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Evidence for shallow focal depths and denser locations for three southwest seismic zone earthquake clusters, 2011

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S-P times recorded by the new Australian Centre for Geomechanics (ACG) network in southwest Australia demonstrate that three earthquake clusters northeast of Perth, between September and December 2011, are much more tightly grouped than the epicentres as determined by Geoscience Australia (GA) suggest. Data indicate that events down to about M_L 1.0 can be detected by humans. Several new localities are added to a list of relatively well defined, and possibly long-lived, swarm centres in the Southwest seismic zone. The present limited GA seismograph network in the region is inadequate to provide the fine resolution needed to define tight swarms, and distinguish separate cluster locations which may be in close proximity. The data suggest a higher proportion of co-dependent seismicity in the region than previously proposed and support an earlier conclusion that a northeast trend seen within clusters in the region is largely illusory.

1 Introduction

A number of minor earthquakes (up to Richter Local Magnitude M_L 3.1) were felt northeast of Perth, near the localities of Wyalkatchem, Bencubbin and Koorda, between 1st Sep and 31st Dec 2011. A temporary recorder was installed near one of the locations (north of Koorda) in early Nov 2011 in order to better define this seismicity. This report investigates these events and the area around them (Figure 1) in greater detail.

Figure1 Locality and seismicity map, Sep-Dec 2011

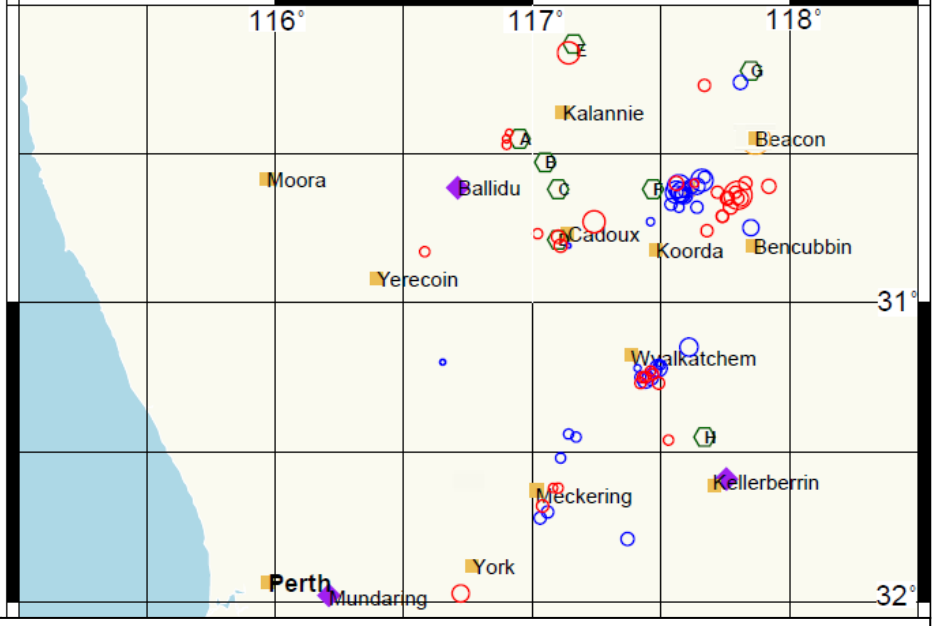


Figure 1 Red circles =events Sep - Oct 2011, blue = Nov-Dec 2011. Green stars = swarm locations as per Table 2. Mauve diamonds = GA seismic stations, yellow squares = towns

In the four months September to December 2011, 72 events were located in the area by Geoscience Australia (GA) as plotted on Figure 1 and listed in Appendix 1**.** The largest was an M_L 3.1 event northwest of Bencubbin on 27th Sep 2011, and other significant events $M_L \geq 2.4$) are shown in Table 1. At least 50 of the located events are probable "cluster" events, originating from one of the three locations mentioned above, and most of the others are related to other cluster locations which were active before 2011.

Table 1 – principal events, Sep-Dec 2011

Date	UTC	M_L	GA comment
09 Sep	2312	2.4	SW of York
27 Sep	1913	3.1	NW of Beacon
11 Oct	2122	2.7	N of Kalannie
14 Oct	0222	2.7	Near Cadoux
01 Nov	0111	2.5	Nr Wyalkatchem
24 Nov	0411	2.6	NE of Koorda
27 Nov	0621	2.8	Near Koorda
27 Nov	0654	2.7	Near Koorda
28 Nov	0227	2.7	NE of Koorda

For the purposes of this study, a cluster is defined as a group of two or more events, linked spatially and also in time. When there are many events and the largest events have similar magnitudes, it is often described as a "swarm".

The clusters described here are within the southwest seismic

Zone (SWSZ), which is in the southwestern region of Archaean Yilgarn Craton, and an important site internationally for intra-plate seismicity.

The SWSZ is, at its closest point, only about 100 km from Perth, and has been the location of many of Australia's more significant earthquakes (e.g., Meckering,1968, M6.7; Cadoux, 1979, M6.1; Calingiri,1970, M5.9). The Wyalkatchem – Koorda- Bencubbin region is near the centre of the SWSZ, and is only about 50 km east of Cadoux.

Leonard (2008), in a review of Australian seismicity stated that ~60% of SWSZ events are cluster-related. Dent (2009) suggested the percentage may be higher. As noted above, 72 events are located in the study area in this time interval, and it will be shown that about 90% are cluster-related.

1.1 Previous swarm investigations in the SWSZ

The most significant recent earthquake swarm in the SWSZ, and probably Australia, was the Burakin swarm northwest of Cadoux between 2001 – 2003. It, and a precursor swarm, in October 2000, were described by Leonard & Boldra (2001) and Leonard (2002). The Burakin swarm had three events of $M_L \geq 5.0$. Other swarms since then, north of the townships of Kalannie, Koorda and Beacon, were described by Dawson et al. (2008) and Dent (2009, 2010). Dent (2010) suggested that a prominent northeast lineation seen in some of the swarms was due to location inaccuracies, introduced by the poor distribution of seismographs around the events.

Table 2 – Proposed cluster centres

Location	Lat	long	Reference	Loc
NW of Burakin	-30.46	116.95	Leonard & Boldra	A
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
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	This report	I
N of Bencubbin	-30.64	117.80	This report	J
Lk Mollerin	-30.62	117.60	This report	K
SW of York	-31.98	116.72	This report	L
Cunderdin	-31.45	117.15	This report	M
Meckering	-31.62	117.08	This report	N
S of Meckering	-31.70	117.04	This report	O

It has been shown (e.g. Leonard, 2001; Dent, 2009, 2011) that many of the clusters actually originate from small source localities, probably less than ~ 3km in diameter. Source localities within the study area which have been previously defined are summarised in Table 2, and labelled (A-H). Localities A to D were proposed by Leonard & Boldra (2001) in their study of the swarm in Oct-Nov 2000, northeast of Cadoux. The Burakin swarm which commenced a year later was centred around Locality B. Locality E was precisely defined by Dawson et al. (2008) in their study of a cluster in Nov 2005 north of Kalannie. Localities F, G and H were defined in recent studies by Dent (2009, 2010, 2011).

The "time" descriptor in the definition of a cluster is poorly constrained. In the four month time interval considered here, any two events probably at the same location will be considered "clustered". Whether events a year or more apart, and at the same location should be considered as part of a cluster is debateable.

1.2 Seismic monitoring of the region

1) The Geoscience Australia Network

Geoscience Australia (GA) operates seismographs in the study area at Mundaring, Kellerberrin and Ballidu (Figure 1) as part of their national (ANSN) network. Other seismographs just outside the area, but important for earthquake locations, are at Narrogin and Morawa. The GA stations sample at 40 s/s.

2) The ACG Network. Low-cost seismographs, which have been progressively installed in the region by UWA since 2005 (Dent, 2006, 2010), have supplied extra data which have allowed better estimates of the locations of many of these events. The ACG stations at Beacon and York are particularly significant, as is the temporary station KOO4, which was installed north of Koorda in November 2011, soon after residents in the area reported experiencing severe earth tremors. Coordinates and operational periods for these stations are listed in Table 3.

Table 3 – Operational data for field seismographs in the Koorda region

Stn	Lat.	Long.	Opened	Closed	Auth	Location
BEAC	-30.4511	117.8687	Mar 2009	continues	ACG	Beacon Primary S
YORK	-31.5933	116.7603	May 2007	Dec 2011	ACG	York High School
KOO4	-30.6307	117.6401	11Nov 11	Dec 2011	ACG	Harrap's Farm
KOO1	-30.6498	117.7598	Mar 2005	Feb 2007	GA	N^{th} of Koorda
KOO2	-30.5102	116.9991	Jan 2005	Aug 2006	GA	Burakin
KOO3	-30.0620	117.3449	Jan 2006	Feb 2008	GA	Kalannie

The earthquake locations in Appendix 1 were made by GA using their standard ANSN stations i.e., ACG net data were not used. Locations in the GA catalogue are given to 3 decimal places (i.e. to the nearest 100 m approx.). This can be misleading as the GA earthquake locations have uncertainties of about ± 10 km in location, and the uncertainty in depth is probably greater than this. The smaller the earthquake the larger the uncertainties are likely to be. The only positive factor in quoting a location to three decimal places is that it serves as a method of distinguishing one event from another.

1.3 S-P times as a location tool

Measuring the time difference between the P and the S wave arrivals for an earthquake at a station is a useful way of determining the distance to the earthquake epicentre. Factors which influence the S-P interval include the P and S wave velocities in the region, and the earthquake focal depth. In southwest Australia, the ACG software assumes a P wave velocity of 6.1 km /sec, which is close to that of the WA2 earth model (Dent, 1989), and an S/P velocity ratio of 0.59. From these values, S-P tables, as graphed in Appendix 2(A, B and C), have been determined. The graphs assumes the earthquake foci are very shallow (< 5 km), and this matches the probable focal depth range of earthquakes in this region. Appendix 2(A) also shows computed S-P times for a P velocity of 5.0 km/sec, assuming the same S/P velocity ratio. It indicates that, for a slower P wave velocity, the epicentral distance for a given S-P time is less.

The S-P method for determining distance works well for the ACG stations, as the stations have a high sampling rate (200 s/s) which is desirable when the seismic frequencies are high. The S and P arrivals are also more distinct when the stations are close to the events. These factors combined mean that there is a relatively low degree of uncertainty in measuring the S-P intervals from these stations.

S-P data and approximate magnitudes for events detected by the ACG network, Sep to Dec 2011, including some events not located by GA, are listed in Appendix 3. The S-P data will be used to demonstrate that many events are much more tightly grouped than the GA locations suggest.

1.4 A summary of activity, September 2011– December 2011

The four months of the study period represent a period of heightened seismicity in the northern section of the SWSZ. There were 134 events in the study area during 2011, of which 68 occurred in the three months September-November 2011 (Appendix 1). The largest event in the area during 2011 was an M_L 3.4 event at Burakin on 26th Apr 2011 and the largest event in Appendix 1 was an M_L 3.1 event northwest of Bencubbin on 27th Sep 2011.

