Seismicity of the Quairading area, Western Australia, with special reference to an earthquake cluster in 1992

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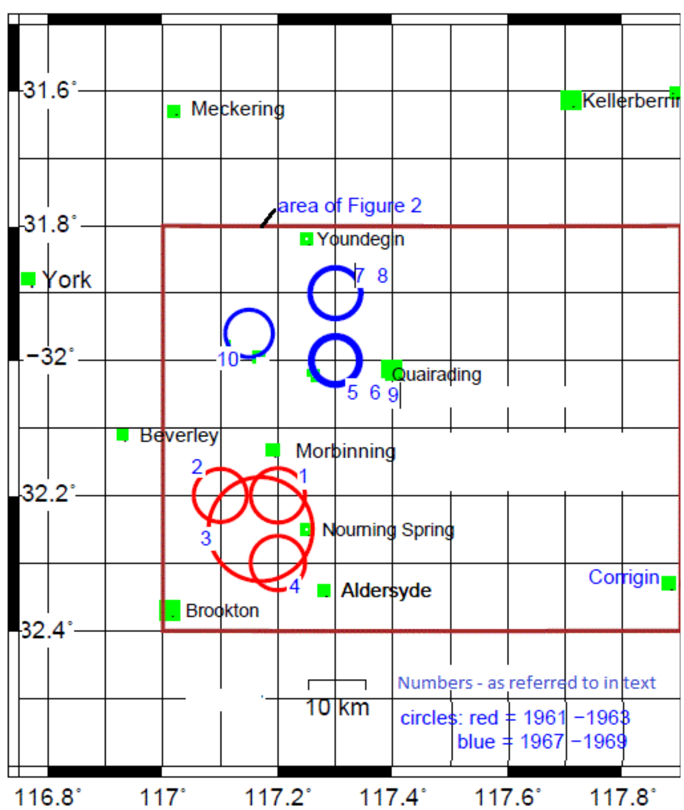
Abstract

Quairading is a small town in the wheatbelt region of Western Australia, about 140 km east of Perth, and within the South West Seismic Zone, a region of elevated intra-plate seismicity. The largest known event in the area was an ML 5.4 event about 25 km northeast of Brookton in 1963. A group of felt earthquakes west of Quairading in 1992 prompted the installation of two temporary recording instruments. The seismic environment of these earthquakes and the results of the survey are discussed in relation to the historical seismicity of the region. It is concluded that the 1992 events and many other events in the area may represent a continuation of a period of stronger seismicity recorded in the same area, which started with an ML 4.5 event in 1967. The suggested central location for the 1992 events is close to 31.98°S, 117.27°E, and, by inference, is the probable location of the larger events of 1967 and 1985.

1 Introduction

Quairading is a town of about 500 residents in the West Australian wheatbelt, about 140 km east of Perth (Figure 1). It is within a region known as the south west seismic zone (SWSZ) (Doyle, 1971). Residents at a farm north of Dubelling, about 12 km west of Quairading, experienced a group of about 40 mostly small earthquakes in early1992, the largest being an ML 3.3 event on 4th January 1992. Two seismic instruments were temporarily deployed to monitor the activity, although they missed the most active period. No specific report on this activity has been made until now. This group of earthquakes is a good example of the relatively frequent earthquake clusters which occur in the WA wheatbelt.

Figure 1 Locality Map & events ML ≥ 4.0, 1960-2018 (excluding Meckering region)



Legend, Figures 1 & 2: Circles = earthquakes (size proportional to magnitude) Squares = population centre

1.1 Seismic environment

Earthquake clusters are frequent in the SWSZ, as noted by Dent (2016). Some clusters in the SWSZ region for which reports have been published include Yorkrakine (north of Kellerberrin) in 1996 (Dent 2011), Burakin in 2002 (Leonard, 2003), northwest of Beacon in 2009 (Dent, 2009), Woodanilling (north of Katanning) in 2013 (Dent, 2014), and north of

Corrigin in 2017 (Dent & Judge, 2017). Besides these, three large earthquakes which caused surface rupturing, Meckering 1968 (Gordon & Lewis, 1980), Calingiri 1971(Gordon & Lewis, 1980) and Cadoux 1979 (Lewis et al.,1981) can also be considered as cluster events.

Dent has been reviewing the seismicity of the SWSZ in 12-monthly periods, beginning in June 2012, (eg. Dent, 2017; Dent, 2016) in an attempt to identify cluster locations, and to see how precisely in space their locations can be defined and to track their progress with time. The report for 2013-14 (Dent 2014) used five events near Morbinning to define a cluster centre, location V, renamed to location F3 in Dent (2017). A study of activity in 2012-2013 (Dent & Collins, 2018) identified a probable cluster location (E4) west of Quairading. These two locations are indicated on Figure 3 and subsequent figures. This study of Quairading events uses archival data to investigate a swarm of events west of Quairading in 1992, and other events, to see if events in the region could be attributed to single location. Events in the Morbinning area will also be reviewed. These investigations use data from Public Seismic Network (PSN) stations (Dent et al., 2010) where available, which provide extra phase arrival information to improve earthquake locations.

1.2 Earthquake Locations

All West Australian earthquake locations from 1959 to 2000 were made by the Mundaring Geophysical Observatory (MGO), a division of Geoscience Australia (GA). Initially, manual location methods and the WA1 earth model were used, but from 1991 onwards the EQLOCL (© SRC, Melbourne) earthquake location program, and the WA2 earth model were used. In 1959, Mundaring was the only station in the network. Kalgoorlie (KLG) was added in 1964, Meekatharra (MEK) in 1968, and more stations (Narrogin, Kellerberrin and Ballidu) were added following the Meckering event (October 1968) and the Cadoux event (June 1979). In 2000, the MGO closed, and all West Australian earthquake locations since then have been made by GA. In 2009 GA changed from using EQLOCL to the Antelope earthquake analysis program.

