although numerous aftershocks were recorded, they were all of quite low magnitude (Dent 2008b). A magnitude 5.2 event near Meckering in 1990 had no apparent aftershocks, and is also here called "isolated" although some causal relationship with other Meckering events seems likely. The Bonnie Rock event of 26 April 1994 (ML 4.1) had a single located aftershock on the same day (ML 2.4) and is also provisionally called isolated, although it is in an area known to host seismic clusters. It is remote from most seismographs, and it is possible that there are smaller events associated with this event, but which were not detected by the network.

Remote clusters

Most of the clusters described here have occurred within the Yilgarn Craton, and within the area defined by Leonard (2008) as "The southwest Australia seismic Zone" (Figure 1). Sinadinovski (2004) defined a zone ("Zone 1"), which enclosed known magnitude 5+ earthquakes in the region, and which approximately

reflects the region originally identified as the "Yandanooka – Cape Riche Lineament" by Everingham (1966) and later renamed "The southwest seismic zone" by Doyle (1971).

"Zone 1" encloses about half of the cluster centres plotted on Fig 1, but many of the plotted centres are to the east of the zone. This may indicate a temporal eastwards shift in the seismicity of the region, but a simpler explanation could be that the last magnitude 5 event in the region was more than ~ 100 years ago.

Some clusters are relatively "remote" from the majority of the clusters. An offshore cluster is listed in Appendix 1, south of Walpole in December 1999; the largest event was ML 2.7. Note that this is almost the same location as an isolated M 4.6 earthquake in August 2007.

Outside of the time period described here, Dent (2008a) noted a small cluster offshore from Margaret River in July 1989 (approximate location -33.97^{o}S 114.89^{o}E, largest ML 3.2). Another cluster, relatively spread-out in time, occurred off shore from Dongara in 1986-1990 (approximate location -29.4^{o}S 114.5^{o}E, max ML 3.0). Slightly more remote from the current area of interest, many large events followed an ML 5.0 event which occurred south east of Norseman on 28th May, 2016. The largest was a ML 5.6 on 8th July, 2016. This cluster was only about 30 km to the ENE of a similar cluster in 1985 (largest event ML 5.6) and this lends support to the possibility that earthquake clustering may be a feature of the entire Yilgarn craton.

Gibson (2004) stated "Since most large Australian earthquakes are preceded by precursory events that occur in the months to years before the mainshock, recognition of these may allow for alerts, forecasts, or even predictions". Identification and mapping of cluster centres may eventually be found to be equally significant.

Historical cluster events

Everingham (1966, 1968) reviewed the known seismicity of Western Australia and tabulated reports of felt tremors from 1904 to mid-1965. This work was supplemented by further research into newspaper reports by McCue (2014). Some of the reports are obviously related to relatively large events, felt over wide areas, and some are accompanied by many apparent aftershocks. One such event was the magnitude 5.8 "Gabalong" event of August 1955, which resulted in frequent felt reports coming from the New Norcia/Yerecoin region. Another was the magnitude 5.4 "Nourning Spring" event northeast of Brookton in January 1963. Isoseismal maps were prepared for both of these events (Everingham et al., 1982). Other felt reports listed by Everingham (1966) can be interpreted as being related to local, relatively small events, and sometimes numerous events were reported. Some of the localities which can be interpreted as experiencing localised cluster activity are indicated on Figure 1. Some of these may correlate with the newly identified cluster centres. For example, the 1937 activity noted at Boongadoo may correlate with cluster location Tau and the 1955 activity at Gabalong/Yerecoin could correlate with location Mu. Because the activity collated by Everingham occurred when the seismograph network in WA was still in its infancy, most of the events are very poorly located, or not located at all.

ACKNOWLEDGEMENTS

The author wishes to thank Clive Collins and Virginia Ward for their valuable work editing the report drafts, and Kevin McCue for his review of the paper.

REFERENCES

Dawson, J., Cummins, P., Tregonning, P., and Leonard, M. (2008). Shallow intraplate earthquakes in Western Australia observed by Interferometric Synthetic Aperture Radar. *Journ. Geophys. Res. V.113*, B11408.