The first significant event in Appendix 1 was a solitary M_L 2.4 event southwest of York on 9th Sep. Then on 12th Sep, a small event (M_L 1.8) occurred east of Wyalkatchem, which was a precursor to a swarm (cluster 1) which began at that location on Sep 27th. This cluster of small events (maximum M_L 2.0) continued until 2nd Oct, when there was a pause in activity for about 4 weeks.

The M_L 3.1 event on 27th Sep northwest of Bencubbin, marked the start of a significant series (cluster 2) in the area with a classical main-shock/aftershock nature. The last located event in this series was on 18th Oct 2011.

A solitary M_L 2.7 event occurred north of Kalannie on 11th Oct, and a solitary M_L 2.7 event occurred close to Cadoux on 14th Oct.

The Wyalkatchem activity resumed on 1st Nov, with a group of relatively large events (max. M_L 2.5), and lasted for about a week. It is likely that other, smaller events occurred within this cluster, and the cluster northwest of Bencubbin, but were below the GA location threshold. This is demonstrated by recordings from KOO4, the temporary station at the centre of the Lake Mollerin swarm.

The third significant cluster, the sequence near Lake Mollerin, north of Koorda, started with two minor events on 27th & 28th Oct (M_L's 1.6 and 2.2). From about the 7th Nov, the events in the swarm increased in size and frequency, prompting a call to UWA, and the installation of a field recorder. The period 16th – 23rd Nov was quiet, but the most intense phase was between 24th – 28th Nov, including three events with M_L's between 2.7 and 2.8. Occasional minor events then continues until February 2012.

A group of relatively small events NE of Meckering commenced on 8th Nov with an M_L 2.1 event. The following events were smaller.

Figure 2 Wyalkatchem swarm events

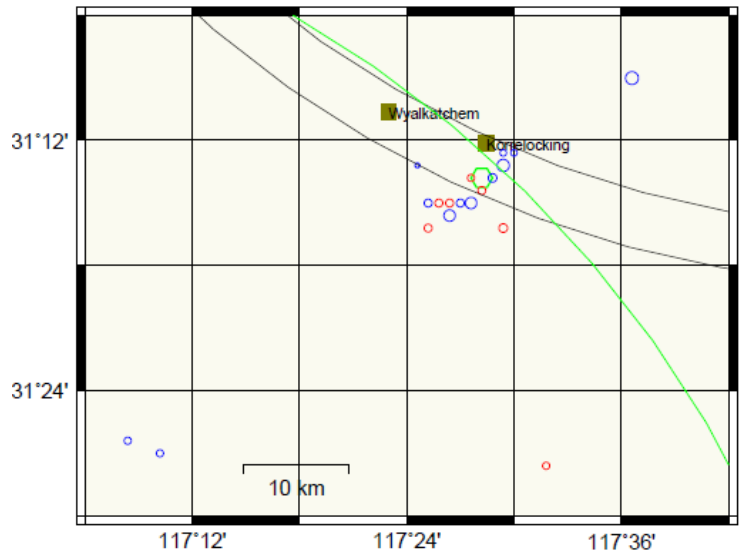


Figure 2 Grey radii are 91 & 96 km from Beacon, green radius = 100 km from York. Red circles – Sep/Oct 2011events, blue = Oct/Nov 2011events. green hexagon = assumed cluster centre (point I)

2 Analysis of individual clusters

2.1 Cluster 1 - SE of Wyalkatchem

This series, contains 15 located events, which, according to the GA locations, fall on a NE trending line about 12 km SE of Wyalkatchem (Figure 2). A group

of six relatively minor events (M_L's 1.8 to 2.0), occurred between 27th Sep and 2nd Oct, but the BEAC recordings suggest that a small event on 12th Sep, which GA located about 20 km to the south, was actually the first event in the sequence. Another group of events, including the largest events of the cluster (M_L's of 2.5 and 2.4) occurred between 1st Nov and 9th Nov. Two small events not located by GA were detected by the ACG net (on 27th Sep and 1st Nov).

Depths assigned by GA varied between 0 and 10 km, although, as discussed in earlier papers (e.g. Dent 2011) these depths are unreliable. Some of the events were reported as felt by the few residents of the small community of Korrelocking, about 12 km east of Wyalkatchem.

As was demonstrated for some earlier swarms in the Koorda area (Dent 2010), it is proposed that the northeast trend seen in the GA locations is due to the poor distribution of seismic stations around the events, and is not real. The S-P times on the Beacon seismograph for all the events (Appendix 3) are very similar (between 10.3 & 10.9 secs), which equates to a distance range of 91 – 96 km (Appendix 2), which is not consistent with the elongated northeast trend seen in the GA locations. S-P times recorded at the York station show the same tight grouping (11.8 – 12.5 secs, or 97-102km, Appendix 3), also supporting the conclusion that the events are closer to each other than the GA solutions suggest.

A common location for the Wyalkatchem cluster, at 31.25°S, 117.45°E, (green hexagon, Figure 2) is proposed. Most of the GA locations only need to be moved short distances (< 5 km) to be positioned at this point. There are two significant outliers (12th Sep and 1st Nov (0111 UT)), which are about 20 km distant, but the S-P's of these events at the Beacon and York stations (Appendix 3) suggest they should be co-located with the other Wyalkatchem swarm events.

2.1.2 Previous clusters near Wyalkatchem

A review of earthquake swarms in the SWSZ since 1983 (Dent, 2009) shows earthquake clusters both east (Dec 1987 – Feb 1988) and west of Wyalkatchem (Mar-May 1994). However, no field instruments were deployed then to refine the locations, and hence the GA locations are not very accurate. The 1987 cluster east of Wyalkatchem was quite substantial with numerous events over M_L 2.0. Most events were in March 1987, but a significant reactivation was noted in December 1987, with occasional events of lesser magnitude in the months in between. The best located events of the 1987 cluster were close to 31.20°S, 117.50°E , which is at the north-eastern extremity of the cluster of GA locations described here. It is possible that the 1987 swarm events occurred at locality I, the location proposed above for the 2011Wyalkatchem events.

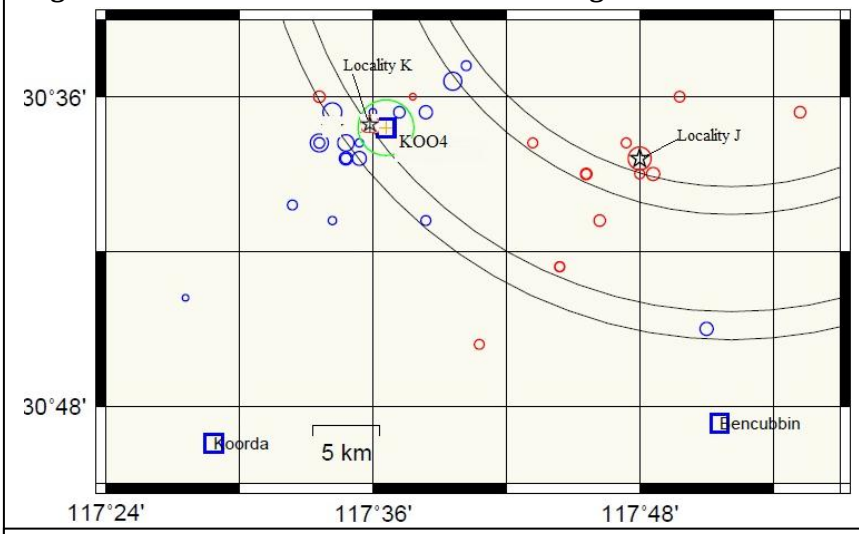
2.2 - Northwest of Bencubbin, Sep - Oct 2011

There are 14 GA-located events in the Bencubbin cluster. The series began with an M_L 3.1 event on 27th Sep and the sequence can be described as a typical main shock-aftershock cluster, as all the following events are significantly smaller.

In common with many other clusters in the region, including the Wyalkatchem swarm described above, the plot of GA locations (Figure 3**)** suggests a northeast lineation in the events. As concluded for these earlier clusters, this grouping can be attributed to the poor seismograph distribution, particularly the absence of a station to the north-east, which results in a lack of constraint in a NE direction.

The ACG station BEAC, in service since 2009, was about 40 km northwest of these events, and recorded most of them well. The S-P times at BEAC are all between 2.6 and 2.8 secs. (Appendix 3). This equates to distances between 23 to 25 km from BEAC (from Appendix 2), as plotted on Figure 3. This is strong support for the suggestion that the lineation is due to location errors.

Figure 3 Events in the Bencubbin-Koorda region



Radii shown are at 23,25,32 & 34 km from BEAC, and 2 km from KOO4. Red circles = Sep/Oct events. Blue circles = Nov/Dec events. Stars = assumed cluster centres K (left) and J (right)

S-P's at York also show a fairly narrow range from 9.3-9.7 sec., (distance range 81-85 km) although for the largest event, it seems to be 10.3 sec.

The GA locations for the two largest events of the series (M_L 3.1 and M_L 2.3) are very close to each other (~ 2km), and all of the events in this cluster have been assigned the (rounded) location of the M_L 3.1 event – i.e. 30.64°S, 117.80°E (locality J, Figure 3)

Five new, small, events which were also probably at locality "J" were also detected by the ACG network (Appendix 3).

2. 3 The Lake Mollerin swarm, Nov – Dec 2011.