Relocations in this report

Good earthquake locations require probably 6 or more recording stations surrounding an earthquake, and for the phase arrivals to be clear. In the SWSZ this is often not the case. The PSN in southwest Australia has been expanding since ~2007 (Dent et al., 2010), and this new network has been providing additional phase arrival data. These data can be used to improve the GA locations in the region. In the study area, a PSN station was installed at the Beverley Cooperative Resource Centre (CRC) in July 2014. The station was relocated to the Quairading CRC (2015-2017) and then to a farm north of Corrigin (August 2017-present). Data from these stations, and other more distant stations in the PSN network, have been used to compute new locations for some of the epicentres in the area and they will be discussed in relevant sections of this report.

1.3 Larger events of the region (Magnitude 4.0 and above)

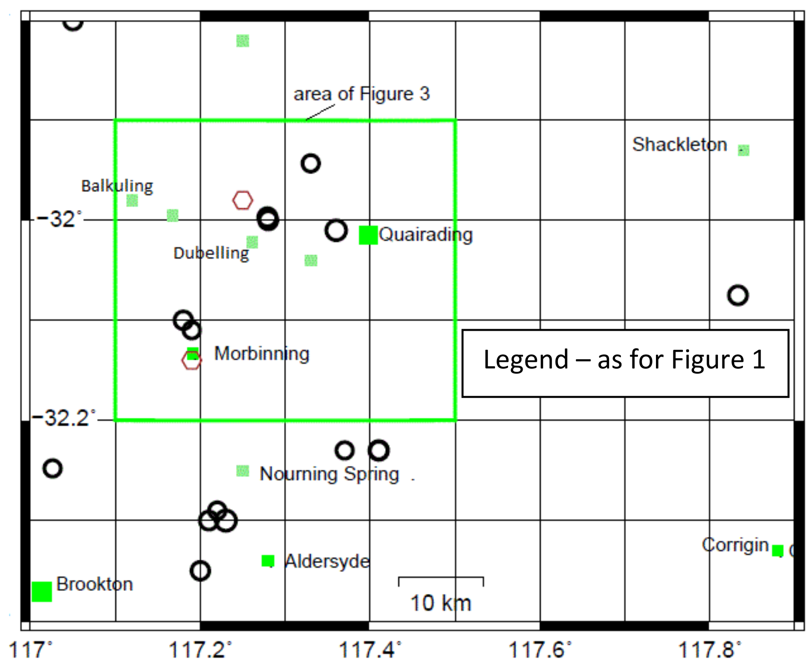
There were 10 events in the Quairading area of ML ≥ 4.0 between 1960 and 2018 (labelled 1 to 10 on Figure 1), and they were all before 1970, a period when earthquake locations were relatively unreliable. They form two groups, of 4 and 6 events. The first group was south of Morbinning (southwest of Quairading), between June 1961 and April 1963. Events 1 & 2 were both ML 4.4 (June and August, 1961). Event 3 was the “Nourning Spring” earthquake (Everingham et al., 1982) magnitude 5.4 event of 18 January 1963. It was felt at MMI VII near the epicentre, and MMI VI at Brookton, and is plotted about 5 km south of the 1961 events. Event 4 was a magnitude 4.7 event which occurred three months later. Given the poor quality of the locations, it is possible or probable that they all came from virtually the same location. A large number of smaller events accompanied these events. The GA catalogue indicates about 140 events between 1961 and 1964, but there would have been many more that were not located.

The second group of large earthquakes (6 events), was north of the previous group, and just west of Quairading, and occurred between 17 July 1967 and 01 February 1969.The first event (event 5) was an ML 4.0 event near Dangin, and events 6 & 7 occurred 5 weeks later, on 29 August 1967, (ML4.4 and ML 4.5) about 10 km north of the July event. In all probability, they are all at the same location. In the next 2 months events 8 and 9 occurred at the same location as the July 1967 event (event 5). In February 1969 event 10 occurred about 15 km west of the July 1967 events, near the abandoned town of Balkuling. Again, as with the earlier "Nourning Spring" events, it is possible that all events could have originated from a common location.

1.4 Events near Quairading, Magnitude 3.0 and above

Earthquake locations improved from about 1970, when more seismographs were in place. Events with ML≥3.0 near Quairading 1970 – 2018 are plotted on Figure 2. As indicated on Figure 1, there were no magnitude 4 events, and the largest was an event west of Quairading (ML 3.6) in 1985. The largest event of the 1992 sequence is also shown on this figure. These events are probably related to the northerly group of magnitude 4+ events of 1967-1969 shown in Figure 1. Considering location uncertainties it is reasonable to suggest that the events southwest of Nourning Spring in 1974, and to its northeast in 1984 are related to the ML 5.4 event of 1963.

Figure 2 events ML ≥ 3.0 in the greater Quairading area, 1970 – 2018



2 Data review (1991 -2018)

Events of all magnitudes in the study area shown in Figure 2, between 1991 and 2018 will be reviewed below. Events in 1992 will be examined in more detail, to see if a common location can be established. The seismicity will be studied in three periods. Period 1 covers the year of the cluster (1992) and the year either side. The second and third periods review events between 1994 – 2005, and 2006-2018 respectively. Earthquake locations in the third period can be reviewed more closely because of the addition of data from the new "PSN" network.

