Earthquake clusters in southwest Australia seismic zone, June 2016 – May 2017

V.F. Dent

University Associate, Curtin University, Perth, W.A.
Email: vic_dent@yahoo.com

Abstract

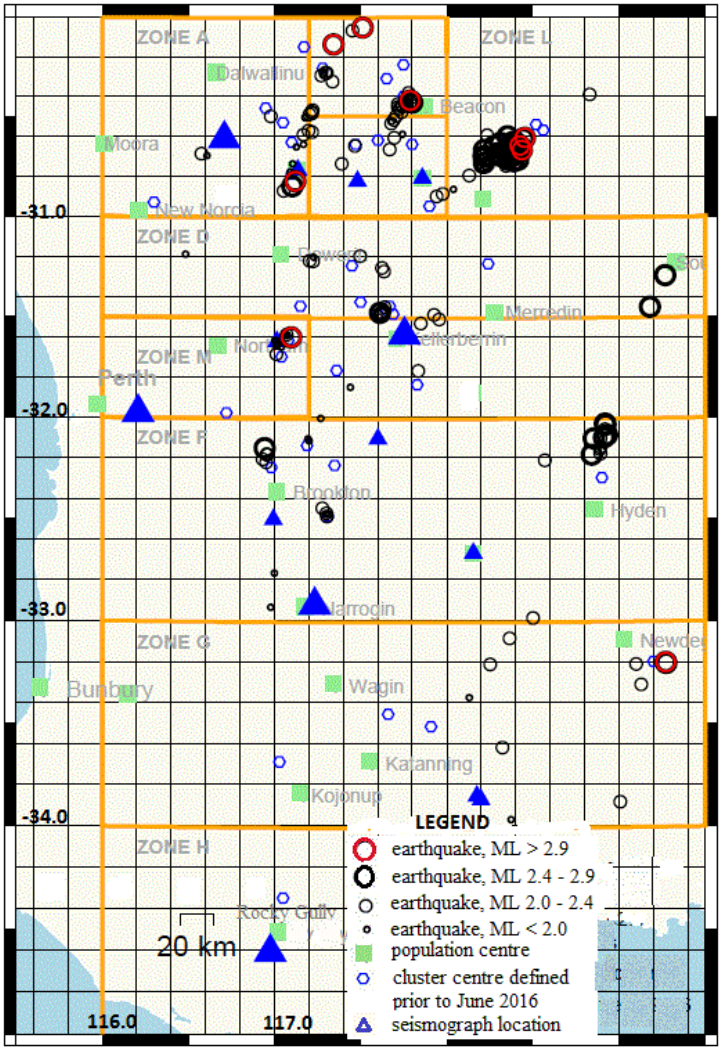
This report is the 4th in a series of annual reports describing the annual seismicity of the South West Australia (SWA) zone since June 2013. In previous reports, 36 earthquake cluster localities were identified. In this report, covering the period June 2016-May 2017, 101 of the 207 events located by Geoscience Australia in the SWA zone have been relocated using extra data. Of the 207 events, about 170 have been allocated to one of 19 centres identified as being active during the year. Ten of these centres were identified in previous annual reports, and nine have been noted for the first time. However, of these nine, at least five were also active prior to 2013. The relocations have resulted in a number of good focal depth determinations, all less than 7 km, and it is implied that most focal depths in the zone are less than 5 km. Identification of additional events not located by GA suggests that the magnitude-completeness level in SWA is above the ML 1.6 level previously suggested.

Introduction

1.1 Preamble

The South West Australia (SWA) seismic zone, to the east of Perth, as defined by Leonard (2008) (Figure 1), is of interest because it is one of the best regions in the world to study the less-well-known phenomenon of intra-plate seismicity. It saw three ground-rupturing events in the 11 year period 1968 – 1979. Since 2014 the author has been examining the region in 12 month periods. The aim has been to demonstrate the clustered nature of the seismicity, and to pinpoint as exactly as possible the location of each cluster. We are attempting to determine if seismicity in particularly active areas is recurring from the same location, or if it is migrating to a slightly different location, as might be expected if seismicity was occurring along a fault line

Figure 1 Seismicity in the SWA zone, Jun2016- May 2017



1.2 Overview of seismicity in 2016-2017

In simple numerical terms, 2016 was more active than the previous 3 years studied (Table 1). However, much of this can be attributed to the ML 4.2

event in January 2017 near Bonnie Rock, (the first ML4 event in SWA since May 2009), and which had ~ 50 aftershocks. Ten events occurred at nearly the same location (foreshocks?) in November 2016. Even without this large event and its aftershocks, there were more magnitude 3 events than in recent years, although the number of active cluster locations seems to be similar. As in previous years, the region 30º– 31ºSouth has been by far the most active part of the SWA zone.

Table 1 Summary of yearly earthquake numbers

Magnitude (ML) Range	1994	2013-2014	2014-2015	2015-2016	**2016-2017**
All events	132	290	167	73	**209**
ML 2.0 – 2.9	53	214	124	48	**168**
ML 3.0+	6	4	2	2	**9**
ML 4.0+	1				**1**

1.2 Earthquake zonation and classification

As in the previous reports, the SWA seismic zone has been divided into a number of rectangular zones (Figure 1) to aid analysis. Two of the 8 zones used in the previous reports have been subdivided, so there are now 10 zones. A new term introduced here is the "proto-cluster" – this is for a small number of earthquakes which may define a cluster, but there is a degree of uncertainty, either that they are a cluster, or in the correct location of that cluster.

To aid in comparing this year with earlier data, events for the previous 12 months are also plotted in the zonal analyses. Also, the author noticed that in 1994, many of the cluster locations noted here were also active, so events in that year are also plotted.

