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# The geological context of six earthquake groups in Central Western NSW

**V. F. Dent**

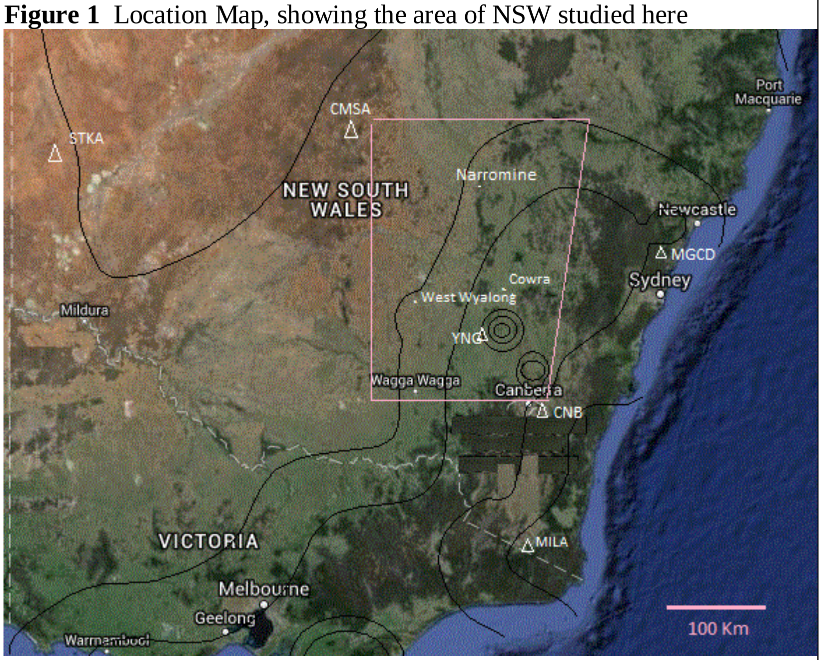
Curtin University, Perth, WA. Email: vic_dent@yahoo.com

**ABSTRACT:** The central west region of NSW, a region of metamorphosed Paleozoic sediments and volcanics with frequent granitoid intrusions, has been the source of many of NSW's largest earthquakes. Earthquakes in the region are often strongly clustered, but the clustering can be obscured by relatively large errors in earthquake locations, particularly for events before the 1970s. Attention has been drawn by previous authors to the possible connection between earthquakes and granite intrusions, and also the lack of connection between earthquakes and faults. Six earthquake groups in the Central West of NSW are examined here, and their geological environment is examined in an attempt to clarify any connection between faults and intrusive rocks. A possible connection to granitic intrusives is established in five of the six cases, but a connection with mapped faults is less clear. A possible connection between swarm-like behavior and earthquake focal depth is noted.

## 1 INTRODUCTION

The definition of the Central West region of NSW is variable, but it is here taken to include the centres of Narromine, Cowra , Wagga Wagga and West Wyalong (Figure 1). The most recent earthquake hazard map of Australia (Burbidge, 2012) shows two areas of high hazard in the southeast of the region, just north of Canberra, and also near Young (Figure 2). The region has been the locus of several of NSW's largest earthquakes, including the M 5.6 Dalton events of 1934 and 1949 (McCue et al., 1989). In Figure 1, seismographs of the Australian National Seismograph Network (ANSN) (open triangles) are important for monitoring the seismicity in the region. They are Young (YNG), Canberra (CNB), Cobar (CMSA), Broken Hill (STKA), Dalton (DLN), and west of Gosford (MGCD)