The original GA solutions for the period 1991-2009 (EQLOCL text outputs) have been reviewed here, allowing location quality to be assessed. Locations which used data from at least 4 seismographs, and had a low RMS of residuals (< 0.2 secs.) are assumed to be "good" locations. Some of the more relevant solutions are presented in Appendix 1.

2.1 Period 1 seismicity (1991 -1993)

A plot of events from the GA catalogue (Figure 3) shows the majority of events in the study area are near Dubelling. These are the events comprising the 1992 earthquake "swarm". There are also a few events near Morbinning, and one event about 20 km SSE of Quairading, as will be discussed in more detail below.

Events near Dubelling (1991 – 1993)

Events from the Dubelling area between 1991 and 1993, are shown in more detail in Figure 4). There were four events in 1991, all small (largest ML 2.0), and they are scattered, mostly within 5 km of Dubelling.

The 1992 events are more concentrated, at a location about 3 km north of Dubelling, and most are in the 4 weeks following the ML 3.3 event on 4th January 1992. The largest aftershock was ML 2.9 on 14th January 1992.

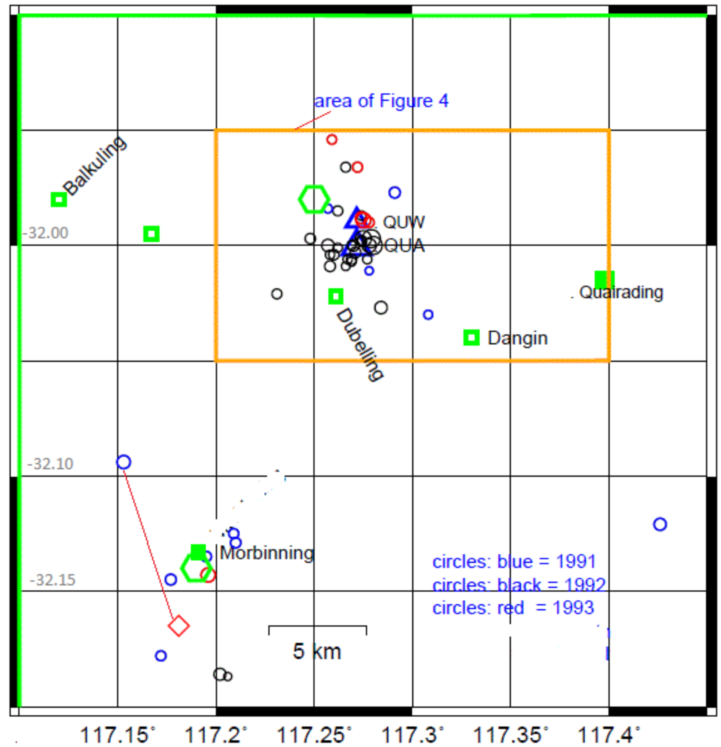
The field station deployment at Dubelling

Little has been documented about this deployment and unlike the solution data mentioned above, the data recorded by this survey have not been located. The author recalls that the deployment was in response to worried calls from the local farmer (Dave Whyte), and a Kelunji digital seismograph (code QUA) was deployed at his residence, but did not have GPS timing. An MO2 accelerograph (code QUW), without good time control, was deployed in an open field about 1 km north of QUA (Figure 3). The dates of these deployments have not been recorded. The Australian Seismological Report for 1992 (Leiba and Dent, 1994) notes that QUW recorded accelerograms for three small events.

Events of late 1992, and 1993

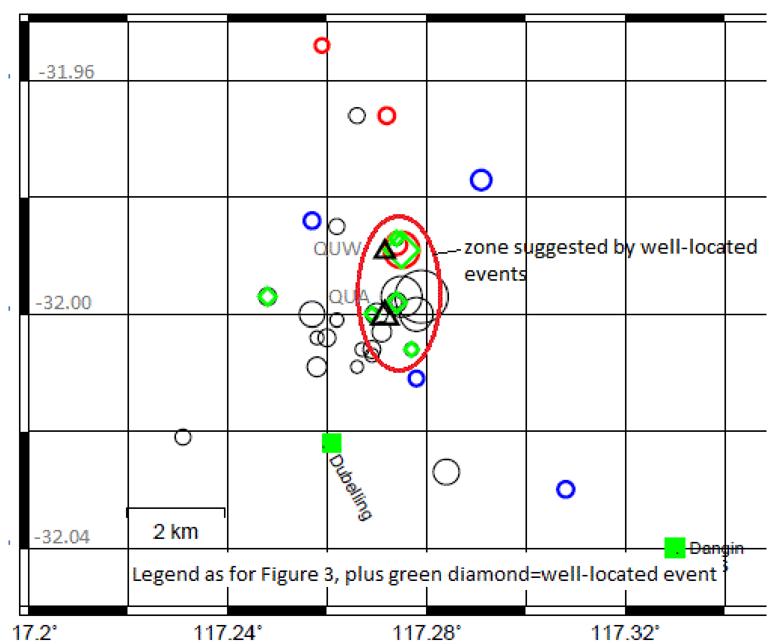
An ML 1.7 event was located near the cluster centre in November 1992. The EQLOCL solution suggests it was recorded at the QUA station, with an S-P of 0.2 secs., but the solution was poor as there were only 2 other stations used (Appendix 1). In 1993 there was an ML 2.7 event on 18 January 1993, and it had two aftershocks, with all events plotting near the cluster centre.