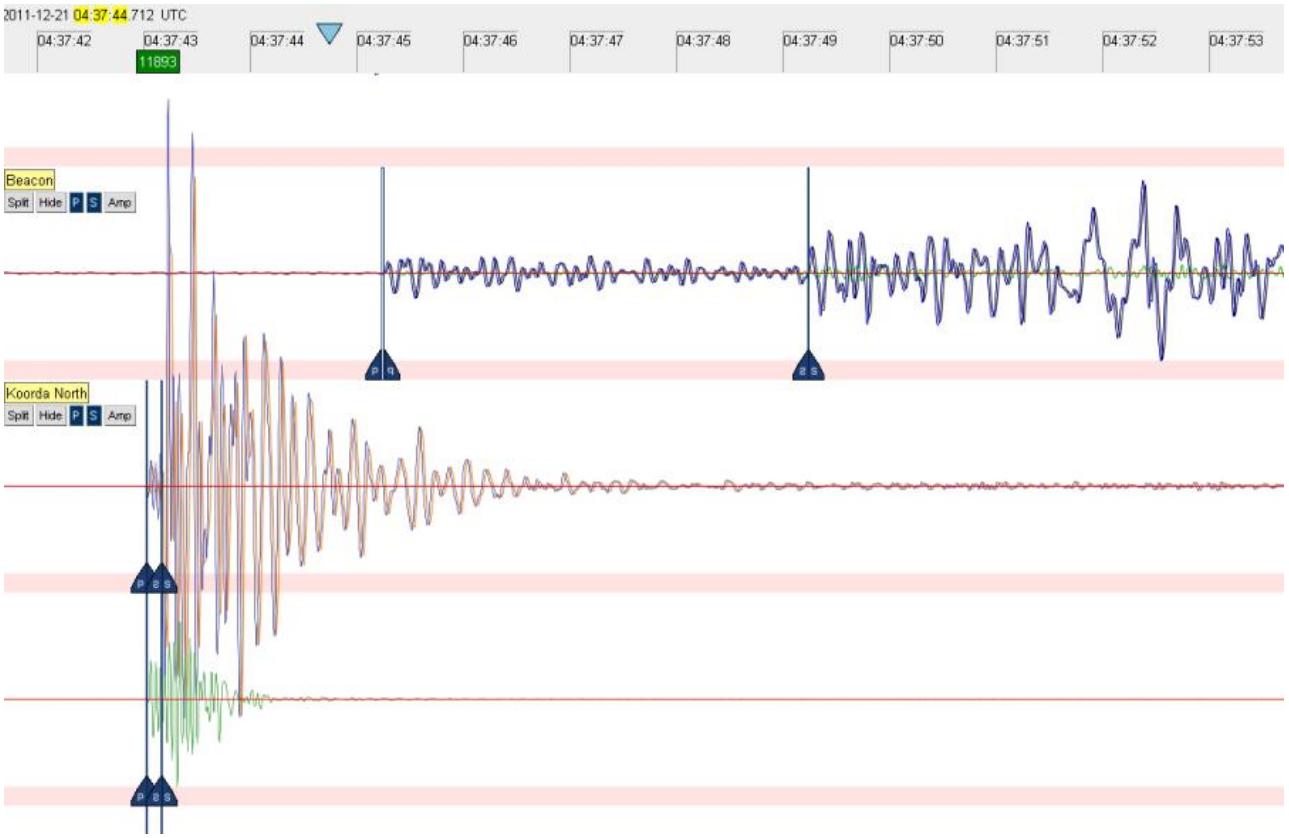
There are 19 GA-located events at this cluster location, about 20 km north of Koorda. Because the cluster is only about 10 km east of a swarm of events in 2005 (referred to in the literature as north of Koorda or N-O-K), it is proposed to call this activity the "Mollerin" swarm. The Mollerin swarm began in late October 2011 with two minor events (M_L's 1.6 & 2.2). As the swarm progressed, the severe felt effects observed at the Harrap's residence prompted them to contact the University of Western Australia. In response, a temporary seismograph (KOO4) was installed at the residence 4 days later, on 11th Nov 2011. Temporary stations KOO1–KOO3 were operated in the region by GA between 2005 and 2008, to monitor the 2005 N-O-K swarm (Dent 2010), although little useful data were obtained. Operational data for the temporary stations near Koorda are given in Table 3.

The GA locations for these events (Figure 3) are quite scattered, although the ubiquitous apparent NE-SW lineation similar to that noted in the clusters at Wyalkatchem and north of Bencubbin, is evident.

Because KOO4 was only about 1 km from the centre of the activity, it recorded many small events not seen at other stations, and has consequently provided much extra data. Some of the larger unlocated cluster events are included in Appendix 2. It is estimated that some of these have magnitudes of about M_L 2.0.

Being so close, the S-P intervals at KOO4 are extremely small, and have been measured at about 0.15 sec, with a possible range of 0.11 to 0.19 sec (Figure 4 and Appendix 3). Because of the high seismic frequencies expected, the KOO4 seismograph operated at 500 samples/sec., for extra precision.

Figure 4 –recordings of a typical Lake Mollerin swarm event at KOO4 and BEAC



The narrow range of S-P times recorded by KOO4 (Appendix 3) indicates a much tighter grouping of epicentres than the GA solutions suggest. Reference to Appendix 2(A**)** indicates that the hypocentral distances from KOO4 are between 1 and 2 km.

The event catalogue for the Mollerin swarm would have been more extensive had the KOO4 been installed earlier in the history of the swarm. Events later in the swarm may also have been missed due to periods of instrument down-time. Note that the station did not initially have GPS-controlled timing, although this is not relevant when hypocentral distances are computed using the S-P interval.

Using the extra data available from the ACG seismographs KOO4, BEAC and YORK, one of the larger events (24th Nov 0411, M_L 2.6) has been relocated using the EQLOCL earthquake location program. EQLOCL was used routinely by GA between about1990 and 2010, but the solution quoted here was made using "ANTELOPE" software. The "WA2" velocity-depth model (Dent, 1990) was used by both methods. The new "improved" solution, shown in Appendix 4 **(**30.62°S, 117.60°E) is about 3 km to the northeast of the GA location, and is about 1 km distant from KOO4 as required by the S-P interval at KOO4. The new solution also gives a good fit for the phase data from BEAC and BLDU, but many of the other phase data from slightly more distant stations do not fit the solution by

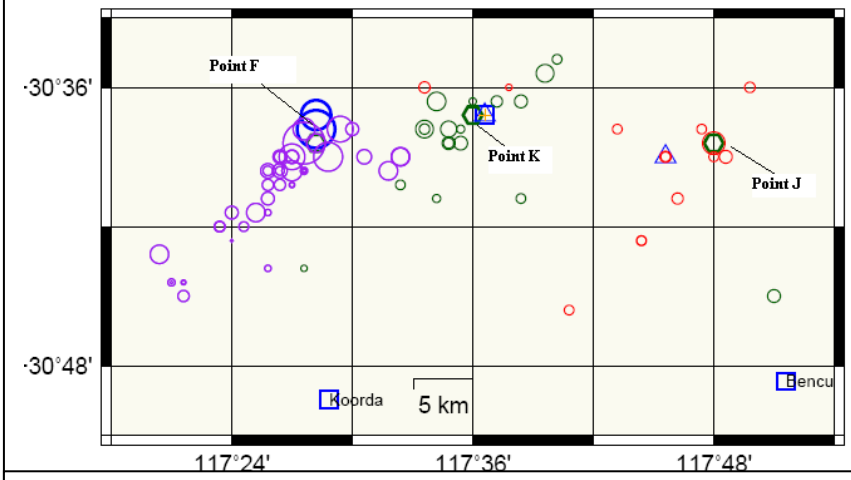
about ¾ of a second or more. This misfit is larger than might be expected for relatively close seismographs, and may indicate a need for a revised velocity-depth model for the region. Further research on this topic needs to be undertaken.

It is considered that the uncertainty in the location above is about ± 2 km, mainly due to the fact that that the very short S-P interval at KOO4 places a very tight constraint on the epicentral distance from that station. This is a very large improvement on the uncertainty in the GA location (about ± 10 km)

2.3.2 Other recent swarm activity near Koorda

The GA catalogue suggests that no previous swarm activity has been noted from the location of the Mollerin swarm, although other swarms have occurred nearby. The Mollerin swarm commenced only weeks after the north-of-Bencubbin swarm described above, and about 20 km west of it. It is also only about 15 km east of a the 2005 "North of Koorda" (N-O-K), cluster mentioned above. The 2005 epicentres (from Dent 2010) are included in Figure 5. The 2005 events were not well located, and the "streaming" of small events in a NE-SW direction is part of the common pattern attributed to the non-optimal distribution of GA seismographs around the events. The temporary stations deployed by GA to monitor the 2005 swarm had major technical problems, and did not significantly contribute to the GA locations of the events.

Figure 5 – seismicity plot of the Koorda region, including the 2005 seismic cluster



Circles: Purple = 2005 earthquake cluster. Red = Sep/Oct 2011. Blue = Nov/Dec 2011. Triangles = seismic stations. Green hexagons = source localities F, J & K.

The 2005 events, and two large ever
decimal places) are plotted on Figure 5. A common location for the 2004-05 events (and also the May 2009 event) is proposed to be at 30.64°S, 117.46°E, (locality F**).** Locality F is about 12 km from locality K (the Mollerin swarm) and this separation is considered large enough to be outside of the range of experimental error.

3 Other seismicity in the September 2011– December 2011 period

The three clusters described above represent 52 of the 73 events in Appendix 1. However, some of the remaining 21 events in Appendix 1 also show interesting correlations with seismicity of earlier years and, for completeness, will be briefly described below. The remaining seismicity has been divided into two regions – i.e.,"North", between 30° and 31° South (with 10 events), and "South", between 31° and 32° South (with 11 events).

3.1 Region North (30-31°S)

The 10 events are divided into four groups "north of Kalannie", "north of Beacon", "Cadoux-Burakin region" and "Wongan Hills".

3.1.1 ” N of Kalannie event” This was a solitary event (M_L 2.7 on 11th Oct) about 20 km north of Kalannie. This event is within 5 km of an important swarm in Sep 2005 described by Dawson et al. (2008), and it is suggested that this event is related to that series. Dawson et al (2008), using satellite imagery, were able to accurately locate the largest events of the 2005 swarm to be very close to 30.184° S, 117.170° E. This has been called locality E, (Table 2). Dent (2010) showed that smaller events in the swarm were also close to that location using data from field seismographs. Others have occasionally occurred very close to locality E since 2005.

Figure 6 – other seismicity (north)

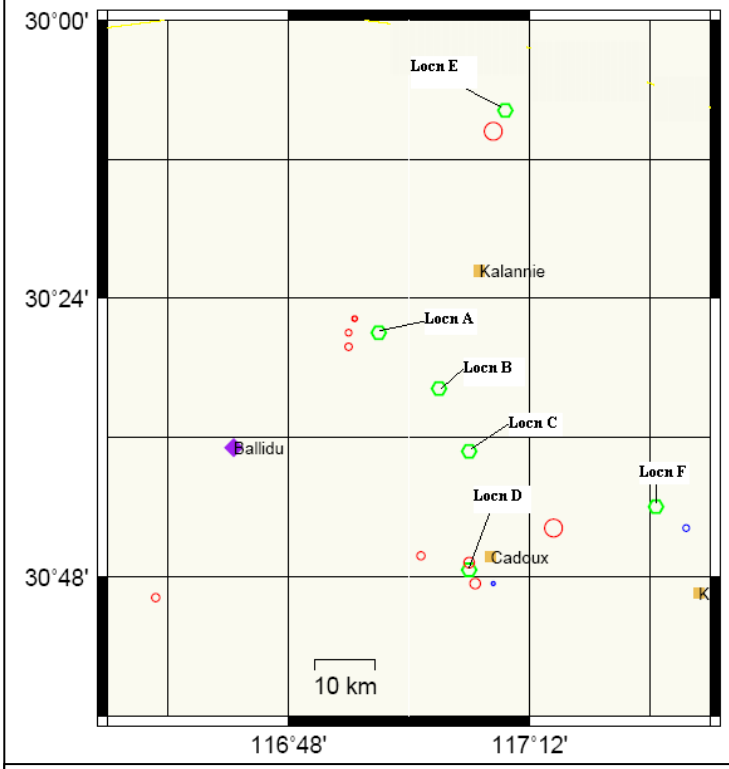


Figure 6 red circles= events Sep/Oct blue circles = events Nov/Dec green hexagons = swarm centres. blue diamond = seismic station

3.1.2 NW of Beacon. There are two small events in this area (M_L 2.0 on 4th Sept 2011and M_L 2.2 on 6th Nov) about 25 km NNW of Beacon. The later event (M_L 2.2) has an S-P of 2.8 secs, which is the same as that of the majority of the 2009 swarm events, and it is proposed to reposition this event about 4 km to the northwest of its GA location, at locality G (30.62°S 117.47°E, the assumed centre of the 2009 swarm). The earlier event (M_L 2.0) has a well-defined S-P of 3.12 secs., and may be further to the northwest of Beacon, as suggested by the GA location.