Denham, D., Alexander, L., Everingham, I., Gregson, P., R McCaffrey, & Enever J., (1987). The 1979 Cadoux earthquake and intraplate stress in Western Australia, *Aust. J. Earth Sci*., 34, 507-521.

Dent, V. F., (2008a). Graphical representation of some recent Australian Earthquake Swarms, and some generalisations on swarm characteristics. In *Proc. AEES 2008 Conference*, Ballarat, Vic.

Dent, V. F., (2008b). Improved Hypocentre estimates for two recent seismic events in south-western Western Australia, using temporary station data. In *Proc. AEES 2008 Conference*, Ballarat, Vic.

Dent, V. F., (2009). The Beacon, WA, earthquake swarm of 2009. In *Proc. AEES 2009 Conference*, Newcastle, NSW.

Dent, V. F., (2010). A northeast lineation of epicentres northeast of Perth – fact or fiction? A review of earthquake hypocentres in the region, 2005. In *Proc. AEES 2010 Conference*, Perth, WA.

Dent V. F., (2011). The Yorkrakine, W.A., seismic deployment, April – May 1996. In *Proc. AEES 2011, Conference*, Barossa Valley, SA.

Dent, V. F., (2012). Evidence for shallow focal depths and denser locations for three southwest seismic zone earthquake clusters, 2011. In *Proc. AEES 2012 Conference*, Gold Coast, Qld.

Dent, V. F. (2014). Earthquake clusters in southwest Australia in 2013-14. In *Proc. AEES 2014 Conference*, Lorne, Vic.

Dent, V.F. (2015). Clustered seismicity in the Southwest Australia seismic zone, 2014-15 In *Proc. AEES 2015 Conference*, Sydney, NSW.

Dent, V.F. (2016). Clustered seismicity in the Southwest Australia seismic zone, 2015-2016. In *Proc. AEES 2016 Conference*, Melbourne, Vic.

Dentith, M.C., & Featherstone, W. E., (2003). Controls on intra-plate seismicity in southwestern Australia. *Tectonophysics* 376 (2003), 167-184.

Doyle, H. A., (1971). Australian Seismicity. *Nature* V. 234, 174-175.

Everingham, I. B., (1966). Seismicity of Western Australia, *Bureau of Mineral Resources Record* 1966/127.

Everingham, I. B., (1968). Seismicity of Western Australia, *Bureau of Mineral Resources* Report 132

Everingham, I. B., McEwin, A.J., & Denham, D.(1982). Atlas of Isoseismal maps ofAustralian Earthquakes, Bur*eau of Mineral Resources Aust*. Bulletin 214.

Gibson, G., & Brown, A. (1999) Earthquake clusters, small earthquake clusters, small earthquakes and their treatment for hazard estimation. In *Proc. AEES 1999 Conference*, Sydney, N.S.W.

Gibson, G., (2004). Australian Earthquake Clusters. *AEES 2004 Conference*, Mt. Gambier, SA. (Poster).

Leonard, M. (2002). The Burakin WA Earthquake sequence Sept 2000 – Jun 2002 . In *Proc. AEES 2002 Conference*, Adelaide, SA.

Leonard, M. (2003) Respite leaves Burakin quaking in anticipation. *Ausgeo News* 70. June 2003.

Leonard, M. (2008). One Hundred Years of Earthquake Recording in Australia. *Bull. Seismol. Soc. Am.* 98, 1458–1470.

McCue, K. (2014). Historical earthquakes in Western Australia, http://www.aees.org.au/category/member-article/page/2/

Sinadinovski, C. (2004). Seismicity in the Southwest of Western Australia. *Geoscience Australia Record* 2004/15.

..