**Figure 1** Location Map, showing the area of NSW studied here



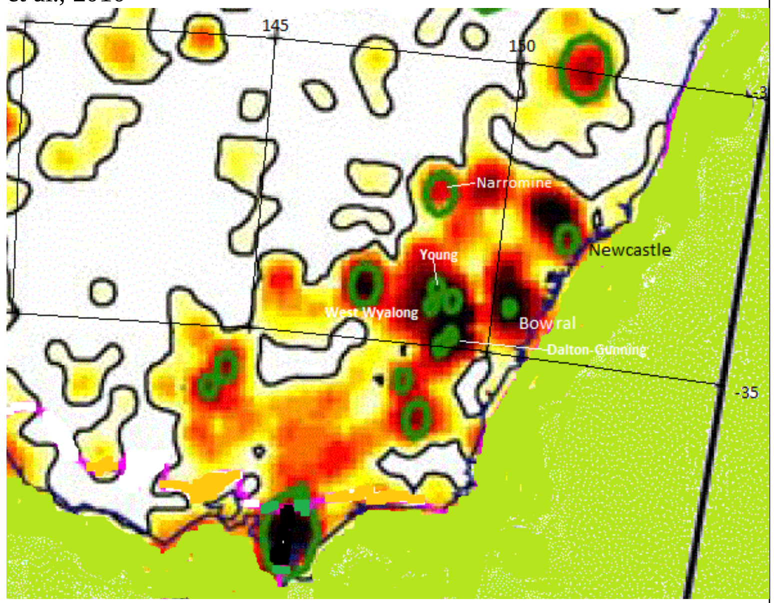

The geology of the region comprises mainly metamorphosed Palaeozoic rocks with frequent granitoid intrusions, in a region known as the Lachlan Fold Belt, and is west of the Mesozoic sedimentary rocks of the Sydney Basin.

Figure 2 shows the seismic "hot-spots" identified by Leonard et al. (2012) in the 2012 Earthquake Hazard Map of Australia.

The "hot spots" include:

1) Two in the Dalton-Gunning region (these have been coalesced into a single area in the 2012 Hazard map).
2) Three around the Young - Boorowa region (these have also been coalesced into a single area in the 2012 Hazard map).
3) The West Wyalong region.
4) Near Narromine. This hotspot appears to include an area near Narromine which was very active in the 1930s (McCue, 2014)

**Figure 2** Earthquake hotspots in south-east Australia, from Leonard et al., 2010




Many of the significant historical events in the region are part of earthquake clusters, which may contain dozens of events, or more. The numbers of events listed in clusters in the Central West probably is partly determined by the sensitivity of the seismic network existing at the time.

Several papers have discussed some of the important earthquakes and earthquake clusters in the region. McCue et al. (1989) discussed the seismicity of the Dalton-Gunning region between 1886 and 1986, a period that included two of the largest seismic events in NSW (M 5.6 near Dalton in 1934 and 1949). Gibson et al. (1994) discussed events from a cluster near Eugowra in 1994, (largest event ML4.1). Levinson & Leonard (2002) discussed a cluster of small events just north of Canberra in 2002, (largest event ML2.5). McCue (2014) discussed a significant cluster near Narromine (maximum magnitude 5.0) that occurred between 1930 and 1933. Denham et al. (1984) discussed the West Wyalong cluster of 1982, (largest event ML 4.6). There have been periods of lesser activity near this location since then (eg 1989, 1999) and it is marked in the map of hotspots in southeast Australia (Figure 2).

In reviewing the seismicity of the Gunning region between1958 and 1961, Cleary (1967) drew attention to the possible connection of earthquakes in the area with granite intrusions. In this report, this possible connection will be looked at in relation to other areas of the Central West. Clusters near Eugowra, Sutton, West Wyalong and Narromine will be discussed, as well as two other earthquakes, near Young and Cowra.

Earthquake swarms are a particular class of earthquake clusters, in which there are several events close to the maximum magnitude in the cluster, and frequently the largest event is towards the middle of the cluster (temporally). Some of the clusters occurring in the Central West can be classified as swarms. Dent (2008), in a discussion of earthquake swarms in Australia since 1982, suggested that earthquake swarms may be related to granitic terranes, and this association was also discussed by Clark et al., (2014). Part of the purpose of this paper is to present more data pertinent to this discussion.