3.1.3 Events in the Cadoux-Burakin region

This region is of interest because it was a region of intense seismicity between 2000 and 2003. Leonard & Boldra (2001) defined 4 source localities (A-D, see Table 1) to encompass the Sept-Oct 2000 activity, and much of the post 2000 activity, including three $M_L \geq 5$ events, was close to their locality B.

The magnitude 2.7 event on 14th Oct does not correlate with any of their localities, but is about 15 km ENE of locality D. However, four of the smaller events Sept-Dec (29/9, 19/10, 28/10 14/11) do fall within locality D. Another 3 events (15/9, 22/9, 8/10), closely correlate with Locality A. The seven events are tentatively placed at those two locations

3.1.4 A small event (M_L 1.8) northwest of Wongan Hills on 29th Oct does not appear to be cluster-related.

3.2 South Region - (31°-32° S)

Other than the Wyalkatchem cluster events, there are 11 GA-located events in this region, the largest of which is a solitary M_L 2.4 event on 9th Sep 2011, about 12 km southwest of York. This location is

within 1 km of a swarm of events in Nov 1994. A field survey conducted at the time accurately located many relatively small events, all very close to 31.98°S, 116.72°E. It is proposed that the 2011 event (as well as numerous other events since 1994) are also at this location, (locality L Figure 7).

Figure 7 – other seismicity (south)

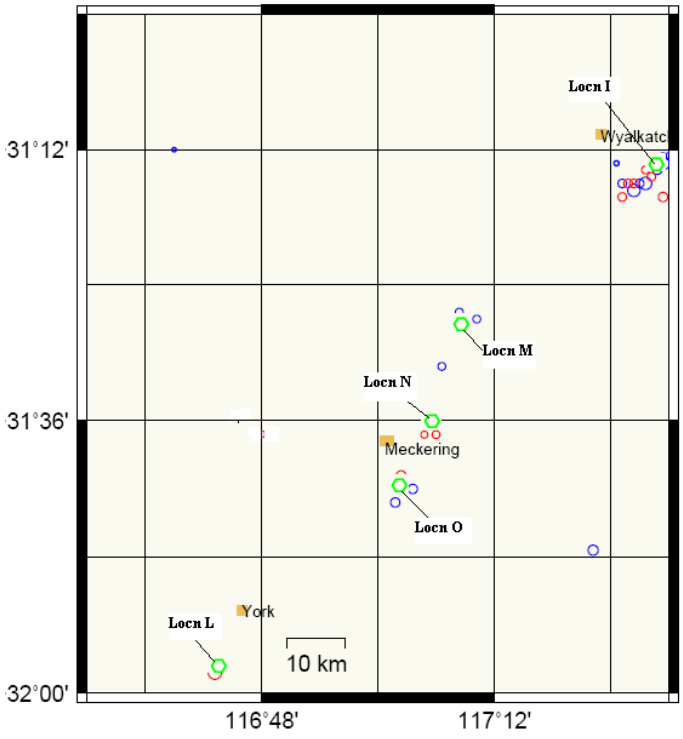


Figure 7 red circles = events Sep/Oct, blue circles = Nov/Dec

Eight of the remaining 10 events form a northeast trending line through Meckering. Considering that a known fault zone (the Meckering Fault – Gordon & Lewis,1980) goes through this area, it is to be expected that, over time, the whole fault zone will be a source of seismic events. Nevertheless, it is suggested that these remaining events can be grouped into 3 separate clusters.

Cluster M – north of Cunderdin. S-P times at York, as well as proximity in time, suggest that the events on 8 Nov at 20:29, 9th Nov at 20:56 and 16th Nov at15:05 are linked, and a common location at 31.45°S, 117.15°E (Locality M) is proposed.

Cluster N – Near Meckering. The two events 8th Sep and 22nd Oct are close in space and time, and a common location at 31.62°S, 117.08°E (Locality N) is proposed.

Cluster O – south of Meckering. This proposed cluster contains 3 events (10th Oct, 25th Dec and 28th Dec) and a common location at 31.70°S, 117.04°E (Locality O) is proposed.

The remaining two events (8th Nov, 1930, and 23 Nov) are relatively isolated. The first is about 15 km SE of Cunderdin, but occurred only an hour before the first of the events in cluster M, north of Cunderdin, and it seems likely that this event is actually a part of this cluster. The 2nd event (23 Nov, near Bolgart) is very small (M_L 1.4) and this also casts doubt on the location accuracy. Its location does not suggest any relationship to earlier seismicity.

4 Macroseismic (felt) effects

The only events from Appendix 1 for which "felt reports" were received at UWA were the larger events of the Lake Mollerin swarm. Returns were received for 19 separate events, 11 of which were not detected by GA. These returns are summarised in Appendix 5 and annotated on Figure 3. They indicate that events of magnitude down to about M_L 1.0, and possibly less, can be detected by humans if they are close enough.

Besides reports from the Harrap's, two reports (indicating relatively minor effects) were received from a location ~7 km southwest of the epicentres. This area is very thinly populated, which severely limits the preparation of an accurate isoseismal map. Many other events were "felt", but not reported. Minor events were noted audibly, rather than being felt, and the tendency was not to report them.

However, the larger events caused genuine alarm, and the maximum Modified Mercalli intensity (MM) experienced is estimated to be at least MM V.

The information received for the largest event (27th Nov M_L 2.8), including a verbal report from a farm ~10 km north of the swarm, has allowed a rough isoseismal map to be prepared (Figure 8).

Figure 8 Isoseismal map – Lk. Mollerin event 27/11/11 @ 0621

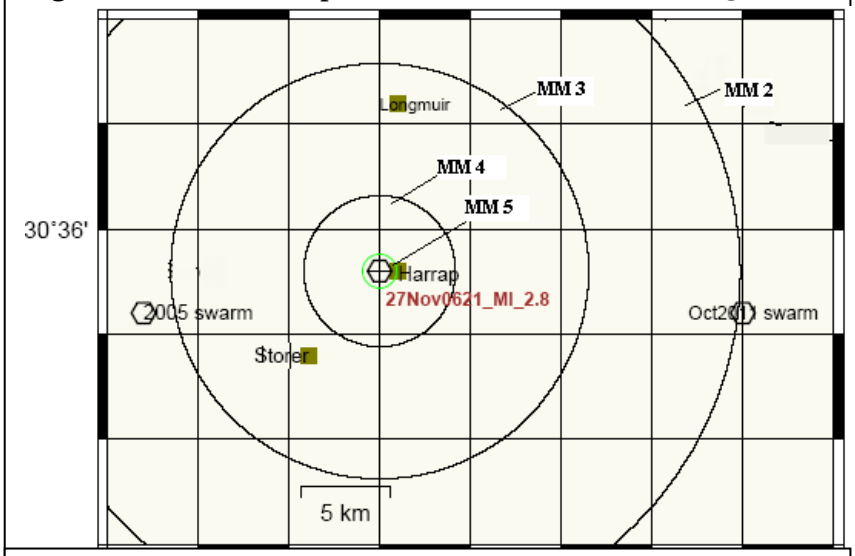


Figure 8 Isoseismal map for event 27th Nov, Ml 2..8 showing suggested modified mercalli (MM) boundaries. Hexagons = proposed swarm centres

A field trip to the area southeast of Wyalkatchem determined that some of the events in that region in Nov 2011 (max. M_L 2.5) were felt at the small community at Korrelocking, but not at Wyalkatchem itself (about 12 km WNW of Korrelocking). Because of the poor locations for the events, and the lack of felt reports near the epicentre, an isoseismal map has not been prepared. It is unlikely the events were closer than ~ 3 km to Korrelocking, because the felt effects would probably have caused significant alarm.

No felt reports were received from the cluster northwest of Bencubbin (max M_L 3.1)

5 Proposed revised seismicity map

Because of large uncertainties in locations, i.e. an estimated 10 km or more, a detailed plot of cluster events using the GA catalogue (where epicentres given to the nearest 100m) suggests unreal spatial relationships between events. The detailed S-P observations given above indicate that events in clusters are within 1-2 km of each other, rather than the diffuse clusters suggested by the GA catalogue. Therefore a new catalogue of Sep- Dec 2011 seismicity is presented (Appendix 6) where cluster events are all placed at individual locations proposed earlier in the text. The approximate distance each event has been moved is also noted. It is suggested that a plot generated from Appendix 6 (Figure 9) more realistically represents the seismicity of the region in the period Sep–Dec 2011, than the plot

Figure 9 – Seismicity map using revised locations.

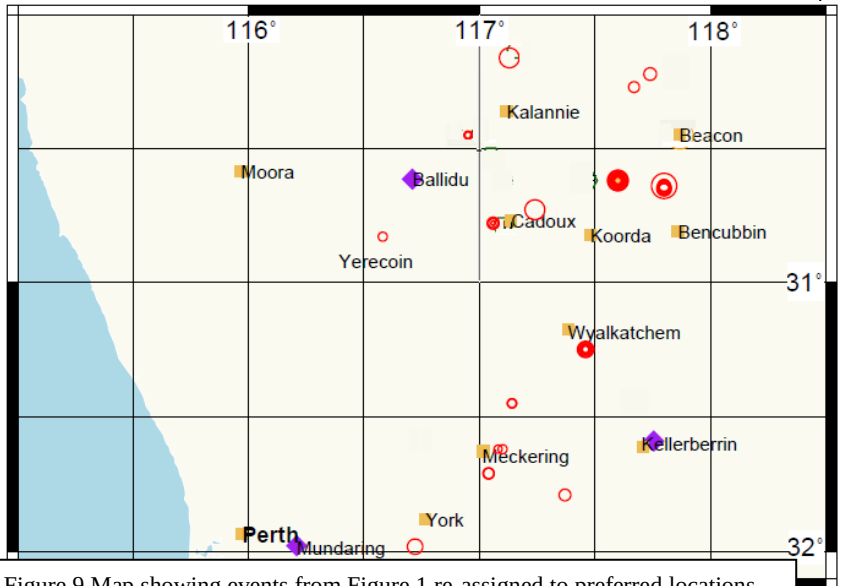


Figure 9 Map showing events from Figure 1 re-assigned to preferred locations. Green hexagons = centres not active during study period (labels as per Table 2) purple diamond = seismic station

of GA locations in Figure 1. In Figure 9, clusters appear as "bullseyes" rather than diffuse groupings of epicentres.

6 Discussion

Data from the KOO4 seismograph have shown that the Lake Mollerin swarm events are very tightly grouped in space, and that focal depths are very shallow (<2 km). This is consistent with other detailed studies of SWSZ events (e.g. Dent 2011) . S-P data from other ACG stations also suggest (but with less certainty) that events in the Wyalkatchem and north-of-Bencubbin swarms are also tightly grouped.