Figure 1a Clusters in Southwest Australia (north)

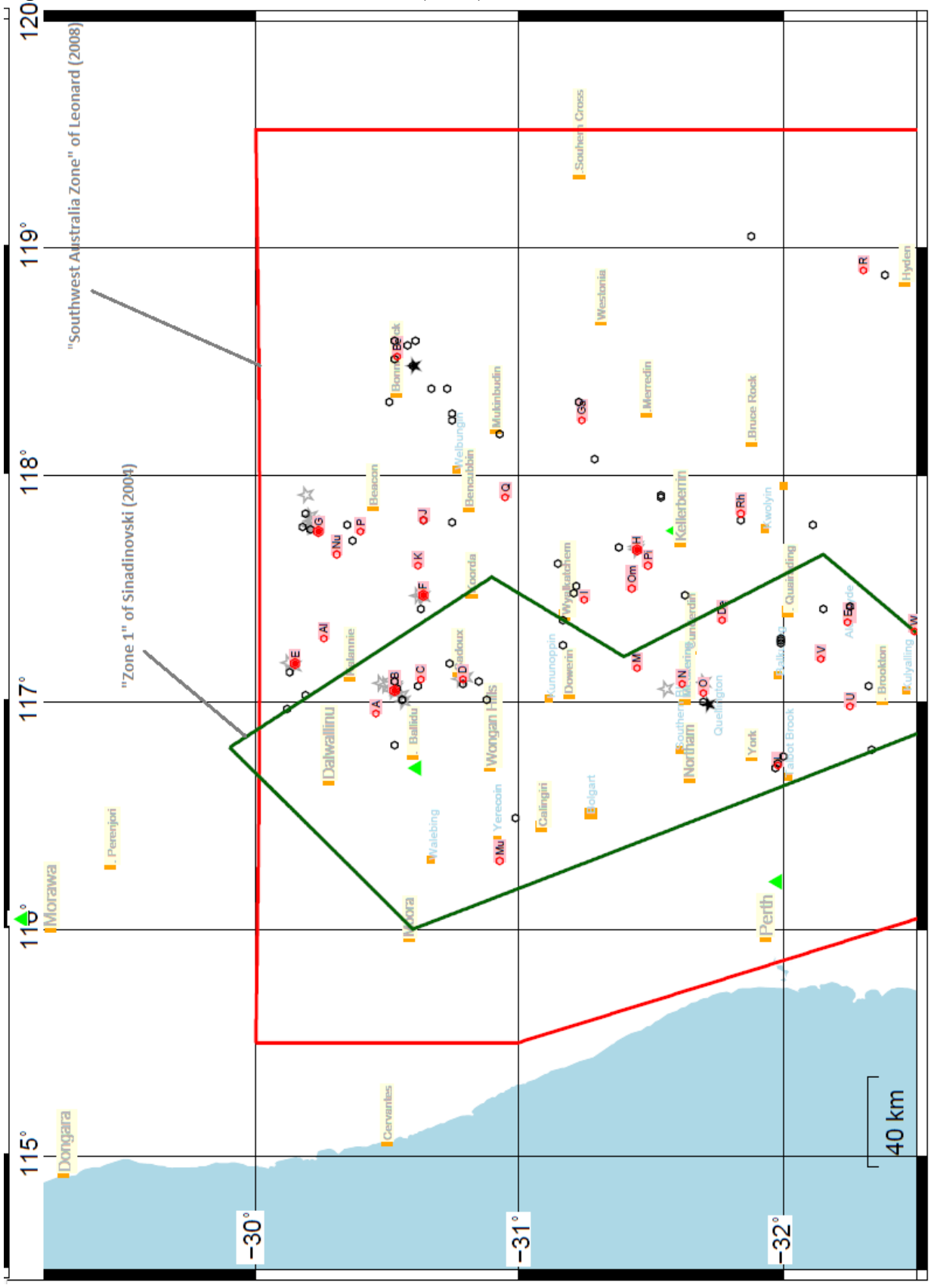
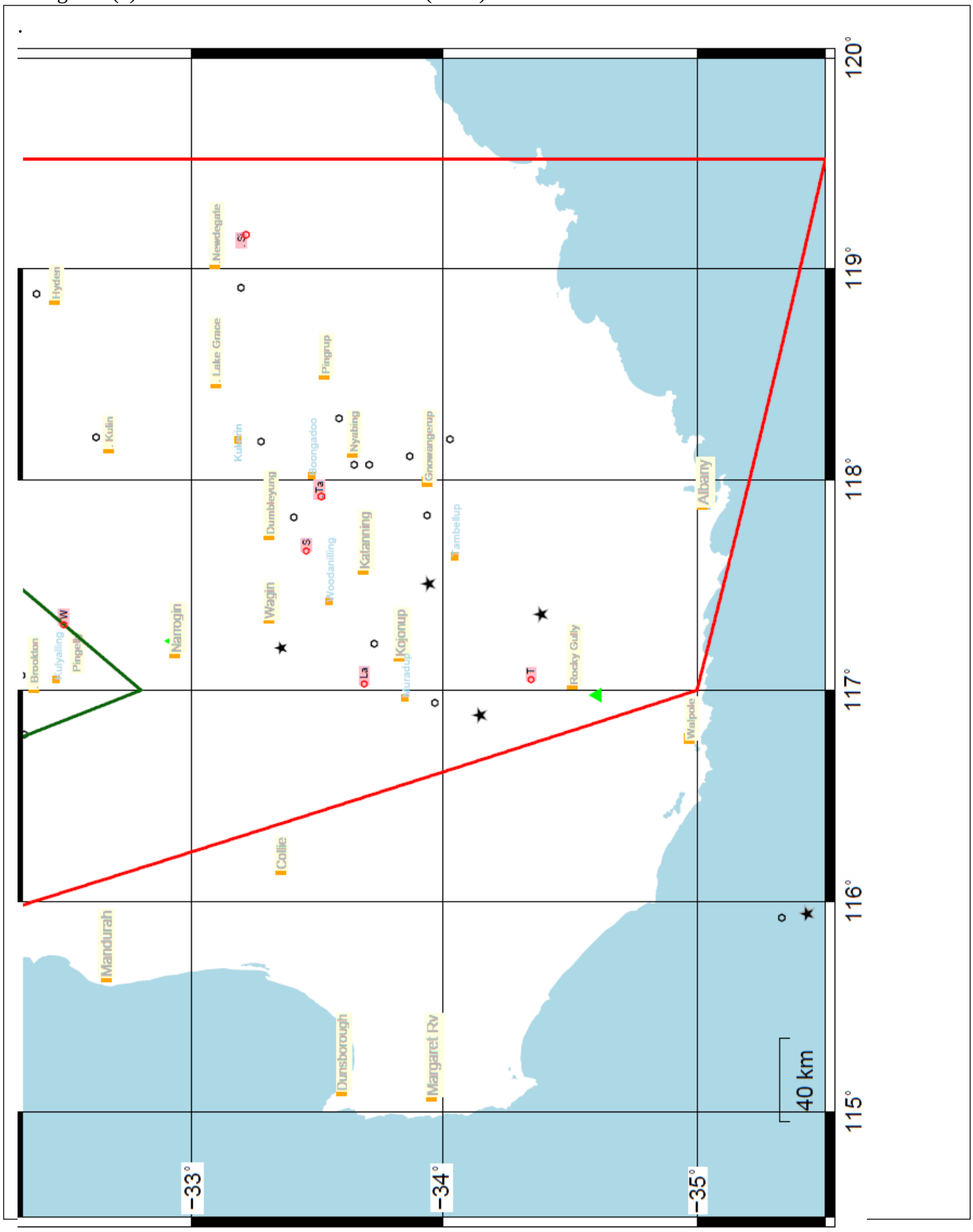