1.3 Relocations and the Public Seismic Network (PSN)

As has been done in previous reports, about half of the Geoscience Australia (GA) locations for events in the study year (2016-17) have been revised (i.e., relocated) using the EQLOCL location program, and with the addition of phase data from Public Seismic Network (PSN) stations in the SWA region. The relocations generally have much lower

Table 2. Cluster Locations , also showing old and new names for earlier clusters

Location	zone	New name	Old name	Ref.	Latit-ude.	Longit-ude.
N of Burakin	A	A1	A	(1)	-30.46	116.95
W of Burakin	A	A2	B	(1)	-30.53	117.05
SW of Burakin	A	A3	C	(1)	-30.63	117.10
W of Cadoux	A	A4	D	(1)	-30.79	117.10
Kalannie	A	A5	E	(1)	-30.15	117.17
New Norcia	A	A6	Mu	(4)	-30.93	116.30
W of Kulja	A	A7	new			
N of Beacon	B	B1	G	(1)	-30.24	117.75
Nw of Beacon	B	B2	P	(2)	-30.40	117.75
Kalannie	B	B3	Alpha	(3)	-30.26	117.28
NW of Beacon	B	B4	Nu	(4)	-30.31	117.65
NE of Kalannie	B	B5	new			
N of Koorda	C	C1	F	(1)	-30.64	117.47
N of Bencubbin	C	C2	J	(1)	-30.64	117.80
NE of Koorda	C	C3	K	(1)	-30.62	117.60
S of Bencubbin	C	C4	Q	(2)	-30.95	117.90
Yorkrakine	D	D1	H	(1)	-31.45	117.67
Wyalkatchem	D	D2	I	(1)	-31.25	117.45
N of Cunderdin	E	D3	M	(1)	-31.45	117.15
Nungarin	D	D4	Gam	(3)	-31.24	118.24
NW of Kellerb	D	D5	Omi	(4)	-31.43	117.50
N of Kellerb	D	D6*	Pi	(4)	-31.49	117.69
W of Wyalkcatch	D	D7	new			
SE of Wyalkcat.	D	D8	new			
Youndegin	E	E1	Delta	(3)	-31.77	117.36
W of Bruce Rock	E	E2	Rho	(4)	-31.84	117.84
N of Doodlakine	E	E3	new			
North of Hyden	F	F1	R	(2)	-32.30	118.90
Kokeby	F	F2	U	(2)	-32.25	116.98
Morbinning	F	F3	V	(2)	-32.14	117.19
East of Pingelly	F	F4	W	(2)	-32.49	117.31
S of Quairading	F	F5	Epsil	(3)	-32.24	117.35
SE of Dumblyun	G	G1	S	(2)	-33.46	117.66
N of Kojonup	G	G2	Theta	(3)	-33.69	117.03
Newdegate	G	G3	A	(1)	-33.21	119.16
Nyabing	G	G4	B	(1)	-33.50	117.92
N of Rocky G.	H	H1	T	(2)	-34.35	117.05
Bonnie Rock	L	L1*	Beta	(3)	-30.56	118.57
Barbalin	L	L2	new			
Mt Jackson	L	L3	new			
S of York	M	M1	L	(1)	-31.98	116.72
N of Meckering	M	M2	N	(1)	-31.62	117.08
S of Meckering	M	M3	O	(1)	-31.70	117.04
Meckering	M	M4	new			

Refs. (1) =Dent (2012) (2) =Dent (2014) (3) =Dent (2015) (4) =Dent (2016)
* = amended location, as discussed in text

uncertainties in their parameters than the original GA locations.

The PSN network is a group of low-cost seismographs set up by the author, and had its beginnings in 2006 (Dent, Harris & Hardy, 2010). There are now more PSN stations in the SWA region than there are GA stations, and, while they may have significant periods of "down-time", they usually provide sufficient data to allow significantly more reliable locations to be achieved.

1.4 Precis of previous findings and research directions

Results from previous years point to the possibility that almost all SWA events belong to cluster groups, and 36 such locations were defined in the papers mentioned above. The simple alphabetical naming system used in those papers is proving inadequate, and the cluster locations have been renamed, as shown in Table 2, to a new, zonal-based nomenclature. The cluster locations which have been identified appear to be active for variable periods, and then become dormant for variable periods, in a similar fashion to palaeo-seismic activity as described by Clark et al., (2012), but on a very different time-scale. It is obviously necessary to study the whole SWA zone for a relatively long period, to establish is this is in fact the case. At first appraisal, the seismicity seems to be consistent with the above hypothesis, although the 4 year time period so far studied is relatively short.

Table 3 Cluster properties

Location	zone	New name	Old name	status	Latit-ude	Longit-ude	# of event	Max mag	Most active period
Burakin	A	A3	C	old			5	2.4	21 Sep 2016
West of Kulja	A	A7	--	new	30.47	117.18	7	2.4	19 Jun 2016
N of Kalannie	B	B3	alpha	old			7	2.3	August 2016
NE of Kalannie	B	B5		new	30.10	117.41	3	3.3	Jun/Jul 2016
WNW of Beaco	B	B2	P	old			~27	3.0	Sep-Dec 16
Bonnie Rock	L	L2		new	30.66	118.42	~65	4.2	Jan 2017
Barbalin	L	L3		new	30.87	118.04	3	2.1	29 Aug 2016
Mt Jackson	L	L4		new	30.39	118.74	1	2.4	10 Sep 2016
Nw of Kellerb	D	D6	Pi*	old	30.495	117.695	9	2.5	Jun/Jul 2016
W of Wyalkat.	D	D7		new	31.18	117.28	3	2.4	Jan. 2017
SE of Wyalk	D	D8		new	31.26	117.63	2	2.4	31 Oct 2016
Doodlakine.	E	E3		new	31.52	117.91	3	2.3	April 2017
Meckering	M	M2	N	old			4	3.0	18 Apr 2017
Meckering	M	M4		new	31.648	117.025	7	1.6	26 Nov 2016
N of Hyden	F	F1	R	old			12	2.7	Jan/Feb 17
N of Brookton	F	F2	U	old			6	2.6	Jun/Jul 2016
E of Beverley	F	F3	V	old			2		
E of Pingelly	F	F4	W	old			3	2.1	
Newdegate	G	G3	sigma	old			3	2.6	Oct –Jan 17