Figure 3 Seismicity in Period 1 Jan 1991 – Dec 1993



Legend, figures 3, 4 & 5: Circles = earthquakes (size proportional to magnitude): Squares = population centre : hexagon = cluster location: triangle = seismic station : diamond = earthquake relocation

Figure 4 Seismicity near Dubelling, Jan 1991 – Dec 1993



Discussion

Five of the EQLOCL solutions for the 1992-1993 events were found which fit the above definition of “good” locations, and these are indicated on Figure 3. Data from the QUA seismograph would help greatly in defining earthquake locations, but the outputs indicate that only two events - 4th May 1992 (ML 2.0) and 10th November1992, had QUA data (shown in Appendix 1). However, the 10th November solution does not fit the criteria for a “good” solution.

The ML 2.7 event of January 1993 is one of the “good” solutions, as it was recorded by 5 stations, and has a low RMS (0.19 sec) and it is also close to the adopted group epicentre

The plot of the best-located events (shown in Table 1 and plotted on Figure 4) could be interpreted as having a north-south lineation. However, the author feels the locations are not accurate enough for this trend to be considered real. The most probable origin for all of the events is suggested to be near the centre point of this lineation, ie, 31.998^{o}S, 117.274^{o}E.

Table 1 The best-located events near Quairading, 1991 - 1993 (RMS < 0.20)

Date/Time	Lon	Lat	Rms	dep	Mag	Phases	Comment
U.T.C.	E	Deg.	Secs	km	ML	/stns	
1992-01-12 12:22:26	117.274	-31.987	0.13	4.3	1.7	7/ 4	
1992-01-20 10:48:12	117.269	-32.000	0.14	5.1	1.7	7 /4	
1992-01-26 03:10:12	117.277	-32.006	0.15	7.3	1.7	8 /4	
1992-02-18 14:15:24	117.248	-31.997	0.12	0.9	1.9	8 /4	
1992-05-04 21:33:11	117.274	-31.998	0.17	1.1	2.0	8 /5	Has QUA arrival
1993-01-18 10:46:43	117.275	-31.989	0.19	1	2.7	10 /5	

Focal depths

The focal depths of the best locations (Table 1) vary from 1 km to 7 km, but depths are difficult to compute accurately if there are no close stations, and the computed depths are also sensitive to the earth model used. **Reference to original GA EQLOCL data shows that** the solution for the event on 5th May 1992 uses QUA, and the S-P time is 0.2 seconds. This short S-P time would indicate that the hypocentral distance is less than 2 km, and therefore the earthquake cannot be more than 2 km deep. The event in November 1992 also indicates an S-P time at QUA of 0.2 secs, suggesting this might be a common depth for the earthquakes.

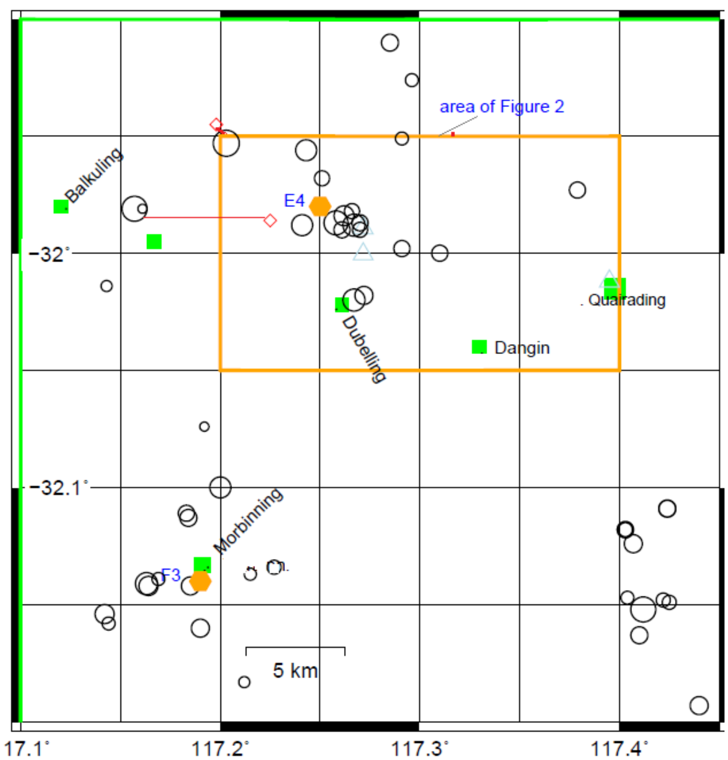
Events near Morbinning and south of Quairading, 1991 – 1993

There are 11 events in this area on Figure 3 (ie,south of 31.05 S. Most are near Morbinning, but the locations of two of the outlying events have been checked for accuracy. It was found that the location of the event south of Quairading was relatively poor (large RMS), but a better solution could not be obtained. For the event NW of Morbinning, an apparently better solution was found, just south of Morbinning (solution 1, Table 2). The concentration of events in the Morbinning area is consistent with the declaration of a cluster location there (F3, Dent, 2017).

2.2 seismicity in Period 2 (1994 – 2005)

Events in the Quairading area, from 1994 – 2005 are plotted on Figure 5. This can be interpreted as showing three groups of earthquakes **1)** a group west of Quairading and north of -32.05, **2)** a group in the Morbinning area and **3)** a group about 20 km south of Quairading.

Figure 5 seismicity in Period 2 1994 - 2005



South of Quairading

There are 10 events in this group. The largest was ML 2.5 on 12 Mar 1994, and all the others are ML 1.8 or less. In total, there were 4 in 1994, one in 1995, four in 1996, and one in 1997.There are suggested to have all come from the same location, assigned to be that of the largest event ie, 32.15°S, 117.41°E.

Morbinning area There are 14 events in this area, the largest ML 2.2 on 5 May 1998. Time-wise, they are fairly evenly spread throughout the period. They are all quite close to the Morbinning cluster centre (location F3), and it is suggested that they can all be assigned to that location.