The north-of-Koorda swarm of 2004-05, Lake Mollerin (2011), and north-of-Bencubbin (2011) swarms are relatively close geographically (i.e. within 15 km of each other), and approximately aligned east-west (Figure 4). There is also an apparent time connection between the Lake Mollerin and north-of-Bencubbin clusters (they were only weeks apart), similar to that between clusters A-D, near Cadoux, in October 2000, where Leonard & Boldra (2001) proposed an ill-defined "rapid stress transfer" process may have occurred. However no reason behind this time-grouping or alignment is proposed here. A regional magnetic map, presented by Dent (2010) includes this area, but does not suggest any particular anomalies or structures at these locations, to indicate a cause for the seismicity.

In both the Wyalkatchem and Lake Mollerin swarms, the most significant phase occurred some weeks after an initial grouping of smaller events. This seems to be often true of swarm sequences – e.g. Burakin (2001) and Yorkrakine (1996). However, the north-of-Bencubbin cluster is more like a typical Main shock /aftershock earthquake sequence.

Of the 73 events listed in Appendix 1 (occurring between Sept & Dec 2011) it is suggested that all but five (events 1,31, 38, 54, 64 in Appendix 1) are linked to one of 11 cluster locations from Table 1 which were active during that period. Some of these events are "solitary", but linked geographically to cluster locations which were active at some time in the past. That is, over 90% of the events in Appendix 1 are cluster-related. A study of seismicity in the same general region in 2005 (Dent, 2010) found that 90% of the 160 events that occurred in 2005 were also cluster-related. This is interesting in the light of an observation by Leonard (2008), that the declustering algorithm, used to create a working catalogue to determine earthquake recurrence relationships, removed 63% of events in the SWSZ (page 1467). Leonard suggested that the declustering algorithm used was too harsh, and removed too many events, but the 2005 and 2011 observations suggest that even more events may be cluster-related than the declustering algorithm determined.

In an analysis of SWSZ seismicity for seismic risk analysis, it is likely that most, if not all events in Appendix 1 would be eliminated from the earthquake catalogue on the basis that they were either not large enough, or were "co-dependent" to some larger event. In a region such as the SWSZ, where seismic swarms seem to be possibly the "normal" expression of seismic activity, a new approach to deciding which events are "dependent" or "co-dependent" may be necessary.

The Wyalkatchem swarm may have occurred at a location which was active in 1987, suggesting that swarm locations may represent points of activity that could have been active decades ago or perhaps much longer. The Meckering region, where a magnitude 6.7 event occurred in 1968, was known to have had swarm activity soon after its settlement (i.e. early 1900s) (Everingham, 1968, Table 5). The active locality "L" southwest of York is probably the area referred to as "Talbot Brook" in Everingham (1968) where periods of intense "felt" activity occurred during the early 20th century, as well as more recent clusters in the 1990s (Dent 2009). This implies that the locations listed in Table 2

could have been the location of large earthquakes in the pre-European past, or may be at some time in the future.

The GA earthquake catalogue gives locations to 3 significant figures, i.e. to the nearest 100 m, although locations in the region typically have errors of > 10 km in latitude, longitude and depth. High-resolution earthquake plots must therefore be viewed with a degree of scepticism. It may be more useful if epicentres were given, or at least plotted, to two decimal places – i.e., to the nearest kilometre.

The data presented here lend further support to the conclusions of Dent (2010) that the northeast trend seen in the GA locations for many of the cluster groups is probably illusory, caused by an absence of recording stations to the northeast of the region.

7 Acknowledgements

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8 References

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

Dent V. F., (1990). A new crustal model for southeast Western Australia *Bur. Min. Res. Aust*. Rept. 1990/44.

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

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

Dent, V.F. (2011) – The Yorkrakine, W.A. seismic deployment, April – May 1996. *Proc. AEES 2010 Conference*, Barossa Valley.

Everingham, I. (1968). Seismicity of Western Australia, Bureau of Mineral Resources report 132.

Gordon, F. R. & Lewis, J.D. (1980). The Meckering and Calingiri earthquakes October 1968 and March 1970. West Australian Geol. Surv. Bull. 126, 229 pp.

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

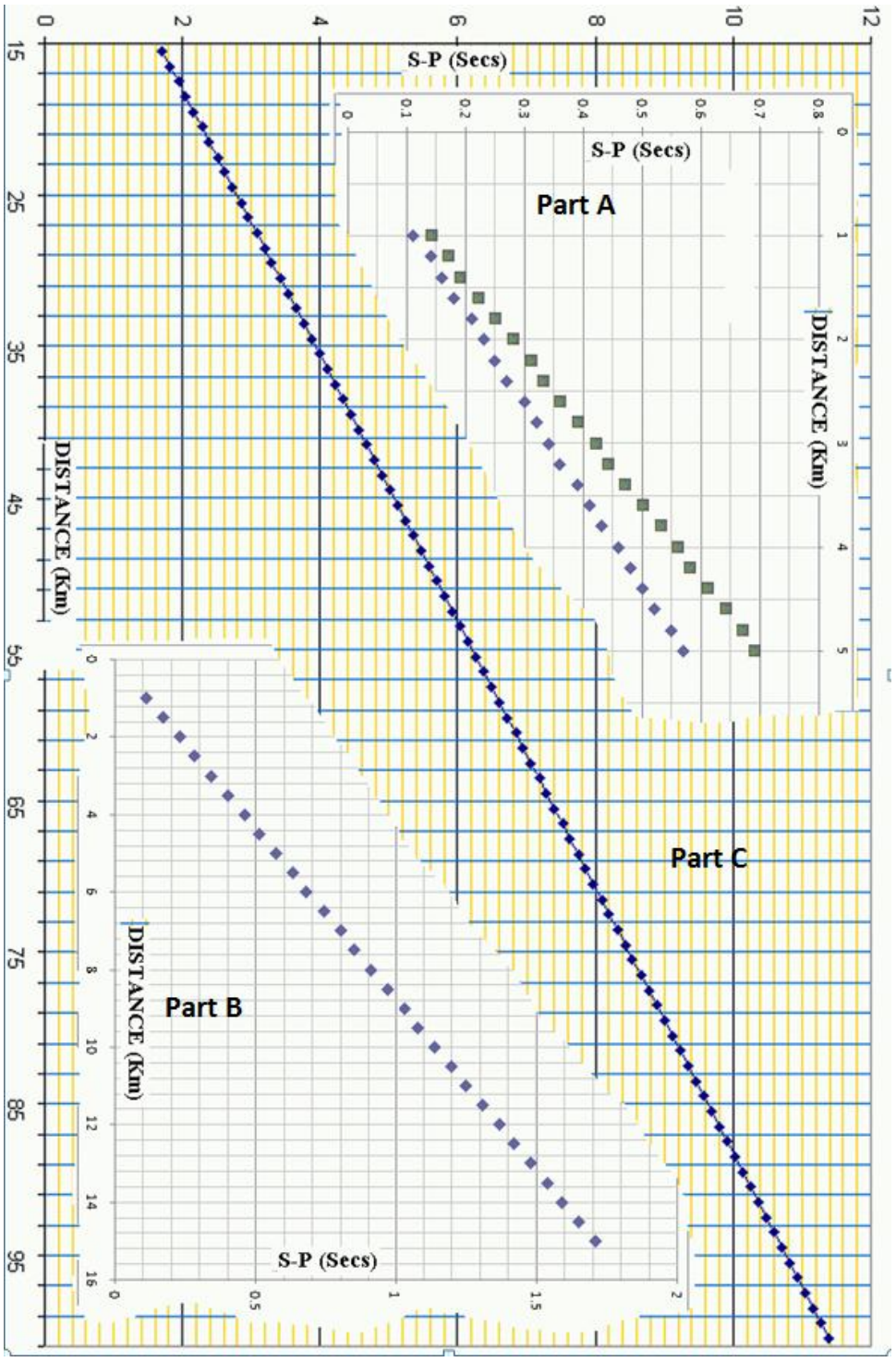
Leonard, M., (2002). The Burakin, WA Earthquake sequence Sep 2000 – Jan 2002 *Proc. AEES 2002 Conference*, Adelaide 2002.