Also relevant to the discussion of earthquakes and geology is the question as to whether earthquakes occur on faults, an issue raised by Love (2013). Using examples from South Australia and elsewhere, he suggested that the assumed match between current earthquakes and mapped faults needs to be critically reviewed, since there seemed little connection between the two.

The interpretation of the connection between seismicity and geology is made more difficult because of uncertainties in earthquake locations. Bondar et al. (2004) showed that unless good local seismic networks exist, uncertainties in locations are of the order of ± 20 km. Before the 1970s, seismic coverage in the area was very poor, and uncertainties are expected to be much larger than this.

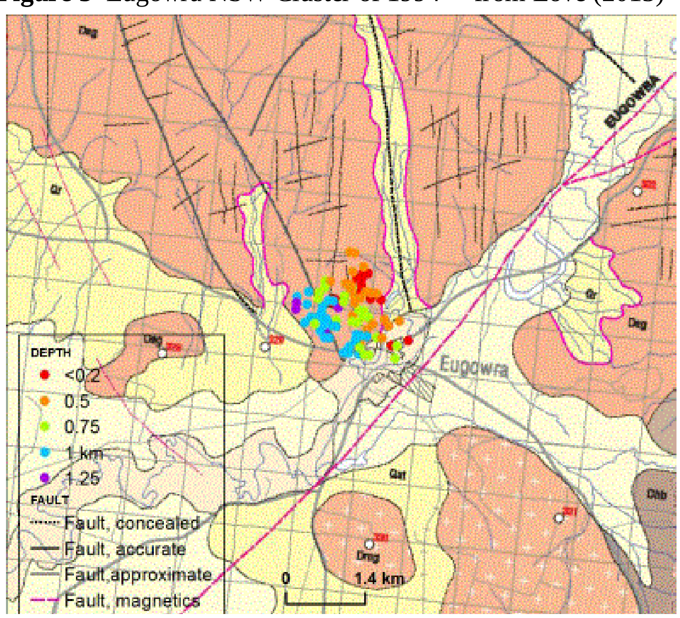
Some of the better-located events in the region occurred in the 1970s and 1980s, when the Australian National University (ANU) had a relatively dense network of seismographs in the region.

In this report, the six earthquake groups chosen for examination have been divided into three groups representing the confidence level of the locations used – ie well located, reasonably located, and poorly located. A lack of well-located clusters in the Central West has meant that only two earthquake groups are represented in the first category. The two groups in the third category (West Wyalong and Narromine) have been included because the large magnitudes of some of their earthquakes makes them significant.

## 2 EVENTS WITH GOOD LOCATIONS

### 2.1 Eugowra, 1994

**Figure 3** Eugowra NSW Cluster of 1994 – from Love (2013)




In Figure 3, the mapped Eugowra sequence, about 100 km north of Young is from Love 2013, data from Gibson et al. (1994).

The sequence started in late July 1994, but was most active in August 1994. It is unique in the seismic history of NSW in that almost the complete sequence was closely monitored on a network of digital seismographs installed in the area for many months. Most, if not all of these events were felt by local residents. The largest event in the sequence was magnitude 4.1, on 21st August, 1994. About 35 earthquakes in this sequence are in the Geoscience Australia (GA) catalogue, many other smaller events have not been listed. At its maximum deployment, there were eight recorders simultaneously monitoring this cluster (Gibson et al, 1994).

Very accurate epicentres (uncertainties ~ ± 200m) were determined by the Seismology Research Centre in Melbourne, Gibson et al. (1994) and they estimated that many locations were accurate to within 100 m in latitude and longitude, and within 300 m in depth. Most events occurred within 1 km of 33.42$^o$S, 148.36$^o$E (**Table 1**).

The accurate locations suggested that the events emanated from a fault to the northwest of the township, which dipped from the northeast to the southwest, at an angle of 38 degrees. This is demonstrated in Figure 3, taken from Love (2013). The defined plane does not correlate to a known fault (Gibson et al. 1994).