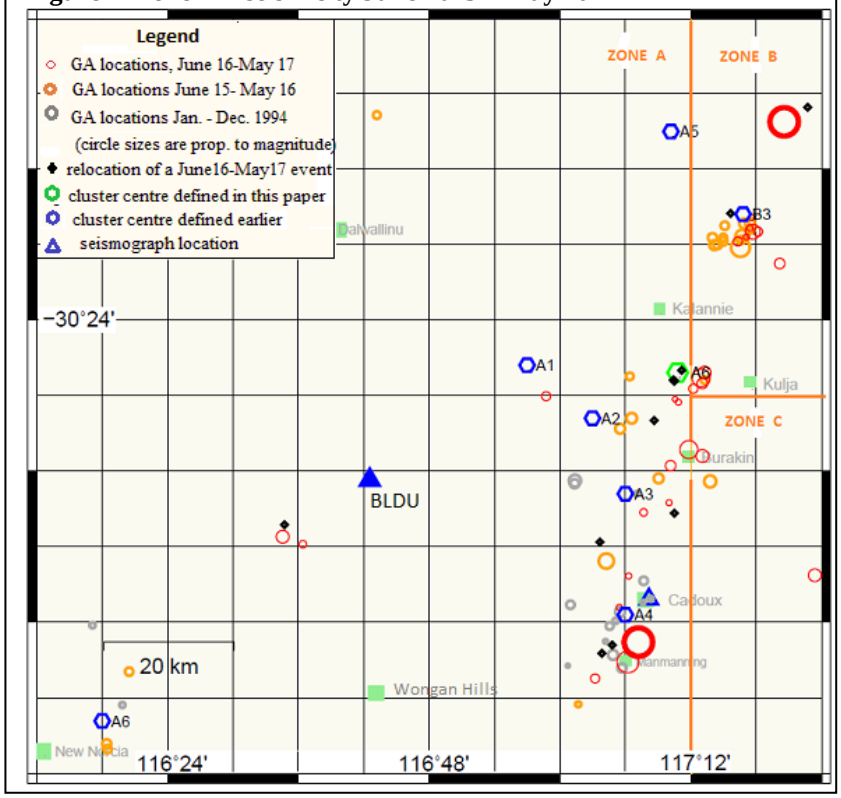
The rupture mechanisms, and the faults responsible for the clustered nature remain uncertain. So far, no clear connection with pre-existing mapped has been established. Data from this year might be an exception, as the Bonnie Rock cluster of January 2017 may be connected to a small mapped fault in the nearby Jouerdine Nature Reserve (Dent, 2017, this volume). Dawson et al., (2008) suggested that the Kalannie sequence of 2005 was related to a group of en-echelon faults, but these faults had not been previously mapped, and seem to have no surface manifestation.

2 Analysis of 2016-17 data by zone

2.1 Zone A "Burakin", 30.0° S- 31.0° S (Figure 2)

This zone includes the centre of Cadoux, site of a Magnitude 6.1 event in 1979. It is not clear if present day seismicity in the area is related to this fault. Since 2001, much of the activity seems to be related to the three ML 5 events near Burakin, about 20 km north of Cadoux, in 2001-2002 (Leonard, 2002). In the current period, there were 14 events in the zone, and a north-south trend seems to be present. The largest event, in December 2016, was an ML 3.4 event south of Cadoux, about 5 km south of Location A4. It seems to be an isolated event, as are some other largish Cadoux events of recent years. Three other small events in the area are not clearly related to the ML 3.4 event.

Figure 2 Zone A – seismicity June 2015 – May 2017



Two events northwest of Wongan Hills (January and March, 2017) could be called a cluster, but since there are only two, and small (both ML 1.9), they are here called a "proto-cluster".

The GA locations of 5 events (largest ML 2.4), ~10 km west of Kulja, between 18- 20 June 2016 plot in zone B, but the relocations move them into Zone A. They define a new cluster, location A7, which is listed in Table 3. This table summarises the activity of each cluster centre active between June 2017 and May 2017.

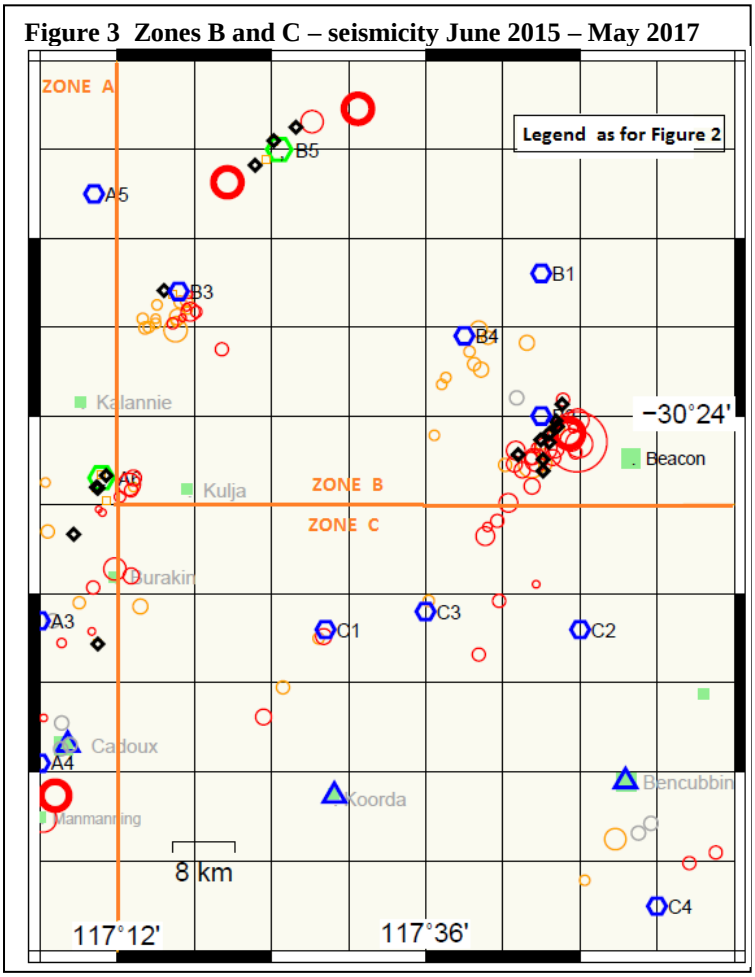
GA locations show a cluster of 5 events close to Burakin in late Sep-mid Oct 2016 (largest ML 2.4). However, the residuals are large, indicating large uncertainties in the locations. The relocations are also not good, but suggest that the true locations are some 10 km south of the ML 2.4 event. This puts them close to cluster location A3, and they are tentatively assigned to that location. This location was the centre of the significant cluster, north of Cadoux, in Sep-Oct 2000, described by Leonard & Boldra (2001).

2.2 Zone B "Beacon" (Figure 3, 34 events, 4 cluster groups)

The two largest events (both ml 3.3) were from a cluster of 3 events north of Kalannie in late June-early July 2016. The GA locations of the two ML 3.3 events are about 20 km apart, but the relocations bring them much closer together. The approximate centre of the group is used to define a new cluster (B5). This cluster is about 20 km ENE of the centre of the large Kalannie swarm of 2005 (Location A5), which was the subject of an in-depth study by Dawson et al., (2008).

Numerically, seismicity in this zone is dominated by a cluster of events northwest of Beacon (~19 events, largest ML 3.0). The most active period was September to December 2016.The GA epicentres have a distinct NE trend, but the relocations of several events at the extremities of the trend suggests that the trend is unreal, and that the events are clustered in a region a few km south of the predefined location, B2
A cluster of seven events closer to Kalannie in September 2016 appears to be at location B3 and the events represent a continuation of activity seen near there in the previous 12 month period.