West of Quairading

There are 22 events on this plot, mostly north of Dubelling but with a few further west near Balkuling. The largest was an ML 2.6 event

Table 2 Earthquake Relocations 1991 - 2018

#	DATE	Time UTC	Mag ML	Relocation Lon	Relocation Lat	Dep km	GA Location Lon	GA Location Lat	per - area*	COMMENT
1	24-11-1991	1704	2.4	117.	-32.165	2N	117.153	-32.094	P1m	
2	11-08-2003	0634	2.5	117.	-31.986	2N	117.157	-31.981	P2d	
3	12-05-2005	0118	2.6	117.	-31.945	2N	117.2013	-31.953	P2d	
4	06-04-2009	2050	3.0	117.	-31.960	0.1	117.330	-31.943	P3d	10 km NW of Quairading
5	02-09-2012	0806	2.0	117.	-31.963		117.236	-31.963	P3d	
6	02-09-2012	1444	2.1	117.	-31.947		117.232	-31.947	P3d	
7	07-02-2013	0216	1.9	117.	-31.967	4.4	117.235	-31.931	P3d	
8	19-07-2013	1842	2.6	117.	-32.132	2.4	117.454	-32.123	P3m	Moves 20 km west
9	05-05-2014	1554	1.8	117.	-32.121	2N	117.192	-32.113	P3m	
10	14-09-2014	1332	2.0	117.	-32.124	2N	117.384	-32.120	P3m	Big move west
11	25-05-2018	2142	2.4	117.	-32.155	2N	117.159	-32.189	P3m	Moves closer to Morbinning
* Period (1,2 or 3) & area : m=Morbinning, d = Dubelling						“N” indicates constrained to “normal” focal depth				

NE of Balkuling on 12 May 2005, and there was an ML 2.5 event in Aug 2003, about 5 km east of Balkuling, The relocation for this event (solution 2, Table 2) moves it about 5 km eastwards, and in the proximity of the 1992 cluster. An ML 2.4 event occurred near the QUA station in Nov 2004. Other notable events are 5 km north of Quairading (5 January 1994, ML 1.6), 20 km NW of Quairading (28 February 1996, ML 1.7) and 2 events near Dubelling on 14 and 16 April 2005. Reference to the catalogue shows that there were 7 events between April and June 2005, largest ML 2.2, and that they congregate around the vicinity of the QUA station. It is suggested that, considering location uncertainties, they can all be assigned to the Dublelling cluster centre (Cluster E4 in Dent 2017).

2.3 Seismicity in Period 3 (2006 – 2018)

These events are plotted on Figure 6, and can be divided into the same regions as the period before.

Events near Morbinning

There are 43 events in this plot, but only 8 are of ML 2.0 and above. The largest was ML 2.4 on 25 May 2018, and was about 5 km south of most of the other events. Its relocation (solution 11, Table 2) moves it closer to location F3. Five events in this area in June 2013- May 2014 (red circles, Figure 6) were used to define point V (32.14^{o}S, 117,19^{o}E) in Dent (2014), renamed to F3 in Dent (2017). The largest event of the 2013-2014 group (ML 2.6 on 19 July 2013) plots past the eastern boundary of the map, but its relocation (solution 8, Table 2) moves it about 25 km westwards. A summary of events assigned to this cluster location is shown in Table 3.

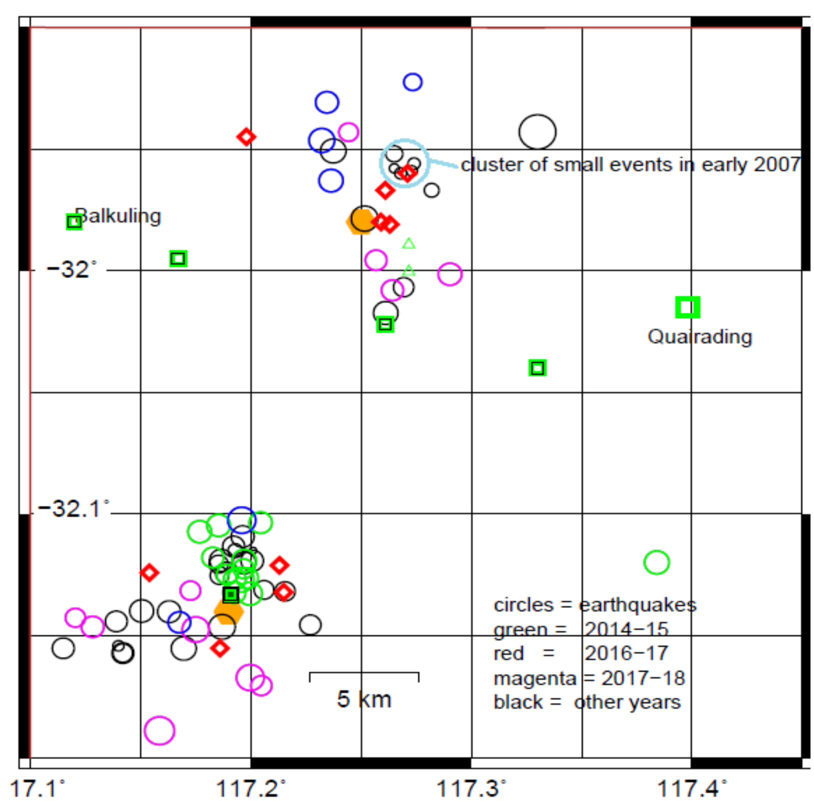
South of Quairading

A single event in this area is plotted on Figure 6 (14 September 2014). It occurred at a time when there were many events near Morbinning, and examination of the solution indicated it is a poor solution, and a relocation (solution 10, Table 2) places the event close to Morbinning.