Figure 3 shows granite in the region of the epicentres, and suggests that a north trending creek bed may reflect the exposure of the presumed fault plane at the surface. It also shows the Eugowra fault, striking to the northeast, a little south of the epicentral region.

Occasional events may have originated on this fault since 1994. The GA location of an ML 2.5 event on 13$^{th}$ August 2012 plots about 15 km southwest of the cluster, however relocation (Table 4) moves it to within 5 km of the cluster location.

There is no apparent seismicity on the northeast trending Eugowra fault.

**Table 1 Suggested locations of cluster centres**

| Cluster group | Year | Lat. | Long. | Max ML | Quality | Comment |
|---|---|---|---|---|---|---|
| Eugowra | 1994 | -33.42 | 148.36 | 4.1 | Good | location of largest event |
| Sutton | 2002 | -35.19 | 149.29 | 2.5 | Good | centre of 3 small well located events |
| Young | 2013 | -34.31 | 148.33 | 2.6 | Medium | location of central event in group |
| Cowra | 2006 | -34.04 | 149.16 | 4.2 | Medium | relocation of event on 21/10/2006 |
| West Wyalong | 1982 | -33.94 | 147.25 | 4.6 | Poor | centre of isoseismal map, ML 4.6 event |
| Narromine | 1932 | -32.3 | 148.3 | 5.0 | Poor | note different assessments of max. ML |

### 2.2 Southeast of Sutton, 2002

This group of 18 located earthquakes listed in the GA data base, occurred about 5 km south-east of Sutton, a village about 15 km northeast of Canberra (Figure 4), between December 2001 and August 2002. Only three of the earthquakes had magnitudes ≥ ML 2.0, and the maximum magnitude was ML 2.5, on 23$^{rd}$ January 2002. Many of these earthquakes were felt by local residents.

The cluster was monitored by a small group of digital seismographs at five different locations, in place between February and April 2002, one station (MP4) was in place longer. Data from this survey increased the number of earthquakes detected in the cluster to about 90 (Levinson & Leonard, 2002).

Figure 5 shows the GA database epicentres from December 2001 to August 2002. Most of these epicentres were determined using data from seismographs at Canberra, Young and MILA only, and are of relatively poor quality. Three of the epicentres in the database used some temporary station data, and are called “medium quality”. The earthquake locations, and data used, are summarized in Table 2.

Levinson & Leonard (2002) located about 35 events using field data, and their plot of the best 15 locations shows a scattered grouping about 2 km wide, roughly centred on the station MP5. The data supporting these locations is unfortunately not available.

GA data which are available have allowed three very small events, not in the data base, to be relocated by the author. These three locations, also shown in Table 1, use data from three or more temporary (field) stations, and are considered to be quite accurate. They are all within 1 km of station MP5, and are less than 1 km deep. The "medium quality" events surround the "accurate" locations, and it is suggested here that all the events in Table 2 also originated from the same area as these three well-located events. The suggested source location (35.19°S, 149.29°E, ± 0.5 km) is shown in Table 1.

Although the GA Catalogue locations are not as accurate as might be desired, the S-P times of the events, recorded at CNB, show little variation – they are all between 1.60 and 1.72 secs, with an uncertainty of about ± 0.1 seconds. This observation strongly supports the conclusion that all of the events are relatively closely spaced.

The earthquakes were located about 10 km west of the Lake George Fault, but are not thought to be related to it. This region has the benefit of some very detailed regional geological mapping, as shown in Figure 6, from Abell (1992). A summary of faults and the numerous lineaments in the region, also from Abell (1992), are shown in Figure 7. The earthquakes do not coincide with any of the mapped faults, although they may correlate with some of the lineaments shown. However, any apparent correlation may be coincidental. Unlike other clusters described here, the host geology for this cluster is not granite, but metamorphosed sediments/volcanics