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

Appendix 1 - GA list of events in study area, Sept – Dec 2011

Long E	Lat.S	M_L	Date & Time (UTC)	Comment	ID#	Depth(km)
117.665	30.274	2.0	04 Sep 2011 @ 02:52:25	NW of Beacon,	1	0
117.098	31.617	1.8	08 Sep 2011 @ 15:09:08	Near Meckering	2	5
116.718	31.973	2.4	09 Sep 2011 @ 23:12:33	NW of York,	3	0
117.526	31.456	1.8	12 Sep 2011 @ 17:08:03	NW of Kellerberrin,	4	0
116.896	30.446	1.6	15 Sep 2011 @ 14:03:41	NE of Ballidu	5	0
116.903	30.474	1.7	22 Sep 2011 @ 22:07:03	NE of Ballidu	6	12
117.493	31.274	2.0	27 Sep 2011 @ 16:09:15	SE of Wyalkatchem	7	3
117.800	30.642	3.1	27 Sep 2011 @ 19:13:38	SW of Beacon,	8	2
117.769	30.678	2.2	27 Sep 2011 @ 22:17:17	SW of Beacon,	9	10
117.761	30.651	2.2	28 Sep 2011 @ 22:38:03	SW of Beacon,	10	0
117.834	30.599	2.1	29 Sep 2011 @ 02:08:14	SW of Beacon,	11	10
117.719	30.627	2.0	29 Sep 2011 @ 02:16:54	SW of Beacon,	12	10
117.022	30.772	1.8	29 Sep 2011 @ 03:27:46	Cadoux,	13	10
117.473	31.242	1.9	01 Oct 2011 @ 17:17:10	SE of Wyalkatchem	14	0
117.675	30.757	2.0	02 Oct 2011 @ 14:21:12	NW of Bencubbin,	15	6
117.455	31.234	1.8	02 Oct 2011 @ 15:10:56	SE of Wyalkatchem	16	7
117.440	31.248	1.9	02 Oct 2011 @ 18:52:31	SE of Wyalkatchem	17	1
117.431	31.247	1.9	02 Oct 2011 @ 19:41:48	SE of Wyalkatchem	18	5
117.418	31.273	1.9	02 Oct 2011 @ 21:54:42	SE of Wyalkatchem	19	0
117.789	30.633	2.0	04 Oct 2011 @ 12:24:24	SW of Beacon,	20	0
117.917	30.608	2.2	05 Oct 2011 @ 12:10:49	S of Beacon,	21	0
117.755	30.649	2.0	06 Oct 2011 @ 14:22:33	SW of Beacon,	22	11
117.735	30.708	2.0	06 Oct 2011 @ 15:08:22	SW of Beacon,	23	1
117.799	30.647	2.0	06 Oct 2011 @ 15:11:06	SW of Beacon,	24	2
117.736	30.71	2.0	06 Oct 2011 @ 15:16:14	SW of Beacon,	25	12
116.911	30.426	1.5	08 Oct 2011 @ 04:01:51	SW of Kalannie	26	0
117.038	31.68	2.0	10 Oct 2011 @ 00:17:02	Meckering,	27	0
118.560	31.20	2.1	10 Oct 2011 @ 09:28:39	Near Westonia,-OUTSIDE		15
117.135	30.161	2.7	11 Oct 2011 @ 21:22:23	N of Kalannie	29	11
118.894	31.459	2.4	13 Oct 2011 @ 16:19:46	E of Merredin OUTSIDE		16
117.236	30.734	2.7	14 Oct 2011 @ 05:20:15	Near Cadoux,	31	4
117.814	30.651	2.3	18 Oct 2011 @ 15:00:35	SW of Beacon,	32	4
117.103	30.782	2.1	19 Oct 2011 @ 02:22:24	Cadoux,	33	8
117.078	31.619	1.7	22 Oct 2011 @ 13:48:16	NE of Meckering,	34	12
117.625	30.60	1.6	26 Oct 2011 @ 05:46:27	SW of Beacon,	35	0
117.563	30.599	2.2	27 Oct 2011 @ 20:13:34	NE of Cadoux,	36	10
117.110	30.805	2.1	28 Oct 2011 @ 21:00:02	Cadoux,	37	0
116.577	30.833	1.8	29 Oct 2011 @ 10:16:01	NW of Wongan Hills,	38	0
117.611	31.151	2.5	01 Nov 2011 @ 01:11:42	Near Wyalkatchem	39	10
117.460	31.246	2.3	01 Nov 2011 @ 02:40:47	Wyalkatchem,	40	9
117.479	31.225	2.0	01 Nov 2011 @ 04:38:14	Wyalkatchem,	41	8
117.486	31.222	2.4	01 Nov 2011 @ 05:27:14	Wyalkatchem,	42	10
117.412	31.217	1.5	03 Nov 2011 @ 18:21:34	Wyalkatchem,	43	0
117.599	30.613	1.7	03 Nov 2011 @ 19:55:04	NE of Koorda,	44	1
117.845	30.75	2.3	04 Nov 2011 @ 19:32:52	N of Bencubbin	45	0
117.492	31.21	1.7	05 Nov 2011 @ 08:10:55	E of Wyalkatchem	46	0
117.499	31.212	1.7	06 Nov 2011 @ 03:19:31	SE of Wyalkatchem	47	2
117.810	30.261	2.2	06 Nov 2011 @ 18:50:08	N of Beacon,	48	10
117.668	30.583	2.0	07 Nov 2011 @ 12:47:37	SW of Beacon,	49	10
117.636	30.605	2.3	07 Nov 2011 @ 13:38:37	SW of Beacon,	50	15
117.579	30.636	2.3	08 Nov 2011 @ 10:54:01	NE of Koorda,	51	0
117.616	30.605	2.2	08 Nov 2011 @ 14:58:22	NE of Koorda,	52	0
117.586	30.634	1.8	08 Nov 2011 @ 16:54:40	NE of Koorda,	53	13
117.366	31.787	2.1	08 Nov 2011 @ 19:30:15	SE of Cunderdin,	54	0
117.114	31.521	1.8	08 Nov 2011 @ 20:29:55	NE of Meckering	55	8
117.440	31.257	2.3	09 Nov 2011 @ 02:33:07	Wyalkatchem,	56	0
117.415	31.247	1.9	09 Nov 2011 @ 08:50:49	Wyalkatchem,	57	6
117.583	30.636	2.1	09 Nov 2011 @ 13:38:41	NE of Koorda,	58	3
117.171	31.45	1.8	09 Nov 2011 @ 20:56:50	NE of Meckering	59	1
117.447	31.254	1.9	11 Nov 2011 @ 20:25:22	SE of Wyalkatchem,	60	0
115.684	29.66	1.9	13 Nov 2011 @ 02:52:48	Yarra Yarra Lakes-OUTSIDE		0
117.139	30.806	1.3	14 Nov 2011 @ 02:10:25	S of Cadoux,	62	0
117.138	31.442	1.8	16 Nov 2011 @ 15:05:36	NE of Meckering	63	10
116.652	31.204	1.4	23 Nov 2011 @ 16:42:57	NE of Bolgart,	64	2
117.578	30.626	2.6	24 Nov 2011 @ 04:11:48	NE of Koorda,	65	10
117.586	30.636	2.4	24 Nov 2011 @ 04:21:09	NE of Koorda,	66	4
117.459	30.729	1.6	24 Nov 2011 @ 06:58:18	N of Koorda,	67	0
117.572	30.61	2.8	27 Nov 2011 @ 06:21:00	Near Koorda,	68	0
117.564	30.625	2.1	27 Nov 2011 @ 06:37:42	Near Koorda,	69	0
117.56	30.633	2.7	27 Nov 2011 @ 06:54:25	Near Koorda,	70	0
117.536	30.668	2.0	27 Nov 2011 @ 16:20:42	Near Koorda,	71	0

117.656	30.586	2.7	28 Nov 2011 @ 02:27:42	NE of Koorda,	72	18
117.639	30.684	2.0	21 Dec 2011 @ 04:37:37	SW of Beacon,	73	0
117.571	30.678	1.8	22 Dec 2011 @ 11:31:02	NE of Koorda,	74	2
117.031	31.722	2.0	25 Dec 2011 @ 20:08:19	Meckering,	75	8
117.057	31.702	2.0	28 Dec 2011 @ 17:05:20	SE of Meckering	6	11



Appendix 2 (A) S-P range 0.1 secs to 0.7 secs (Green dots Vp = 5.0, blue dots Vp = 6.1)
Appendix 2 (B) S-P range 0.1 secs to 1.7 secs (Vp=6.1**)**

Appendix 2 (C) S-P range 1.7 secs to 11.5 secs. (Vp=6.1)

Appendix 3 S-P and M_L data scaled from ACG stations, Sep – Dec 2011

UTC	M_L (GA)	S-P BEAC	M_L BEAC	S-P YORK	M_L YORK	S-P KOO4	M_L KOO4	Locality	Comment
04-Sep 0252	2.0	3.12	ml 2.9	--				G	NW of Beacon
08-Sep 1509	1.8	--	--	5.2	ml 1.7			M	E of Meckering
09-Sep 1244	NL*	1.28	ml 2.6						W of Beacon?
09-Sep 2312	2.4	20.2	ml 3.9	1.14	ml 2.7			L	York
12-Sep 1708	1.8	10.8	ml 3.1					I	Wyalkatchem
15-Sep 1403	1.6	10.7	ml 2.8	17.7	ml 1.7			A	NE of Ballidu
22-Sep 2207	1.7	(11.5)	ml 2.5					A	NE of Ballidu
27-Sep 1555	NL	10.96	ml 3.2	11.8	ml 2.3			I	Wyalkatchem
27-Sep 1609	2.0	10.63	ml 2.9	11.8	ml 2.2			I	Wyalkatchem
27-Sep 1912	NL	2.7	ml 2.2					J	Bencubbin
27-Sep 1913	3.1	2.72	ml 4.4	10.3	ml 3.5			J	Bencubbin main shock
27-Sep 2217	2.2	2.77	ml 2.2	--	(ml2.2?)			J	Bencubbin
28-Sep 2238	2.2	2.71	ml 3.3	9.7	2.8			J	Bencubbin
29-Sep 0208	2.1	2.69	ml 2.9	--	--			J	Bencubbin
29-Sep 0216	2.0	2.68	ml 2.8	--	--			J	Bencubbin
29 Sep 0327	1.8	--	--	--	--			Z	Cadoux
01-Oct 1717	1.9	10.54	ml 2.7	12.5	ml 1.8			I	Wyalkatchem
02-Oct 1421	2.0	2.63	ml 2.6	--	ml 2.2			J	Bencubbin
02-Oct 1510	1.8	--	--	11.84	ml 1.6			I	Wyalkatchem
02-Oct 1852	1.9	10.7	ml 2.4	12.6	ml 1.7			I	Wyalkatchem
02-Oct 1941	1.9	--	--	11.67	ml 1.2			I	Wyalkatchem
02-Oct 2154	1.9	--	--	--	--			I	Wyalkatchem
04-Oct 1224	2.0	2.68	ml 2.5	12.52	ml 1.8			J	Bencubbin
05-Oct 1210	2.2	2.77	ml 2.6	9.4	ml 2.3			J	Bencubbin
05-Oct 1702	NL	2.78	ml 2.3	--	--			J	Bencubbin
05-Oct 1704	NL	2.64	ml 2.0	--	--			J	Bencubbin
06-Oct 1422	2.0	2.77	ml 2.6	--	ml 2.5			J	Bencubbin
06-Oct 1508	2.0	2.77	ml 2.9	9.6	ml 2.4			J	Bencubbin
06-Oct 1511	2.0	2.77	ml 3.3	9.75	ml 2.3			J	Bencubbin
06-Oct 1516	2.0	2.8	ml 3.0	9.24	ml 2.5			J	Bencubbin
06-Oct 1605	NL	2.8	ml 2.1	--	--			J	Bencubbin
06-Oct 1606	NL	(ml 2.1)		--	--			J	Bencubbin
08-Oct 0401	1.5	--	--	--	--			E	Kalannie
10-Oct 0017	2.0			4.12	ml 2.4			N	Meckering
11-Oct 2122	2.7	8.6	ml 4.4	24.2	ml 3.1			E	Kalannie
14-Oct 0520	2.7	8.9	ml 4.6	15.1	ml 3.8			Z	Cadoux
18-Oct 1500	2.3	2.75	ml 3.5	9.48	ml 2.6			J	Bencubbin
19-Oct 0222	2.1	9.24	ml 3.7	--	ml 2.7				Cadoux
22-Oct 1348	1.7	--	--	--	--			M	Meckering
26-Oct 0546	1.6	(3.93)						K	Koorda
27-Oct 2013	2.2	3.87	3.8	--	--			K	Koorda
28-Oct 2100	2.1	9.17	ml 3.7	14.94	ml 2.8			C	Cadoux
29-Oct 1016	1.8	--	--	13.8	ml 2.3			M	Wongan Hills
01-Nov 0111	2.5	10.4	ml 3.9					I	Wyalkatchem
01-Nov 0240	2.3	10.39	ml 3.8	11.9	ml 3.2			I	Wyalkatchem
01-Nov 0438	2.0	10.3	ml 3.5					I	Wyalkatchem
01-Nov 0527	2.4	10.53	ml 3.8	11.83	ml 3.1			I	Wyalkatchem
01-Nov 0610	NL	10.6	ml 4.0	12	ml 3.3			I	missed by GA -big!
03-Nov 1821	1.5	10.8	ml 1.9					I	Wyalkatchem
03-Nov 1955	1.7	3.84	ml 3.0					K	Koorda
04-Nov 1932	2.3	u/s	u/s					J	N of Bencubbin
05-Nov 0810	1.7	u/s	u/s					I	Wyalkatchem
06-Nov 0319	1.7	u/s	u/s					I	Wyalkatchem
06-Nov 1850	2.2	2.81	ml 3.3					G	N of Beacon
07-Nov 1247	2.0	u/s	u/s					K	Koorda FELT
07-Nov 1338	2.3	3.81	ml 3.4	18.6	ml 2.5			K	Koorda FELT
08-Nov 1042	NL	--	--	18	ml 2.6			K	Koorda felt
08-Nov 1054	2.3	--	--	18.39				K	Koorda felt
08-Nov 1458	2.2	--	--	18.65				K	Koorda
08-Nov 1654	1.8	--	--	17	ml 1.6			K	Koorda
08-Nov 1930	2.1	--	--	unclear					Cunderdin
08-Nov 2029	1.8	--	--	unclear				L	Cunderdin
09-Nov 0233	2.3	10.5	ml 3.6					I	Wyalkatchem