Events in the Dubelling area

There are various cluster groups visible in Figure 6, which will be discussed in more detail.
A group of 5 small events, largest ML 1.2, was located about 5 km north of QUA between February and March 2007 (enclosed in red ellipse, Figure 6). Events this small necessarily have few readable phase arrivals, and are usually poorly located. They could easily have come from the cluster centre.

Figure 6 Seismicity in Period 3 (2006-2018)



An ML 3.0 event, in April 2009, was located about 10 km NE of QUA, but has been relocated (solution 4, Table 2), to about 7 km north of QUA. It had one small aftershock three weeks later, for which the GA location is also about 7 km north of QUA.

A group of 4 events about 10 km north and northwest of QUA was examined in a report on SWA seismicity in 2012-2013 (Dent & Collins, 2018.). Three were relocated (solutions 5, 6, 7 in Table 2) and the relocations placed them about 3 km NW of QUA. This location was defined in that publication as location E4. Within the margin of error, these events could also have originated from the 1992 cluster location.

A group of 4 events within 2 km of QUA occurred between July 2015 and July 2018.

The conclusion is that all events could be reasonably attributed to the 1992 cluster location.

Table 3 events assigned to Morbinning cluster location (F3) in Annual Summaries by Dent

Period	**Num. events**	**largest event**	**when**	**Comment**
Jun2012-May13	2	2.3	22 May	
Jun2013-14	5	2.6	19 July	Used to define F3. (largest event moved 25 km by
Jun2014-15	12	2.2	22 Sep.	
Jun2015-16	2	2.1		
Jun2016-17	2	1.9	Feb 2017	
Jun2017 – Aug18	7	2.4	25 May	

3 Discussion

It is suggested that, considering location uncertainties, most of the events can be allocated to two “large” cluster locations, west of Quairading (E4) and near Morbinning (F3), and one “minor” location south of Quairading, suggested to be at 32.15°S, 117.41°E. This location is about 10 km north of cluster location F5, (Dent, 2017) and, considering uncertainties, these two locations could be the same. Locations E4 and F3 may be associated with the magnitude 4+ events of the 1960’s.

Conclusions

A review of epicentral data supports the proposition that the most probable source of the 1992 seismicity was at a location about 1 km NW of the QUA station. It also suggests that this cluster centre has continued to produce seismicity in the subsequent years. The association has been made difficult because of uncertainties in epicentral locations. It is probable that seismicity from this location occurred before 1992. Several large (magnitude 4+) events in 1967 may be related, as may a magnitude 3.6 earthquake in December 1985.

The Morbinning cluster centre was defined in Dent (2014) as location V (now referred to as F3), on the basis of 5 events (largest Ml 2.5) in the 2013-2014 period. A plot of more recent seismicity (green and magenta circles, Figure 6) suggests seismicity has continued at this location since that initial period. Figure 1 suggests that the activity noted above may be related to the two ML 3 events in almost the same location in December 1982 and January 1983.

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APPENDIX 1

EQLOCL outputs for selected events see " 2 Data review (1991 -2018) '

Solution 1 - "good location", 12 January 1992

```
Date           1992-01-12
Origin Time    1222 26.69   +-   1.14
Zone                   50
Easting            525.88   +-   6.80              Longitude     117.274
Northing          6460.92   +-   5.34              Latitude      -31.987
Depth               4.30   +-  37.65

Arrival times    =  7           S.D. = 0.132        Seismographs =  4
Nearest recorder =   63.6 km    Gap  = 135.7 deg    Accuracy = A
Effects Code     =              Imax =  0           Fault =

  11 km  W (283 deg) of  QUAI
WESTERN AUSTRALIA
 135 km  E ( 92 deg) of PERTH
  36 km NE ( 66 deg) of Beverley

No magnitudes known                             Assign ML  1.7

DATA USED
```

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
KLB	e P	37.00	0.50	0.66	37.09	-0.09	63.6	46	4.1	4.1
KLB	e S	44.40	0.30	0.66	44.30	0.10	63.6	46	4.1	4.1
MUN	e P	43.10	0.10	0.88	43.13	-0.03	100.7	270	2.6	2.6
MUN	e S	54.60	0.30	0.64	54.53	0.07	100.7	270	2.6	2.6
NWAO	e P	43.50	0.30	0.71	43.70	-0.20	104.2	182	2.5	2.5
NWAO	e S	55.70	0.30	0.64	55.50	0.20	104.2	182	2.5	2.5
BAL	e S	71.50	0.50	0.55	71.47	0.03	162.3	340	-23.9	23.9

7 times used, S = 0.132

Solution 2 - "good location" 20th January 1992

```
Date           1992-01-20
Origin Time    1048 12.38   +-   0.80
Zone                   50
Easting            525.44   +-   4.92              Longitude     117.269
Northing          6459.51   +-   3.77              Latitude      -32.000
Depth               5.08   +-  24.57

Arrival times    =  7           S.D. = 0.138        Seismographs =  4
Nearest recorder =   64.9 km    Gap  = 136.1 deg    Accuracy = A
Effects Code     =              Imax =  0           Fault =

  11 km  W (276 deg) of  QUAI
WESTERN AUSTRALIA
 134 km  E ( 93 deg) of PERTH
  35 km NE ( 68 deg) of Beverley
No magnitudes known                             Assign ML  1.7
```

```
DATA USED
Code  Wave       AT    +-    WT      CT     DT     Dist  Azim    Ad    Ae
KLB   e P      23.00  0.20  0.80   23.00   0.00    64.9    45    4.7   4.7
KLB   e S      30.40  0.20  0.72   30.36   0.04    64.9    45    4.7   4.7
MUN   e P      28.50  0.30  0.71   28.76  -0.26   100.3   271    3.0   3.0
MUN   e S      40.30  0.20  0.69   40.11   0.19   100.3   271    3.0   3.0
NWAO  e P      29.10  0.20  0.77   29.16  -0.06   102.8   181    3.0   3.0
NWAO  e S      40.90  0.20  0.69   40.80   0.10   102.8   181    3.0   3.0
BAL   e S      57.40  0.30  0.61   57.38   0.02   163.5   340  -23.9  23.9
                         7 times used, S = 0.138
 Deferred Data
BAL   e P      39.00  0.50  0.61   38.05   0.95   163.5   340  -30.8  30.8
```