Figure 1(b) Clusters in Southwest Australia (south)



Legend for Figure 1
Red box = SWA zone as defined by Leonard (2008)
Green box = "Zone 1" as defined by Sinadinovski (2004)
Black hexagons = cluster locations from Table1
Red hexagons = defined cluster location (Table 2)
Star = location of Mag 4+ event (filled star = "isolated" event)
Triangle = permanent seismograph location
Orange square = population centre
Orange square (blue label) = centre which has experienced an earthquake swarm (from Everingham 1968)

Appendix 1. List of cluster locations identified from GA catalogue and plotted on Figure 1

	Longitude	Latitude	when	max ml	comment 1	comment 2
1	117.82	-33.41	17-Mar-90	3.2	Dumblyung 16 k se	
2	116.81	-30.53	30-Apr-90	3.0	Ballidu 7 k n	
3	117.07	-30.62	08-Jan-91	3.3	Cadoux 20 km n	
4	117.07	-32.32	30-Apr-91	2.4	Brookton 7 k E	
5	118.07	-33.65	25-Jul-91	2.5	Nyabing 15 k sw	
6	117.28	-31.99	04-Jan-92	3.3	Quairading 12 k west	
7	117.83	-33.94	17-Sep-92	2.6	Gnowangerup 14 km west	
8	117.00	-31.70	09-Jan-93	2.6	Meckering 9 km se	
9	117.27	-31.99	18-Jan-93	2.7	Quairading 12 k wnw	
10	117.08	-30.79	12-May-93	2.4	Cadoux 6 k sw	
11	118.18	-30.93	18-Aug-93	2.6	Mukinbudin 4 km sw	
12	117.42	-32.25	12-Aug-93	2.6	Quairading 24 km s	
13	117.09	-30.85	26-Nov-93	2.6	Cadoux 9 k ssw	
14	117.41	-32.15	12-Mar-94	2.5	Quairading 20 km s	
15	117.25	-31.17	23-Mar-94	2.5	Wyalkatchem 12 km w	
16	118.48	-30.60	13-May-94	4.1	Bonnie Rock 14 k se	
17	117.90	-31.54	11-Jun-94	2.5	Kellerberrin 20 k ne	
18	118.07	-33.71	06-Jun-94	2.9	Nyabing 16 k south	
19	116.73	-31.98	23-Nov-94	3.0	York 12 k ssw	defines locnn L
20	118.18	-33.28	20-Apr-95	3.3	Nyabing 30 km s	
21	117.71	-30.37	24-Jun-95	2.8	Beacon 18 km nw	
22	117.51	-31.22	18-Aug-95	2.6	Wyakatchem 13 k ese	
23	117.01	-31.66	15-Oct-95	2.3	Meckering 3 km s	
24	117.66	-31.45	10-Mar-96	3.1	Kellereberrin 20 km n	defines locn H
25	116.80	-34.04	14-May-96	3.0	Kojonup 38 km sw	
26	118.02	-33.69	14-Jul-96	2.7	Nyabing 20 k sw	
27	117.67	-31.46	19-Aug-96	3.0	Kellerberrin 19 km n	
28	116.72	-31.98	01-Sep-96	3.1	Talbot Brook 8 k ne	
29	116.59	-31.00	17-Dec-96	2.8	Calingiri 15 k ne	
30	117.67	-31.47	27-Mar-97	3.3	Kellerberrin 19 k nth	
31	118.27	-30.75	27-Aug-97	2.4	Mukinbudin 20 km N	
32	116.49	-30.99	07-Dec-97	3.0	Calingiri 11 k N	
33	117.17	-30.74	08-Dec-97	2.7	Cadoux 7 km n	
34	118.32	-31.23	06-Feb-98	2.4	Merredin 28 k n	
35	118.19	-34.03	27-May-98	2.7	Gnowangerup 22 km ese	
36	116.94	-33.97	21-Jan-99	3.2	Kojonup 20 km sw	
37	117.48	-31.21	13-Jul-99	2.8	Wyalkatchem	
38	115.92	-35.33	17-Dec-99	2.7	Walpole	
39	117.79	-30.75	24-Feb-00	3.3	Bencubbin	
40	118.57	-30.58	05-Jun-00	2.9	Bonnie Rock	
41	117.06	-30.53	22-Sep-00	3.6	Cadoux	defines locn C
42	118.59	-30.61	27-May-01	2.3	Bonnie Rock	
43	117.78	-32.11	12-Jul-01	2.5	Bruce Rock	
44	117.09	-30.53	07-Sep-01	3.0	Kalannie	
45	117.06	-30.54	28-Sep-01	5.2	Burakin	major