09-Nov 0850	1.9	10.5 ml 3.2						I	Wyalkatchem
09-Nov 1338	2.1	3.89 ml 3.3						K	Koorda
09-Nov 2056	1.8	15	ml 3.2	7	ml 1.8				Cunderdin
11-Nov 1118	NL					0.16	4.4	K	Koorda
11-Nov 1250	NL					0.13		K	Koorda too small?
11-Nov 2025	1.9	10.9	2.6	12.1	1.9	6.8		I	Wyalkatchem
12-Nov 1146	NL	(---)	1.8			0.124	1.7	K	Koorda
12-Nov 1323	NL	3.85	2			0.12	2.0	K	Koorda
13-Nov 1331	NL	3.6	1.7			0.146	1.5	K	Koorda
13-Nov 1521	NL	(---)	1.5			0.142	1.4	K	Koorda
13-Nov 1551	NL	(---)	1.7			0.112	1.8	K	Koorda
14-Nov 0210	1.3	9.5	ml 2.5		6.0	2.2			Cadoux
14-Nov 0334	NL					0.11	1.7	K	Koorda
14-Nov 1208	NL	3.7	ml 1.6			0.176	2.2	K	Koorda
15-Nov 2107	NL			unclear				K	Koorda
16-Nov 1505	1.8	--	--	7.2	ml 1.5			L	Cunderdin
16-Nov 1601	NL	--	--	7.3	ml 1.5	11.0		L	Cunderdin
16-Nov 1617	NL	--	--	(6.6)	ml 1.4			L	Cunderdin
16-Nov 1628	NL					0.15	1.0	K	Koorda
23-Nov 1642	1.4								Bolgart
24-Nov 0411	2.6	3.84	4.1	18.5	3.3	0.16	2.8	K	Koorda FELT
24-Nov 0421	2.4	3.73	3.9	18.9	2.7	0.17	2.8	K	Koorda
24-Nov 0658	1.6	3.8	2.6			0.15	2.3	K	Koorda
24-Nov 1245	NL					0.14	1.6	K	Koorda bit small
25-Nov 0550	NL					0.12	2.1	K	Koorda FELT
25-Nov 0554	NL	3.78	2.8			0.14	2.4	K	Koorda FELT
26-Nov 0215	NL	--	--			0.13	2.1	K	Koorda FELT
26-Nov 0252	NL							K	Koorda
27-Nov 0621	**2.8**	3.82	4.2	18.56	3.4	0.17	2.9	K	Koorda FELT
27-Nov 0623	NL							K	Koorda bit small
27-Nov 0637	2.1	3.85	3.5	18.3	2.9	0.17	2.8	K	Koorda FELT
27-Nov 0651	NL	3.84	3.3	18.4	2.6	0.15	2.7	K	Koorda FELT
27-Nov 0654	**2.7**	3.76	4.1	18.4	3.3	0.15	2.9	K	Koorda **FELT**
27-Nov 1020	NL	--	2.3			0.17	2.2	K	Koorda
27-Nov 1620	2.0	3.89	3.1	18.14	2.4	0.13	2.6	K	Koorda FELT
27-Nov 2350	NL	--	--			0.16	2.3	K	Koorda FELT
28-Nov 0020								K	Koorda
28-Nov 0227	**2.7**	3.8	4.1	18.6	3.3	0.14	--	K	Koorda FELT (Clip)
28-Nov 2257	NL	--	--			0.13	2	K	Koorda
01-Dec 0252	NL	--	--			0.12	2.3	K	Koorda FELT
01-Dec 0611	NL	--	--			0.15	2.2	K	Koorda FELT
05-Dec 1435	NL	--	--			0.14	1.9	K	Koorda
12-Dec 0650	NL	3.77	1.9			0.18	0.9	K	Koorda
16-Dec 1049	NL	--	--			0.15	0.5	K	Koorda FELT
17-Dec 1738	NL	8.9	2.8			6.4	1.0		Nth of Cadoux?
19-Dec 1734	NL	3.95	2.7			0.2	1.5	K	Koorda
20-Dec 1148	NL	3.95	3.3			0.11	2	K	Koorda
21-Dec 0437	2.0	4.01	3			0.15	2.1	K	Koorda
22-Dec 1131	1.8	3.95	2.9			0.16	2.9	K	Koorda
23-Dec 2020	NL	4.05	1.8			0.15	1.1	K	Koorda
25-Dec 2008	2.0	18.2	4			14.4	2.2	O	Meckering
26-Dec 2052	NL	3.9	2.5			0.16	1.2	K	Koorda
28-Dec 1705	2.0	17.82	3.7			14.21	1.9	O	Meckering

Annotations

NL == Not Located by GA

u/s = out of service

Locality = locality as in Table 2.

--- indicates a station was recording, but data could not be read.

Appendix 4 Revised EQLOCL solution for KOORDA event, Ml 2.8 , 24th Nov @ 0411 UTC

```
Date            2011-11-24
Origin Time     0411 47.28    +    0.33
Zone                  50
Easting            557.53     +    4.00              Longitude     117.600
Northing          6612.10     +    7.22              Latitude      -30.622
Depth                1.10     +    4.24

Arrival times    =  6           S.D. = 0.020         Seismographs =  4
Nearest recorder =    1.0 km    Gap  = 143.0 deg     Accuracy = B
Effects Code     =              Imax =  0            Fault =

   1 km  N (339 deg) of  KOO4
WESTERN AUSTRALIA
 222 km NE ( 49 deg) of PERTH
  26 km NE ( 27 deg) of Koorda

No magnitudes known                                 Assign ML  2.6
```

DATA USED

Code	Wave	AT	+	WT	CT	DT	Dist	Azim	Ad	Ae
KOO4	S-P	0.17	0.01	2.66	0.20	-0.03	1.0	159	0.0	0.0
KOO4	P	47.65	0.01	2.66	47.64	0.01	1.0	159	54.3	54.3
BEAC	P	53.05	0.03	1.76	53.05	-0.00	32.0	53	-36.7	36.7
BEAC	S	56.89	0.05	1.43	56.90	-0.01	32.0	53	-27.7	27.7
BLDU	P	61.92	0.10	1.28	61.95	-0.03	85.4	270	-38.8	38.8
MUN	P	79.93	0.10	1.19	79.92	0.01	200.3	220	-52.0	52.0
				6 times used, S = 0.020						
Deferred Data										
BEAC	S-P	3.90	0.05	1.59	3.85	0.05	32.0	53	0.0	0.0
BLDU	S	71.93	5.00	0.53	72.10	-0.17	85.4	270	-27.7	27.7
KLBR	P	66.92	0.10	1.25	65.68	**1.24**	108.4	172	-38.8	38.8
KLBR	S	77.93	0.50	0.82	78.64	-0.71	108.4	172	-29.4	29.4
YORK	S-P	18.50	0.50	0.88	19.26	-0.76	162.0	209	0.0	0.0
YORK	P	73.81	0.05	1.39	74.36	-0.55	162.0	209	-38.8	38.8
YORK	S	92.31	0.05	1.25	93.62	**-1.31**	162.0	209	-29.4	29.4
MUN	S	102.96	0.50	0.77	103.74	-0.78	200.3	220	-45.7	45.7
MORW	P	83.94	0.10	1.17	83.58	0.36	228.9	318	-52.0	52.0
MORW	S	109.96	0.50	0.76	110.16	-0.20	228.9	318	-45.7	45.7

Appendix 5 Summary of felt report data received at UWA, Nov – Dec 2011

Date/time(UTC)	7 Nov 12:47	7 Nov 13:38	24 Nov 04:11	25 Nov 05:50	25 Nov 05:54
Magnitude*	Ml 2.0	Ml 2.3	ML 2.6	M(A) 1.1	M(A) 1.5
Reported by	Harrap	Harrap	Harrap	Harrap	Harrap
ground shake	strong	strong	violent	moderate	moderate
your reaction	excitement	somewhat fr	somewhat fr	very little	excitement
urge to run	not at all	not at all	not at all	not at all	not at all
awakened	not applic	not applic	not applic	not applic	not applic
felt in comm	no one	no one	a few	no one	no one
frightened	no one	no one	no one	no one	no one
rattled	a few	strongly	strongly	slightly	slightly
pictures	not displ	not displ	not displ	not displ	not displ
damage	no damage	no damage	no damage	no damage	hairline c
sounds	gunshot	gunshot	explosion	gunshot	thun/expl
loudness	not heard	strong	not heard	moderate	moderate
activity	sitting	sitting	inside	sitting	sitting

Appendix 5 – summary of felt report data received at UWA (continued)

Date/time(UTC)	26 Nov 02:15	27 Nov 06:21	27 Nov 06:21	27 Nov 06:37	27 Nov 06:52
Magnitude*	M(A) 1.1	Ml 2.8	Ml 2.8	Ml 2.1	M(A) 1.8
Reported by	Harrap	Harrap	Storer	Harrap	Harrap
ground shake	mild	violent	not felt	moderate	mild
your reaction	very little	excitement	very little	very little	very little
urge to run	not at all	not at all	not at all	not at all	not at all
awakened	not applic	not applic	not applic	not applic	not applic
felt in comm	no one	a few	a few	a few	a few
frightened	no one	no one	no one	no one	no one
rattled	did not r	a few topp	did not r	did not r	slightly
pictures	not displ	some fell	not displ	not displ	not displ
damage	no damage	hairline cr	no damage	no damage	no damage
sounds	explosion	big explos	thunder	explosion	explosion
loudness	moderate	strong	moderate	moderate	moderate
activity	outside	sitting	sitting	sitting	sitting

Date/time(UTC)	27 Nov 06:54	27 Nov 06:54	27 Nov 16:14	27 Nov 16:21	27 Nov 23:50
Magnitude*	Ml 2.7	Ml 2.7	M(A) 1.0	Ml 2.0	M(A) 1.2
Reported by	Harrap	Storer	Harrap	Harrap	Harrap
ground shake	strong	weak	moderate	mild	not felt
your reaction	very little	no reaction	no reaction	no reaction	no reaction
urge to run	not at all	not at all	not at all	not at all	not at all
awakened	NA	NA	everyone	every	not applic
felt in comm	a few	a few	noone	noone	noone
frightened	a few	no one	noone	noone	noone
rattled	strongly	did not r	slightly	slightly	void
pictures	not displ	not displ	not displ	not displ	not displ
damage	no damage	no damage	no damage	no damage	no damage
sounds	explosion	thunder	explosion	explosion	explosion
loudness	strong	moderate	mod	moderate	moderate
activity	sitting	sitting	sleeping	sleep	sitting