Figure 3 Zones B and C – seismicity June 2015 – May 2017



2.3 Zone C "Koorda" (Figure 3, 11 events largest ML 2.3)

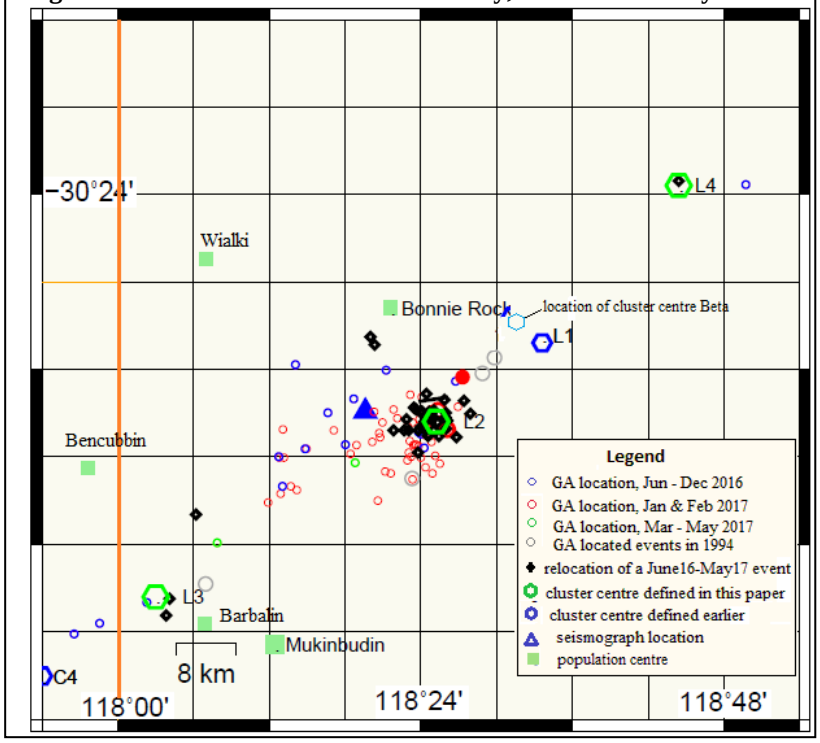
The original zone C has been subdivided, to put events near Bonnie Rock into a unique zone (Zone L). The Koorda region was very active between 2012-2015, and 4 cluster centres have been defined in the zone (C1-C4). In the current period, there are only 11 small and relatively scattered events. 5 of these join clusters in adjacent zones when relocated (2 events southeast of Bencubbin on 29th August, when relocated move into the new Zone L, as described below).

Zone L Bonnie Rock 73 events, largest ML 4.2 (Figure 4)

There is only one defined cluster location in this (new) zone, location Beta, identified in Dent (2015) but here renamed to location L1. This was noted as being an approximate location when defined, and more work, presented in Dent & Collins (2017) has suggested it be moved about 8 km to the southeast, to an active location which was well-defined by a temporary network in June 2000.

The significant activity following the ML 4.2 event north of Mukinbudin on 3rd January 2017, represents about 1/3rd of all the 2016-2017 seismic events studied in this report. The activity in 2016-17 presented below is summarised from the more detailed report of Dent & Collins (2017) mentioned above. The new seismograph (BR4) installed near the epicentre of the main event, 10 days after it happened, has assisted greatly in providing better locations for the events.

Figure 4 Zone L – Bonnie Rock seismicity, June 2016 – May 2017

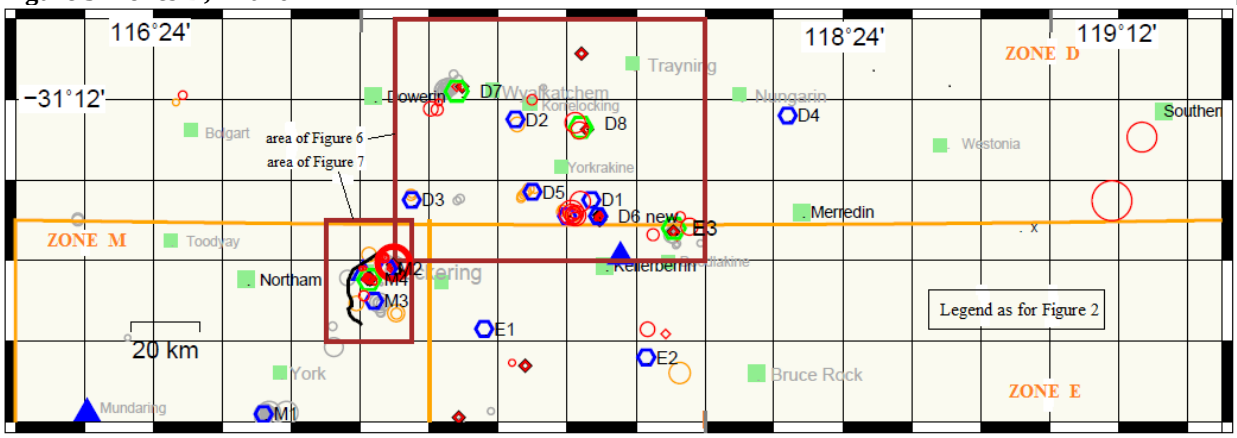


There were two significant cluster groups in the 12 month period, the first being a group of 8 events northeast of Mukinbudin in November 2016 (largest ML 2.6). Relocations in Dent & Collins (2017) suggest that these events came from the same location as the more significant cluster some six weeks later, in Jan 2017. This later cluster was initiated by an Ml 4.2 event (the largest in SWA for 7 years) on 3rd Jan 2017. Dent & Collins (2017) suggest that the cluster centre was at -30.66, 118.42, and this was relatively well determined, as it used data from the close and newly-installed seismograph (BR4). This location is about 20 km southwest of location L1.

The November 2016 events (probable foreshocks) seem to be "swarm-like" (i.e., no particularly dominant event), whereas the events of January 2017, starting with the ML 4.2 event of 3rd January 2017 are more main-shock/ aftershock in character.

Two events in the southeast of Zone C, on 29th August 2016, when relocated, move to the southwest of Zone L, close to another event on 17th June 16. This group location coincides with that of a larger cluster in January 2001, identified as "near Barbalin" in Dent & Collins (2017). This location has been named L3.