46	117.68	-31.38	18-Dec-01	2.6	Kellerberrin	
47	118.32	-30.51	17-Oct-02	2.5	Bonnie Rock	
48	117.03	-30.19	08-Nov-02	2.7	Kalannie	
49	116.79	-32.33	11-Jun-03	2.3	Brookton	
50	118.29	-33.59	28-Jul-04	2.5	Dumbleyung	
51	117.01	-30.88	11-Oct-04	3.1	Manmaning	
52	117.01	-30.56	15-Oct-04	3.0	Burakin	
53	117.26	-31.99	20-Nov-04	2.4	Beverley ne of	
54	117.47	-31.63	24-Nov-04	4.4	Koorda	major
55	117.01	-30.56	12-Apr-05	4.0	w of Burakin	
56	116.71	-31.97	15-Apr-05	2.5	Beverley	
57	117.45	-30.65	27-May-05	3.3	n of Koorda	
58	118.24	-30.75	15-Aug-05	2.5	Mukinbudin n of	
59	117.13	-30.13	22-Sep-05	4.1	n of Kalannie	major defines Locn E
60	118.88	-32.38	11-Sep-06	2.5	n of Hyden	
61	117.91	-31.54	26-Nov-06	2.4	ne of Kellerberrin	
62	118.51	-30.53	20-Apr-07	2.3	e of Bonnie Rock	
63	118.11	-33.87	20-Nov-07	2.3	ne of Gnowangerup	
64	118.59	-30.53	18-Jan-08	2.8	e of Bonnie Rock	
65	118.38	-30.67	24-Mar-08	3.0	s of Bonnie Rock	
66	117.78	-30.35	05-Apr-08	2.7	nw of Beacon	
67	117.36	-31.17	07-May-08	3.7	Wyalkatchem	
68	116.97	-30.12	17-May-08	3.4	ne of Kalannie	
69	116.76	-32.00	20-Jul-08	2.6	nw of Beverley	
70	117.77	-30.18	30-Jan-09	4.1	nw of Beacon	major defines locn G
71	117.41	-30.63	17-Sep-09	2.4	nw of Koorda	
72	118.20	-32.62	29-Jul-10	2.3	Kulin	
73	117.76	-30.21	17-Oct-10	2.9	n of Beacon	
74	118.38	-30.73	03-Nov-10	2.2	s of Bonnie Rock	
75	119.05	-31.88	06-Feb-11	2.3	ne of Hyden	
76	117.80	-31.84	17-Jul-11	2.5	s of Kellerberrin	
77	118.07	-31.29	30-Jul-11	2.6	Merredin 28 k n	
78	117.83	-30.19	31-Jul-11	2.3	n of Beacon	
79	118.91	-33.20	05-Aug-11	2.7	sw of Newdegate	
80	117.22	-33.73	22-Sep-11	3.4	Katanning	
81	117.80	-30.64	27-Sep-11	3.1	sw of Beacon	
82	117.61	-31.15	01-Nov-11	2.5	Wyalkatchem	defines locn I
83	117.57	-30.61	27-Nov-11	2.8	n of Koorda	defines locn K
84	117.82	-30.40	13-Mar-12	3.3	near Beacon	
85	118.20	-31.22	21-Apr-12	3.0	nw of Merredin	
86	117.47	-30.63	17-Jul-12	2.4	n of Koorda	
87	119.18	-32.19	12-Dec-12	2.6	N of Hyden	
88	117.44	-30.63	13-Jun-13	2.8	N of Koorda	
89	117.59	-33.46	05-Jul-13	2.9	Dumbleyung	defines locn S
90	117.61	-30.66	18-Sep-13	2.7	NE of Koorda	
91	117.12	-30.49	07-Dec-13	2.6	Burakin	
92	117.69	-30.64	22-Jul-14	3.3	NE of Koorda	
93	117.11	-33.70	05-Nov-14	2.7	Kojonup	
94	117.30	-30.28	05-Mar-15	3.0	NE of Kalannie	defines locn Alpha
95	118.51	-30.57	12-Apr-15	2.3	Mukinbudin	
96	119.19	-33.21	22-Jun-15	2.8	Newdegate	defines locn Tau
97	118.09	-33.51	06-Dec-15	2.9	Nyabing	defines locn Sigma
98	116.94	-32.15	01-Jun-16	2.6	N of Brookton	