Date/time(UTC)	28 Nov 02:27	01 Dec 0255	01 Dec 0257	01 Dec 0239	1 Dec @0252	1st@0611
Magnitude*	Ml 2.7	M(A) 1.2	not GA loc	M(A) 1.0	M(A) 1.2	M(A) 1.1
Reported by	Harrap	Harrap	Harrap	Harrap	Harrap	harrap
ground shake	strong	strong	weak	mild	weak	mod
your reaction	excitement	no reaction	no reaction	very little	very litt	ve little
duration	< 5 sec	< 5 sec	< 5 sec	< 5 sec	< 5 sec	< 5 sec
urge to run	not at all	not at all	not at all	not at all	not at all	not at al
awakened	NA	NA	NA	NA	NA	NA
felt in comm	a few	no one	no one	a few	no one	a few
frightened	no one	no one	no one	no one	no one	no one
rattled	strongly	slightly	did not r	slightly	slightly	slightly
pictures	not displ	not displ	not displ	not displ	not displ	not displ
damage	no damage	no damage	no damage	no damage	no damage	no damage
sounds	explosion	explosion	gunshot	gunshot	gunshot	gunshot
loudness	strong	strong	faint	moderate	faint	moderate
activity	walking	walking	inside	sitting	sitting	sitting

* where there is no GA magnitude, an M(A), magnitude estimated from ACG stations, is given.

Appendix 6 – Events of Appendix 1 showing preferred locations and distance moved

Event#	**date/time (UTC)**	**Long.** (GA determined)	**Lat.**	**Long.** (relocation)	**Lat.**	**Mag**	**GA depth** (km)	**moved** (km)	**Site**	**Comment**
1	04 Sep 02:52:25	117.67	30.27	117.67	30.27	2.0	0	0.0	G	NW of Beacon
2	08 Sep 15:09:08	117.10	31.62	117.10	31.62	1.8	5	0.0	M	Near Meckering
3	09 Sep 23:12:33	116.72	31.97	116.72	31.98	2.4	0	0.7	L	SW of York
4	12 Sep 17:08:03	117.53	31.46	117.46	31.25	1.8	0	22	I	NW of Kellerberrin
5	15 Sep 14:03:41	116.90	30.45	116.95	30.45	1.6	0	5.4	A	NE of Ballidu
6	22 Sep 22:07:03	116.90	30.47	116.95	30.45	1.7	12	5.3	A	NE of Ballidu
7	27 Sep 16:09:15	117.49	31.27	117.46	31.25	2.0	3	4.1	I	SE of Wyalkatchem
8	27 Sep 19:13:38	117.80	30.64	117.80	30.64	3.1	2	0.0	J	SW of Beacon
9	27 Sep 22:17:17	117.77	30.68	117.80	30.64	2.2	10	4.8	J	SW of Beacon
10	28 Sep 22:38:03	117.76	30.65	117.80	30.64	2.2	0	4.0	J	SW of Beacon
11	29 Sep 02:08:14	117.83	30.60	117.80	30.64	2.1	10	5.5	J	SW of Beacon

Event#	date/time (UTC)	Long. (GA determined)	Lat.	Long. (relocation)	Lat.	Mag	GA depth (km)	moved (km)	Site	Comment
12	29 Sep 02:16:54	117.72	30.63	117.80	30.64	2.0	10	8.2	J	SW of Beacon
13	29 Sep 03:27:46	117.02	30.77	117.06	30.78	1.8	10	3.9	C	Cadoux
14	01 Oct 17:17:10	117.47	31.24	117.46	31.25	1.9	0	1.5	I	SE of Wyalkatchem
15	02 Oct 14:21:12	117.68	30.76	117.80	30.65	2.0	6	17	J	NW of Bencubbin
16	02 Oct 15:10:56	117.46	31.23	117.46	31.25	1.8	7	1.7	I	SE of Wyalkatchem
17	02 Oct 18:52:31	117.44	31.25	117.46	31.25	1.9	1	2.0	I	SE of Wyalkatchem
18	02 Oct 19:41:48	117.43	31.25	117.46	31.25	1.9	5	2.9	I	SE of Wyalkatchem
19	02 Oct 21:54:42	117.42	31.27	117.46	31.25	1.9	0	4.8	I	SE of Wyalkatchem
20	04 Oct 12:24:24	117.79	30.63	117.80	30.65	2.0	0	1.7	J	SW of Beacon
21	05 Oct 12:10:49	117.92	30.61	117.80	30.65	2.2	0	12	J	S of Beacon
22	06 Oct 14:22:33	117.76	30.65	117.80	30.65	2.0	11	4.4	J	SW of Beacon
23	06 Oct 15:08:22	117.74	30.71	117.80	30.65	2.0	1	8.8	J	SW of Beacon
24	06 Oct 15:11:06	117.80	30.65	117.80	30.65	2.0	2	0.0	J	SW of Beacon
25	06 Oct 15:16:14	117.74	30.71	117.80	30.65	2.0	12	8.9	J	SW of Beacon
26	08 Oct 04:01:51	116.91	30.43	116.95	30.45	1.5	0	4.6	A	SW of Kalannie
27	10 Oct 00:17:02	117.04	31.68	117.04	31.71	2.0	0	3.0	N	Meckering
29	11 Oct 21:22:23	117.14	30.16	117.13	30.16	2.7	11	0.5	E	N of Kalannie
31	14 Oct 05:20:15	117.24	30.73	not moved		2.7	4			Near Cadoux
32	18 Oct 15:00:35	117.81	30.65	117.80	30.65	2.3	4	1.6	J	SW of Beacon
33	19 Oct 02:22:24	117.10	30.78	117.06	30.78	2.1	8	4.3	C	Cadoux
34	22 Oct 13:48:16	117.08	31.62	117.08	31.62	1.7	12	0.0	M	NE of Meckering
35	26 Oct 05:46:27	117.63	30.60	117.6	30.62	1.6	0	3.2	K	SW of Beacon
36	27 Oct 20:13:34	117.56	30.60	117.6	30.62	2.2	10	4.3	K	NE of Cadoux
37	28 Oct 21:00:02	117.11	30.81	117.06	30.78	2.1	0	5.6	C	Cadoux
38	29 Oct 10:16:01	116.58	30.83	not moved		1.8	0			Wongan Hills
39	01 Nov 01:11:42	117.61	31.15	117.46	31.25	2.5	10	18	I	Near Wyalkatchem
40	01 Nov 02:40:47	117.46	31.25	117.46	31.25	2.3	9	0.4	I	Wyalkatchem
41	01 Nov 04:38:14	117.48	31.23	117.46	31.25	2.0	8	3.1	I	Wyalkatchem
42	01 Nov 05:27:14	117.49	31.22	117.46	31.25	2.4	10	3.8	I	Wyalkatchem
43	03 Nov 18:21:34	117.41	31.22	117.46	31.25	1.5	0	5.8	I	Wyalkatchem
44	03 Nov 19:55:04	117.60	30.61	117.6	30.62	1.7	1	0.7	K	NE of Koorda
45	04 Nov 19:32:52	117.85	30.75	117.80	30.65	2.3	0	11	J	N of Bencubbin
46	05 Nov 08:10:55	117.49	31.21	117.46	31.25	1.7	0	5.1	I	E of Wyalkatchem
47	06 Nov 03:19:31	117.50	31.21	117.46	31.25	1.7	2	5.4	I	SE of Wyalkatchem
48	06 Nov 18:50:08	117.81	30.26	117.74	30.22	2.2	10	8.1	G	N of Beacon
49	07 Nov 12:47:37	117.67	30.58	117.6	30.62	2.0	10	7.7	K	SW of Beacon
50	07 Nov 13:38:37	117.64	30.61	117.6	30.62	2.3	15	3.9	K	SW of Beacon
51	08 Nov 10:54:01	117.58	30.64	117.6	30.62	2.3	0	2.6	K	NE of Koorda
52	08 Nov 14:58:22	117.62	30.61	117.6	30.62	2.2	0	2.2	K	NE of Koorda
53	08 Nov 16:54:40	117.59	30.63	117.6	30.62	1.8	13	2.0	K	NE of Koorda
54	08 Nov 19:30:15	117.37	31.79	not moved		2.1	0			SE of Cunderdin
55	08 Nov 20:29:55	117.11	31.52	117.14	31.45	1.8	8	7.6	L	NE of Meckering
56	09 Nov 02:33:07	117.44	31.26	117.46	31.25	2.3	0	2.1	I	Wyalkatchem
57	09 Nov 08:50:49	117.42	31.25	117.46	31.25	1.9	6	4.5	I	Wyalkatchem
58	09 Nov 13:38:41	117.58	30.64	117.6	30.62	2.1	3	2.3	K	NE of Koorda
59	09 Nov 20:56:50	117.17	31.45	117.14	31.45	1.8	1	3.1	L	NE of Meckering
60	11 Nov 20:25:22	117.45	31.25	117.46	31.25	1.9	0	1.4	I	SE of Wyalkatchem
62	14 Nov 02:10:25	117.14	30.81	117.06	30.78	1.3	0	8.3	C	Sth of Cadoux
63	16 Nov 15:05:36	117.14	31.44	117.14	31.45	1.8	10	0.8	L	NE of Meckering
64	23 Nov 16:42:57	116.65	31.20	not moved		1.4	2			NE of Bolgart
65	24 Nov 04:11:48	117.58	30.63	117.6	30.62	2.6	10	2.3	K	NE of Koorda
66	24 Nov 04:21:09	117.59	30.64	117.6	30.62	2.4	4	2.1	K	NE of Koorda
67	24 Nov 06:58:18	117.46	30.73	117.6	30.62	1.6	0	18	K	N of Koorda
68	27 Nov 06:21:00	117.57	30.61	117.6	30.62	2.8	0	3.0	K	Near Koorda
69	27 Nov 06:37:42	117.56	30.63	117.6	30.62	2.1	0	3.6	K	Near Koorda
70	27 Nov 06:54:25	117.56	30.63	117.6	30.62	2.7	0	4.2	K	Near Koorda
71	27 Nov 16:20:42	117.54	30.67	117.6	30.62	2.0	0	8.0	K	Near Koorda
72	28 Nov 02:27:42	117.66	30.59	117.6	30.62	2.7	18	6.6	K	NE of Koorda
73	21 De 04:37:37	117.64	30.68	117.6	30.62	2.0	0	7.5	K	SW of Beacon
74	22 De 11:31:02	117.57	30.68	117.6	30.62	1.8	2	6.5	K	NE of Koorda
75	25 De 20:08:19	117.03	31.72	117.04	31.71	2.0	8	1.5	O	Meckering
76	28 De 17:05:20	117.06	31.70	117.04	31.71	2.0	11	2.0	O	Meckering