Figure 5 Zones D, M and E

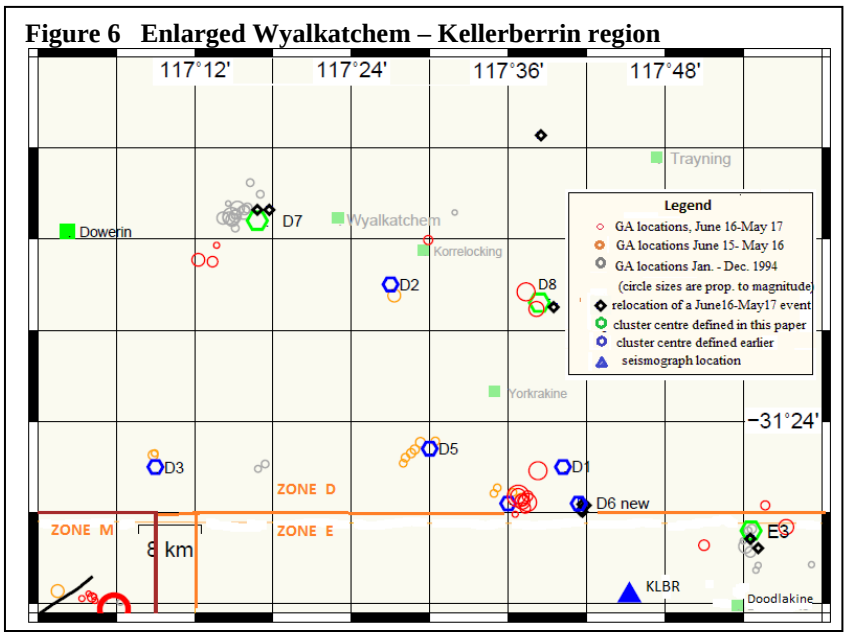


A single event about 50 km northeast of location L1, in November 2016, is apparently at the same location as a group in 2013 ("southwest of Mt. Jackson") as described in Dent (2017). This cluster location is here defined as location L4, at the location given in Dent 2017.

There are other cluster groups in the area noted in Dent 2017 (near Mukinbudin and Welbungin), and together they seem to define a NE-SW trend, and this possible structure was therein named "the Bonnie Rock Seismic Lineation".

2.4 Zone D, "Wyalkatchem" 31.0ºS - 31.5ºS (18 events, largest ML 2.9 Figures 5 & 6)

Figure 6 Enlarged Wyalkatchem – Kellerberrin region



Northwest of Kellerberrin The GA locations of this group of 9 events (largest ML 2.5) in June and July 2016 puts them close to a smaller group 12 months earlier. This group was given the label Pi in last year's report, with the caveat that it was not well determined. Some of the relocations suggested the group was actually about 8 km further east, and relocations of the June/July 2016 events confirm that the locations are east of the GA locations. Location Pi, or D6 in the new convention, has been moved to this new location in Tables 2 and 3.

West of Wyalkatchem

This cluster of three events (Dec 2016-Jan 2017, largest ML 2.2) plots about 5 km southwest of a cluster of 12 events (largest ML 2.5) in March/April 1994, noted in Dent (2008). Relocations of the 2016-17 events suggest the cluster is about 8 km to the northeast of the GA location, and close to the 1994 cluster location. A new cluster location – called Location D7 has been defined for these events.

Southeast of Wyalkatchem
Two events southeast of Wyalkatchem (ML's 2.3, 2.4) on 31 Oct 2016 have been used to define a new cluster location, D8.

Events near Southern Cross. (Two events in September 2016, Ml 2.6 and ML 2.9). These events are designated as a proto-cluster, because there are only two events, and their locations are poor. Note that more intense activity returned to this location in late 2017, and the events will be reviewed in next year's report.

2.5 Zone M – Meckering (Figures 6 & **7,** 14 events, largest ML 3.0).

Three cluster centres have been defined previously in this (new) zone, two near Meckering, and one south of York (Figure 5). Seismicity in the zone in 2016-2017 seems to consist of two distinct clusters, one about 7 km ENE of Meckering (consisting of a mainshock on 18th April 2017, ML 3.0, and 4 small aftershocks on the same day) and the other is a group of

Table 4 List of better-determined focal depths determined by relocations

Date & time	Nearest Town	Dist. to stn	Depth (km)
16-11-26 0133	Meckering	2.1	4.3
16-11-26 0125	Meckering	2.5	3.3
16-11-26 2348	Meckering	2.5	4.3
16-09-24 1607	Meckering	3.9	5.8
17-04-18 2224	Meckering	8.1	6.2
17-01-15 2231	Bonnie Rk	8.1	0.4
17-02-12 0811	Bonnie Rk	8.5	0.3
17-04-18 1258	Meckering	8.7	3.9
17-03-05 1803	Bonnie Rk	9.2	1.9
17-04-18 0826	Meckering	8.3	5.9
17-02-22 1318	Bonnie Rk	10.1	2.0
16-07-15 1533	Cadoux	10.6	1.3
16-10-25 0933	Quairading	10.6	4.3
16-06-18 2343	Kellerberin	11.7	2.7
16-07-12 0055	Kellerberin	12.0	2.8
16-06-25 1946	Kellerberin	12.2	3.7
16-06-25 1837	Kellerberin	12.5	3.6
16-06-25 1837	Kellerberin	12.9	2.7
16-08-30 1050	Kellerberin	16.2	1.4
17-06-05 1020	Bencubbin	16.3	6.2
17-06-05 1519	Bencubbin	16.5	0.3
17-06-05 1519	Bencubbin	17.6	6.7
16-10-12 1825	Quairading	18.5	11.2
17-06-03 0750	Mukibudin	19.8	1.3

Focal depths of Meckering events

The focal depths of Meckering events may be reliable because of the closeness of the MECK station, and are listed in Table 4. This table lists what are considered better focal depths obtained by relocation, as discussed later in this paper. The two cluster centres discussed above are both about 4 km east of the Meckering Fault scarp (Figure 7), and the focal depths are consistent with the assumed easterly dip of the fault (Gordon & Lewis, 1980).

2.6 Zone E, "Kellerberrin" 31.5ºS – 32ºS

(Figures 5 & 6, 5 events, largest ML 2.3.)

This zone was previously called "Meckering" but is now renamed "Kellerberrin" since the Meckering region has been excised to form the new zone "M". There are two pre-defined cluster locations in this zone (E1 and E2, Figure 6), but the only grouping of significance in the 2016-17 year is one of three events north of Doodlakine (August 2016 and April 2017).

small events about 2 km southeast of Meckering (all on November 26th, 2016, largest ML 1.6). Good relocations for events in this zone are now possible, since the installation of a PSN seismograph at a local business in December 2015.