Appendix 2. List of Defined Cluster centres, from Dent (2013, 2015 & 2016)

Longit	Latitude	Label	Location	Remarks	Remarks (2)
116.95	-30.46	A	NW of Burakin		
117.05	-30.53	B	west of Burakin	major	
117.10	-30.63	C	SW of Burakin		
117.10	-30.79	D	SW of Cadoux		
117.17	-30.15	E	N of Kalannie	major	
117.47	-30.64	F	N of Koorda	major	
117.75	-30.24	G	N of Beacon	major	
117.67	-31.45	H	Yorkrakine	major	(N of Kellerberrin)
117.45	-31.25	I	Wyalkatchem		
117.8	-30.64	J	NW of Bencubbin		
117.6	-30.62	K	Mollerin		
116.72	-31.98	L	SW of York		
117.15	-31.45	M	N of Cunderdin		
117.08	-31.62	N	Meckering		
117.04	-31.7	O	S of Meckering		
117.75	-30.4	P	W of Beacon		
117.9	-30.95	Q	S of Bencubbin		
118.9	-32.3	R	N of Hyden		major?
117.66	-33.46	S	Woodanilling		(S of Dumbleyung)
117.05	-34.35	T	N of Rocky gully		
116.98	-32.25	U	N of Brookton		
117.19	-32.14	V	E of Beverley		
117.31	-32.49	W	E of Pingelly		
117.28	-30.26	Alpha	E of Kalannie		
118.52	-30.54	Beta	Bonnie rock		
118.24	-31.24	Gamma	N of Merredin		
117.36	-31.77	Delta	Youndegin		(SW of Quairading)
117.35	-32.24	Epsil	S of Quairading		
117.03	-33.69	Lambda	Kojonup		
116.3	-30.93	Mu	NE of New Norcia		
117.65	-30.31	Nu	NE of Beacon		
117.50	-31.43	Omicron	NW of Kellerberrin		
117.58	-31.48	Pi	N of Kellerberrin		
117.84	-31.84	Rho	W of Bruce Rock		
119.16	-33.21	Tau	Newdegate		
117.92	-33.5	Sigma	W of Nyabing		