Solution 3 - "good location" 26th January 1992

```
Date            1992-01-26
Origin Time     0310 12.68   +-   0.51
Zone                    50
Easting             526.16   +-   2.45             Longitude     117.277
Northing           6458.82   +-   3.04             Latitude      -32.006
Depth                 7.27   +-  12.75

Arrival times    =  8          S.D. = 0.148        Seismographs =  4
Nearest recorder =   64.8 km   Gap  = 137.4 deg    Accuracy = A
Effects Code     =             Imax =  0           Fault =

  11 km  W (273 deg) of  QUAI
WESTERN AUSTRALIA
 135 km  E ( 93 deg) of PERTH
  35 km  E ( 69 deg) of Beverley
No magnitudes known                            Assign ML  1.7

DATA USED
Code  Wave       AT    +-    WT      CT      DT     Dist  Azim    Ad    Ae
KLB   e P      23.50  0.20  0.80   23.33   0.17    64.8    44    6.7   6.7
KLB   e S      30.60  0.20  0.72   30.71  -0.11    64.8    44    6.7   6.7
MUN   e P      29.10  0.20  0.77   29.21  -0.11   101.0   271    4.3   4.3
MUN   i S      40.70  0.10  1.13   40.66   0.04   101.0   271    4.3   4.3
NWAO  e P      29.20  0.20  0.77   29.39  -0.19   102.1   182    4.2   4.2
NWAO  e S      41.10  0.30  0.64   40.97   0.13   102.1   182    4.2   4.2
BAL   e P      38.50  0.30  0.68   38.30   0.20   164.3   340  -30.8  30.8
BAL   e S      57.50  0.20  0.66   57.66  -0.16   164.3   340  -23.9  23.9
                         8 times used, S = 0.148
Deferred Data
MRWA  e SG    101.00  0.50  0.52  104.56  -3.56   332.5   338    1.3   1.3
```

Solution 4 - "good location" 18th February, 1992

```
Date            1992-02-18
Origin Time     1415 24.12   +-   0.72
Zone                    50
```

```
Easting            523.38   +-   4.12              Longitude     117.248
Northing          6459.90   +-   3.97              Latitude      -31.997
Depth                0.88   +-  27.38

Arrival times    =  8            S.D. = 0.119        Seismographs =  4
Nearest recorder =   66.1 km     Gap  = 133.5 deg    Accuracy = A
Effects Code     =               Imax =  0           Fault =

  14 km  W (276 deg) of  QUAI
WESTERN AUSTRALIA
 132 km  E ( 93 deg) of PERTH
  33 km NE ( 66 deg) of Beverley

No magnitudes known                             Assign ML? 1.9

DATA USED
Code  Wave       AT    +-    WT      CT     DT     Dist  Azim    Ad    Ae
KLB   e P       35.00  0.10  0.91   34.90   0.10    66.1    47    1.0   1.0
KLB   e S       42.30  0.20  0.72   42.38  -0.08    66.1    47    1.0   1.0
MUN   e P       40.10  0.10  0.88   40.14  -0.04    98.2   270    0.7   0.7
MUN   e S       51.30  0.30  0.64   51.25   0.05    98.2   270    0.7   0.7
NWAO e P        40.70  0.50  0.64   40.94  -0.24   103.1   180    0.6   0.6
NWAO e S        52.80  0.50  0.57   52.60   0.20   103.1   180    0.6   0.6
BAL   e P       50.00  0.30  0.68   50.00   0.00   162.4   341  -30.8  30.8
BAL   e S       69.00  0.30  0.61   68.99   0.01   162.4   341    0.4   0.4
                         8 times used, S = 0.119
Deferred Data
MRWA e S      106.00  1.00  0.45  105.27   0.73   330.5   338  -40.3  40.3
```

Solution 5 - "good location" – 4th May 1992 USES QUA DATA

```
Date            1992-05-04
Origin Time     2133 11.50   +-   0.73
Zone                    50
Easting            525.87   +-   4.23              Longitude     117.274
Northing          6459.69   +-   5.05              Latitude      -31.998
Depth                1.10   +-   6.63

Arrival times    =  8            S.D. = 0.171        Seismographs =  5
Nearest recorder =    1.5 km     Gap  =  88.9 deg    Accuracy = A
Effects Code     =               Imax =  0           Fault =

   1 km  W (276 deg) of  QUA
WESTERN AUSTRALIA
 135 km  E ( 93 deg) of PERTH
  35 km NE ( 68 deg) of Beverley

No magnitudes known                             Assign ML  2.0

DATA USED
Code  Wave       AT    +-    WT      CT     DT     Dist  Azim    Ad    Ae
QUA     S-P      0.20  0.05  1.97    0.24  -0.04     1.5    96    0.0   0.0
QUA     P       11.70  0.20  1.49   11.84  -0.14     1.5    96   42.5  42.5
KLB   e P       22.40  0.30  0.73   22.01   0.39    64.4    45    1.2   1.2
KLB   e S       29.00  0.30  0.66   29.30  -0.30    64.4    45    1.2   1.2
MUN   e P       27.90  0.30  0.71   27.92  -0.02   100.7   270    0.8   0.8
NWAO e P        28.30  0.20  0.77   28.29   0.01   103.0   182    0.8   0.8
BAL   e P       37.50  0.50  0.61   37.50   0.00   163.4   340  -30.8  30.8
BAL   e S2      57.00  0.50  0.31   56.93   0.07   163.4   340  -23.9  23.9
                         8 times used, S = 0.171
```