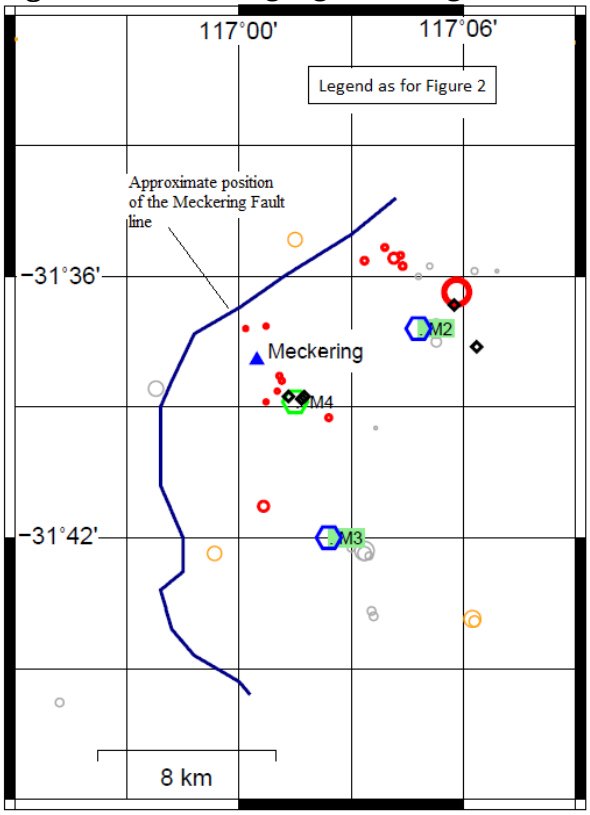
Events ENE of Meckering, April 2017

This group has a mainshock/ aftershock character. Relocations bring the small aftershocks back towards the main event, and closer to cluster centre M2, which was defined in Dent (2012) on the basis of two events in late 2011. The events are allocated to that cluster centre in Table 3.

Events south of Meckering, 26th Nov 2016

Relocations of these events bring them closer together, and in particular, two events just north of the town move south to join this group, identified as a new location, M3, in Table 3. The focal depths average about 4 km. Note that a solitary event about 8 km south of Meckering, on 24th September, also relocates close this location.

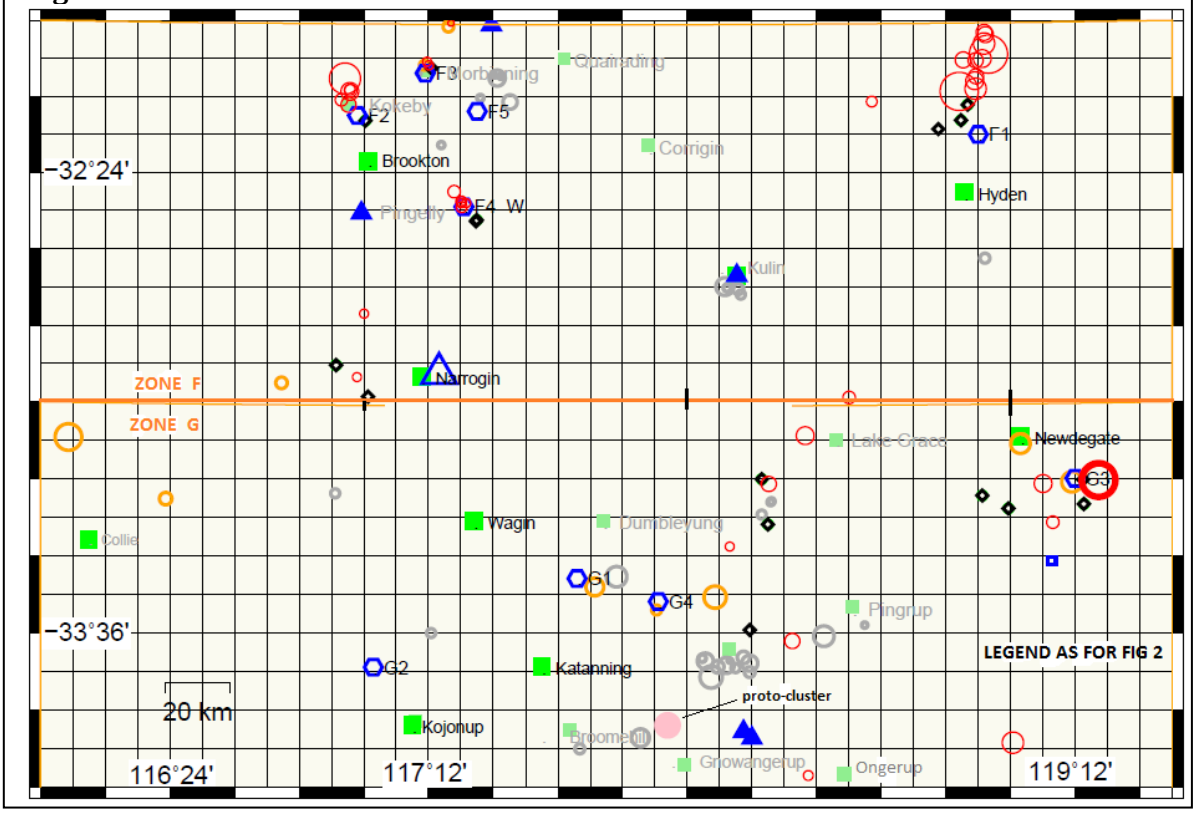
Figure 7 Meckering region, enlarged



Relocations tighten the group, and the location appears to coincide with a cluster in June 1994 (grey events in Figure 6), which was noted in Dent (2008). This is cluster location has not been named before, and is here defined as location E3.

2.7 Zone F, "Brookton-Hyden" 32ºS - 33ºS (Figure 8, 30 events largest – 2 events

Figure 8 Zones F and G



both ML 2.7, north of Hyden)

North of Hyden

Activity in Zone F in 2016-17 is dominated by events which are here allocated to Location F1, north of Hyden, a centre which was quite active in early 2013. The events north of Hyden were in two cluster groups, in late January-early February 2017 (6 events), and the 6 events in the later group were all on 22nd May 2017. They are typical "earthquake swarms" i.e., there is no single dominant event. Other smaller events from this location were detected by the PSN network, but not located by GA.

North of Brookton

This cluster of ~ 6 events (June-Aug 2016, largest ML 2.6) may emanate from the same location (F2), near the village of Kokeby, as a cluster in December 2013. Both the current cluster and the 2013 cluster were main/aftershock in character as the first events were large relative to the following events.