Appendix 3 Earthquakes of Magnitude 4.0 and above, 1980 -2016

Long.	Lat.	UTC Date	UTC Time	Mag	Dep(km)	ser	Cluster location	Comment
117.15	-30.73	10/12/1980	04:35:05	5.0	13	1	-	
117.21	-30.77	07/04/1981	20:15:58	4.5	14	2	Manmanning	
117.12	-30.9	24/01/1982	04:06:20	4.3	5	3	Manmanning	
117.13	-30.91	25/01/1982	23:26:58	4.4	5	4	Manmanning	
117.15	-30.88	06/02/1982	15:24:39	4.9	10	5	Manmanning	
117.1	-30.87	06/02/1982	15:30:36	4.6	10	6	Manmanning	Felt, MM=5
117.09	-30.89	07/02/1982	13:07:31	4.1	10	7	Manmanning	
117.1	-30.89	08/02/1982	04:39:34	4.1	10	8	Manmanning	
117.13	-30.73	26/01/1983	06:16:15	4.8	10	9	-	
117.08	-30.72	28/03/1984	14:53:33	4.2	10	10	Cadoux7KM NW	
117.11	-30.75	10/10/1985	13:34:30	4.3	10	11	Cadoux3KM NW	
117.08	-30.77	27/11/1985	23:18:20	4.5	10	12	Cadoux 4KM W	
117.2	-33.36	17/05/1986	12:41:26	4.0	5	13	WAGIN, 15KM WSW	Isolated
117.06	-31.63	01/09/1986	13:53:49	4.1	5	14	MECKERING, 5KM ESE	
117.09	-30.77	07/03/1987	05:38:07	4.5	5	15	Cadoux, 4KM W	
117.5	-31.2	06/01/1988	03:42:08	4.3	2	16	WYALKATCHEM, 12KM E	
116.99	-31.72	17/01/1990	06:38:08	5.5	6	17	Meckering	Isoseismal map made
117.102	-30.779	08/05/1990	18:40:56	4.5	3	18	Cadoux, 4KM W	
117.36	-34.389	13/12/1991	04:48:17	4.4	1	1	CRANBROOK, 20KM WSW	Isolated
118.481	-30.605	26/04/1994	15:49:39	4.1	5	20	BONNIE ROCK, 14KM SE	Isolated
117.057	-31.56	21/06/1996	14:56:59	4.1	6	21	MECKERING 5 KM SE	
117.684	-31.449	31/08/1997	15:23:50	4.6	5	22	Kellerberrin, 20 KM N	
117.672	-31.45	03/09/1997	05:12:54	4.2	5	23	Kellerberrin, 20 KM N	
117.061	-30.536	28/09/2001	02:54:56	5.2	2	24	Burakin	Felt in Perth
117.069	-30.531	25/12/2001	00:56:49	4.0	1	25	Burakin	Felt
117.068	-30.533	28/12/2001	16:31:36	4.5	2	26	Burakin	Felt
117.084	-30.479	05/03/2002	01:47:38	5.0	1	27	Burakin	Widely felt
117.075	-30.495	05/03/2002	03:29:57	4.6	0	28	Burakin	Felt
117.065	-30.521	23/03/2002	13:16:22	4.8	2	29	Burakin	
117.049	-30.524	30/03/2002	21:15:46	5.2	1	30	Burakin	Felt
117.087	-31.702	24/03/2003	11:50:31	4.0	5	31	Meckering	Widely felt
117.472	-30.633	24/11/2004	02:42:59	4.4	0	32	N of Koorda	
117.464	-30.639	16/03/2005	01:27:17	4.2	3	33	N Koorda	
117.005	-30.564	12/04/2005	12:00:02	4.0	0	34	W of Burakin	
117.912	-30.194	01/05/2005	09:43:16	4.1	3	35	N of Beacon	
117.108	-30.802	12/06/2005	10:51:19	4.3	2	36	SW of Cadoux	
117.03	-30.558	12/06/2005	20:36:44	4.5	8	37	W of Burakin	
117.159	-30.148	21/09/2005	22:46:41	4.0	2	38	N of Kalannie	
117.173	-30.126	22/09/2005	03:52:59	4.1	3	39	NE of Kalannie	
115.942	-35.429	28/08/2007	15:33:04	4.6	18	40	SE of Augusta	Isolated
117.505	-33.946	09/10/2007	23:58:40	4.8	0	41	S of Katanning	Isolated
117.774	-30.212	30/01/2009	17:33:11	4.1	0	42	N of Beacon,	
117.784	-30.23	31/01/2009	08:47:03	4.6	2	43	North of Beacon	
117.798	-30.215	31/01/2009	11:55:21	4.4	0	44	N of Beacon	
117.819	-30.209	01/02/2009	00:42:40	4.0	0	45	N of Beacon	
117.795	-30.214	01/02/2009	21:57:40	4.0	0	46	N of Beacon	
117.774	-30.208	05/03/2009	12:53:51	4.5	0	47	N of Beacon	
116.881	-34.148	08/04/2009	05:31:50	4.1	0	48	NW of Rocky Gully	Isolated
117.468	-30.619	25/06/2009	15:16:49	4.2	0	49	SW of Beacon	