Deferred Data

MUN	e S	40.00	0.30	0.64	39.31	0.69	100.7	270	0.8	0.8
NWAO	e S	40.30	0.20	0.69	39.94	0.36	103.0	182	0.8	0.8
RKG	e P	50.00	2.00	0.44	52.64	-2.64	286.1	184	-42.2	42.2
RKG	e S	86.00	2.00	0.40	83.27	2.73	286.1	184	-40.3	40.3

Solution 6 -10th November, 1992 uses QUA - but is not "good" (insuffient stations/phases)

Date 1992-11-10
Origin Time 0311 39.72 +- 9.94
Zone 50
Easting 525.43 +- 42.20 Longitude 117.269
Northing 6458.75 +- 109.82 Latitude -32.007
Depth 0.50 +- 117.57 C

Arrival times = 5 S.D. = 0.131 Seismographs = 3
Nearest recorder = 2.1 km Gap = 203.1 deg Accuracy = A
Effects Code = Imax = 0 Fault =

2 km W (248 deg) of QUA
WESTERN AUSTRALIA
134 km E (93 deg) of PERTH
34 km E (69 deg) of Beverley

No magnitudes known Assign ML 1.7

DATA USED

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
QUA	S-P	0.10	0.30	1.36	0.26	-0.16	2.1	68	0.0	0.0
KLB	e P	50.40	0.20	0.80	50.39	0.01	65.4	45	0.7	0.7
KLB	e S	57.80	0.30	0.66	57.78	0.02	65.4	45	0.7	0.7
MUN	e P	56.00	0.10	0.88	56.07	-0.07	100.3	271	0.4	0.4
MUN	e S	67.50	0.20	0.69	67.41	0.09	100.3	271	0.4	0.4

5 times used, S = 0.131

Deferred Data

QUA	P	39.60	0.30	1.36	40.08	-0.48	2.1	68	20.8	20.8
KLB	e SMP	58.30	0.30	0.37	59.46	-1.16	65.4	45	-64.7	43.7
BAL	e S	84.50	0.50	0.55	85.07	-0.57	164.2	340	0.3	0.3

Solution 7 - "good location" 18th January 1993

Date 1993-01-18
Origin Time 1046 43.68 +- 0.61
Zone 50
Easting 525.99 +- 3.33 Longitude 117.275
Northing 6460.75 +- 6.73 Latitude -31.989
Depth 0.55 +- 9.09

Arrival times = 10 S.D. = 0.186 Seismographs = 5
Nearest recorder = 63.6 km Gap = 197.9 deg Accuracy = A
Effects Code = Imax = 0 Fault =

1 km NW (311 deg) of QUA
WESTERN AUSTRALIA

```
 135 km  E ( 92 deg) of PERTH
  36 km NE ( 66 deg) of Beverley

No magnitudes known                             Assign ML? 2.7

DATA USED
Code  Wave       AT    +-    WT      CT     DT     Dist  Azim    Ad    Ae
KLB  i+P      54.20  0.10  1.31   54.06   0.14    63.6    46    0.8   0.8
KLB  e S      61.00  0.30  0.66   61.25  -0.25    63.6    46    0.8   0.8
MUN  i-P      60.10  0.10  1.26   60.13  -0.03   100.8   270    0.5   0.5
MUN  e S      71.50  0.50  0.58   71.53  -0.03   100.8   270    0.5   0.5
BAL  i-P      69.80  0.10  1.21   69.59   0.21   162.5   340  -30.8  30.8
BAL  e S      88.40  0.20  0.66   88.56  -0.16   162.5   340    0.3   0.3
MRWA e P      90.00  0.50  0.57   90.27  -0.27   330.6   338  -42.2  42.2
MRWA   PG     97.50  0.50  0.82   97.62  -0.12   330.6   338    0.1   0.1
COOL e P      96.90  0.20  0.68   97.21  -0.31   387.9    72  -42.2  42.2
COOL e S     137.00  0.30  0.56  137.01  -0.01   387.9    72  -40.3  40.3
                        10 times used, S = 0.186
Deferred Data
QUA    S-P     5.00  5.00  0.76    0.23   4.77     1.9   131    0.0   0.0
RKG  e P2     87.10  0.30  0.39   87.06   0.04   287.2   184  -30.8  30.8
RKG  e SG    123.00  1.00  0.46  123.02  -0.02   287.2   184    0.2   0.2
MRWA e S     124.00  0.50  0.52  124.92  -0.92   330.6   338  -40.3  40.3
MRWA e S2    131.00  1.00  0.25  131.40  -0.40   330.6   338  -23.9  23.9
COOL e PG    106.20  0.10  0.78  106.96  -0.76   387.9    72    0.2   0.2
COOL e SG    148.00  0.50  0.51  150.83  -2.83   387.9    72    0.2   0.2
MEEK e P     125.00  0.50  0.46  123.71   1.29   607.0    12  -42.2  42.2
MEEK w S     196.00  2.00  0.39  183.15  12.85   607.0    12  -40.3  40.3
```