East of Beverley, February and April 2017
Two small events in February and April, 2017, may come from location F3, near Morbinning, about 20 km east of Beverley, where a cluster of events occurred in July 2013.

East of Pingelly, May 2017

This group of 5 small events (largest ML 2.0), mostly in May 2017, probably comes from location F4, first identified from a group of three events in March 2014.

2.8 Zone G "Katanning", 33ºS to 34ºS (Figure 8, 10 events, largest ML 3.1)

There are 5 previously defined cluster locations in this zone, shown in Figure 8 as G1 – G5.The most significant group of events in the zone in 2016-17 is a cluster of 4 events southeast of Newdegate, (largest ML 3.1 on 13th May 2017). The activity represents a renewal of activity at location G3, which was defined in Dent (2016) on the basis of two events in June 2015. Relocation of the ML 3.1 event brings it closer to Location G3. Note that event locations in this region will have large uncertainties because of the poor distribution of seismographs.

Examination of seismic data from PSN stations has identified numerous relatively small events not located by GA, but for which approximate locations can be determined using S-P times (Table 5). One of these (2nd Jan 2017 at 2035 UTC) also seems to be from the G3 cluster, and is also plotted on Figure 8. Its magnitude is estimated at ML 2.2

Three small events within ~ 20 km of Lake Grace (Sept. 2016, March & May of 2017) could represent a cluster, with the disparity of locations being attributed to the difficulty of locating events in this region. However, they not defined as a cluster here. Other small unlocated events suspected of being in the Lake Grace area were detected by the PSN network (Table 5), and future work may result in the definition of a cluster centre there.

A single event about 20 km northeast of Nyabing plots very close to an event in December 2014, and relatively close to clustered events in 1994 and 1995. A "proto-cluster" is declared for this location, and future events may help to define its location more precisely.

Table 5 Some of the unlocated earthquakes seen on PSN seismograms during 2016-17

Date/time	Estimated area	est. ML!	Date/time	Estimated area	est. ML!
01/08/2016_09:41	Lake Grace?	1.9	15/08/2016_10:55	N of Gnowangerup	1.2
01/08/2016_10:02	Lake Grace?	1.8	15/08/2016_11:40	N of Gnowangerup	0.9
10/08/2016_23:38	N of Gnow	1.8	29/08/2016_1435	SW of Cadoux	1.5
11/08/2016_00:30	N of Gnow	2.3	13/09/2016_1426	Muja	2.4
11/08/2016_22:07	N of Gnow	1.6	29/12/2016_2332	Westonia	2.4
12/08/2016_19:14	N of Gnow	0.9	02/01/2017_2036	SE of Newdegate	2.2
12/08/2016_19:15	N of Gnow	1.2	03/01/2017_1621	Bonnie Rock	2.0
13/08/2016_18:39	N of Gnow	1.3	31/01/2017_2316	SE of Meckering	1.3
14/08/2016_12:01	Lake Grace?	1.6	05/04/2017_1825	N of Hyden	
15/08/2016_09:45	N of Gnowa	1.4	28/04/2017_1952	N of Hyden	1.8
15/08/2016_10:01	N of Gnowa	1.7	16/05/2017_1523	Lake Grace	1.9
			28/05/2017_2140	E of Hyden	

! estimated ML (Local magnitude) - estimated from amplitudes on PSN stations.

Other events near Gnowangerup

Random examination of seismograms from the seismograph GNOC, (located about 20 km northeast of Gnowangerup), revealed a group of small, unlocated events, mostly in mid-August, 2016, as indicated in Table 5. A composite location, using S-P times from PSN stations in the region, suggests their origin is about 20 km north of Gnowangerup (largest event about ML 2.0). This is also declared a "proto-cluster" location. Examination of

historical data shows an ML 2.4 event at almost precisely this location in April 2013. This cluster resembles a cluster of probably hundreds of small (but felt) events from a location, thought to be just north of GNOW, in late 2007, which was described in Dent (2008). Only three events in that cluster were large enough (largest 20th Nov 2007, ML 2.3) to be located by the regional (GA) seismograph network. Local farmer's concerns following that cluster prompted the installation of the GNOW and GNOC seismographs.

2.9 Zone H, "Cranbrook", 34º S – 35º S

There were no events in Zone H in the 12 month period, although, a small event (ML 1.9) near Ongerup relocates to 34.05ºS, which moves it into the Zone H region. The last cluster to be observed in the Zone H region was that north of Rocky Gully in May-June 2013 (location H1), largest ML 2.9.

3 Summary and Discussion

3.1 Summary of the zonal analysis of 2016-17 seismicity

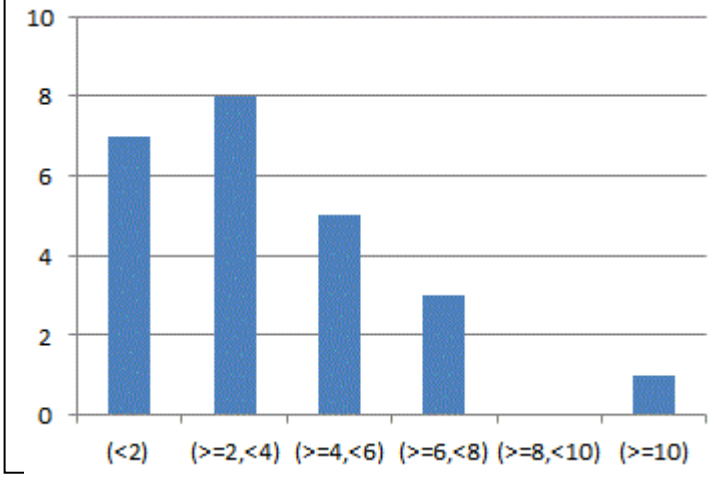
Of the 207 events reviewed here, Table 3 shows ~170 have been assigned to 19 cluster locations. Nine of these locations are defined here for the first time, including location L2, source of the Bonnie Rock cluster, which was by far the most significant seismic event of the year. Although it is defined here for the first time, work by Dent (2017) suggests that the location has shown at least occasional activity over the last 25 years. Of the other new cluster locations, at least four been active in earlier years, but also were not defined as cluster locations. These are L2 (active in 2001), L4 (active in 2013), D7 (active in 1994), and E3 (also active in 1994). Ten of the cluster locations active in this year were defined in earlier reports, and the most significant being B2 (northwest of Beacon, 20 events), and F1, (north of Hyden, 12 events).

In total now, 44 cluster locations have been defined in SWA. Of the remaining ~ 40 events not assigned to a cluster location, later relocations may move some to a known cluster location. Alternatively, they may represent remnant activity from cluster locations not yet defined. Some, probably a minority, will remain as "isolated" events. The most significant isolated event in the 2016-17 period was the ML 3.4 event southwest Cadoux, in December 2016. Note however that it is very close to cluster location A4.

3.2 Earthquake focal depths.

Focal depths are usually less well determined than latitude/longitude, and close seismographs (<~20 km) are needed in order to determine a depth with some confidence. GA depths have been constrained to 10 km since December 2016, and many of the PSN relocations of events plotted here have been constrained at 2 km depth. In some instances in this year, events are close to PSN seismographs, e.g. Bonnie Rock, Meckering, and the depths computed have reduced

Figure 9 Distribution of well-determined focal depths



uncertainties, estimated to be about +/- 4 km. These more-reliable depths (i.e., nearest recorder is < 20 km distant) are listed in Table 4, and the depth-distribution is shown in Figure 9. Based on this data, it is suggested that most earthquakes in the SWA zone are less than 5 km deep.

The number of defined cluster locations seems to be increasing by about 10 locations each year. Whether this will decrease over time, as most "recurring" locations become identified, is yet to be seen.

3.3 Discussion

The analyses presented in these reports were inspired by the Leonard & Boldra (2001) report on a field survey conducted to monitor an earthquake swarm north of Cadoux in September-October 2000 (largest event ML 3.6). They identified four cluster locations (A1 to A4 in Table 2), and concluded that the majority of the ~ 1,700 events detected by the survey came from location A3. This location seems to have been relatively quiet since 2000, but location A2 seems to have been the focus of the extremely active Burakin swarm of 2001 – 2003, which included three magnitude 5 events. Activity at A2 seems to have continued, but was only minor or non-existent in the current period.

Leonard & Boldra (2001) quoted a personal communication from Gibson, saying that such clusters occurred in SWA every 1 – 2 years. Major clusters following the Cadoux 2000 swarm were at Burakin, as mentioned above, and also near Koorda in 2004 (Location C1), Kalannie in 2005 (location A5), Beacon in 2007 (location B1), again near Beacon in 2012 (location B2), and near Bonnie Rock in 2017. Gibson's observation might be correct if you consider only "major" clusters, but results over the last 4 years indicate that at least 10 cluster locations generally show activity in any given year, and clusters can be of all "sizes", from "minor" to "major".

Interestingly, the "major" clusters in the above paragraph are all in the northern part of the SWA zone, between 30 and 31 degrees south. Understanding the behaviour of clusters over time is also probably important. The report of Ghasemi et al., (2013) would seem to assign them to being "extended aftershock sequences", but in many cases, there seems to be no obvious "main-shock" present. In the case of the January 2017 sequence near Bonnie Rock, there was a main-shock, but there was a cluster of events at the same location some 2 months earlier, without a mainshock, and the report by Dent (2017) suggests that this location (L1) has seen active periods back as far as 1968. It seems it is possible that clusters from a single location may show a wide variety of magnitude distributions, from fore-shocks/main-shock and aftershocks to a true swarm-like nature, where there can be several or many events near the maximum magnitude of the group.

Notable from the studies so far is the fact that activity seems to return to the same location, after long periods of quiescence, possibly decades or longer. This would not be unusual if faults were observed at these locations, but this is not the case so far. More data is required to confirm this observation, and obviously earthquake location errors will need to be reduced, from the order of +/- 10 km, to about +/- 2 km or less.

Completeness of GA earthquake catalogue

The density of the PSN network, and the relative nearness of many of the stations to the cluster centres, has revealed numerous events not located by GA, the larger ones of which are listed in Table 5. Approximate magnitudes can also be determined, and these are also shown. Leonard (2008) suggested that the GA earthquake catalogue in the SWA region was probably complete for events > ML 1.6 since 2009. However, this study, and also that of Dent (2009)

suggest that events up to magnitudes ~ ML 2.2 may escape location by GA. This may not have a significant effect on the Seismic Hazard Analysis for the region, because, as they are usually small events within a larger cluster, they are usually eliminated as being "dependent events".

Events outside the SWA seismic region

There are few events around the perimeter of the SWA region, possibly partly because of the inability of the existing seismic network to detect small events (i.e. below ~ ML 2.5) in these areas. However, there were significant activity north of Ravensthorpe in March and September 2017 (three events between ML 3.2 and 3.5), some 50 km east of the SWA boundary used here (119.5°E). The Ravensthorpe region has seen some large earthquakes in the past (e.g. ML 5.2 in October 2000), and also has a significant palaeo-scarp (Estrada, B. 2008). This suggests that there is little difference in the seismic characteristics of this region, and the rest of the SWA region to its west.

Acknowledgements

The author wishes to acknowledge the significant contributions of Clive Collins and Virginia Ward in preparing this paper, and also Eddie Leask of GA for providing necessary data.

4 References

Clark, D., McPherson, A. & Van Dissen, R., (2012). Long-term behaviour of Australian continental region (SCR) faults. *Tectonophysics*, 566, 1-30.

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.

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

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

Dent, V. F., Harris, P, and Hardy, D., (2010). A new seismograph network in the southwest seismic zone of Western Australia. In *Proc. AEES 2010, Conference*, Perth, WA.

Dent, V. F., (2010). A NE 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., (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, N.S.W.

Dent V.F., (2016) A preliminary map of cluster locations in southwest Western Australia, 1990 – 2016 in *Proc. AEES 2016 Conference*, Melbourne, Vic.

Dent V.F., & Collins C.D.N., (2017) . A review of seismicity in the Mukinbudin Bonnie Rock area of WA. In *Proc. AEES 2017 Conference*, Canberra ACT

Estrada, B. (2008). Neotectonic and Palaeoseismological studies in the southwest of Western Australia PhD thesis, University of Western Australia.

Ghasemi, H., Leonard, M., Robinson, D., Owen, K. & Horspool, N. (2013) Aftershock probability model for Australia *Proc. of the AEES 2013 Conference*, Hobart.

Gordon, F.R., and Lewis, J.D., (1980). The Meckering and Calingiri earthquakes, October 1968 and March 1970. *Geological Survey of Western Australia.* Bulletin 126.

Leonard, M. & Boldra, P. (2001) Cadoux swarm September 2000 – an indication of rapid stress transfer? In *Proc. AEES 2001 Conference*, Canberra, ACT.

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

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