**Figure 4** Locality map, southern region of the Central West

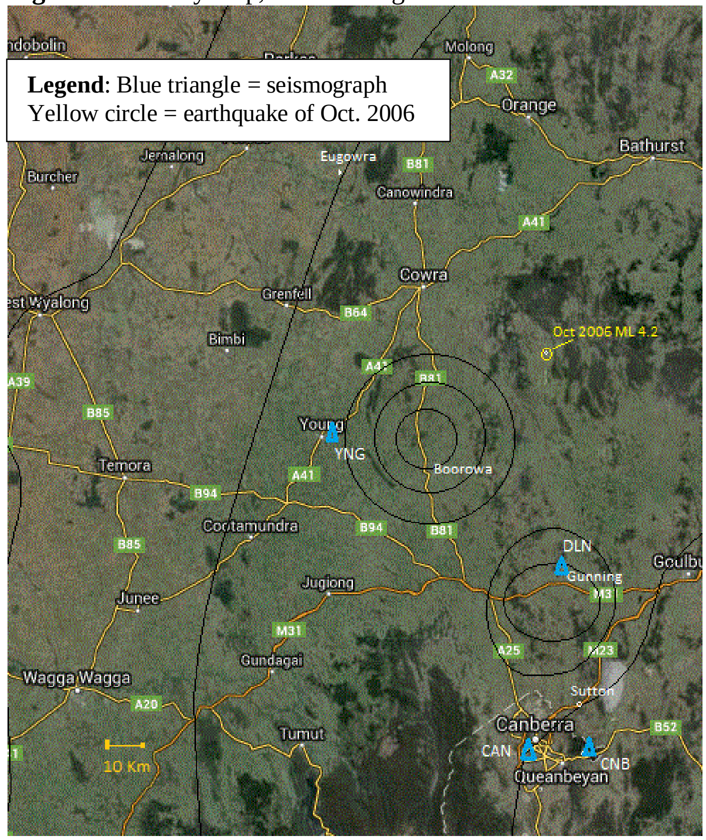
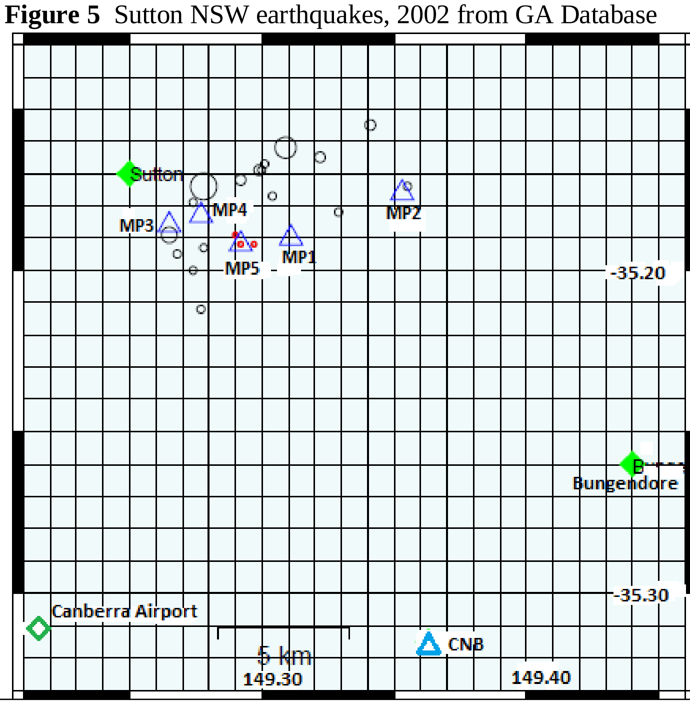



**Figure 5** Sutton NSW earthquakes, 2002 from GA Database




Legend: Blue triangle = seismograph; Blue circles=earthquakes from GA database;.Red circles (near MP5) = small relocated earthquakes.

**Figure 6** Geology of the Sutton area – from Abell (1992).
Red star = epicentral region  Grid interval = 1 km

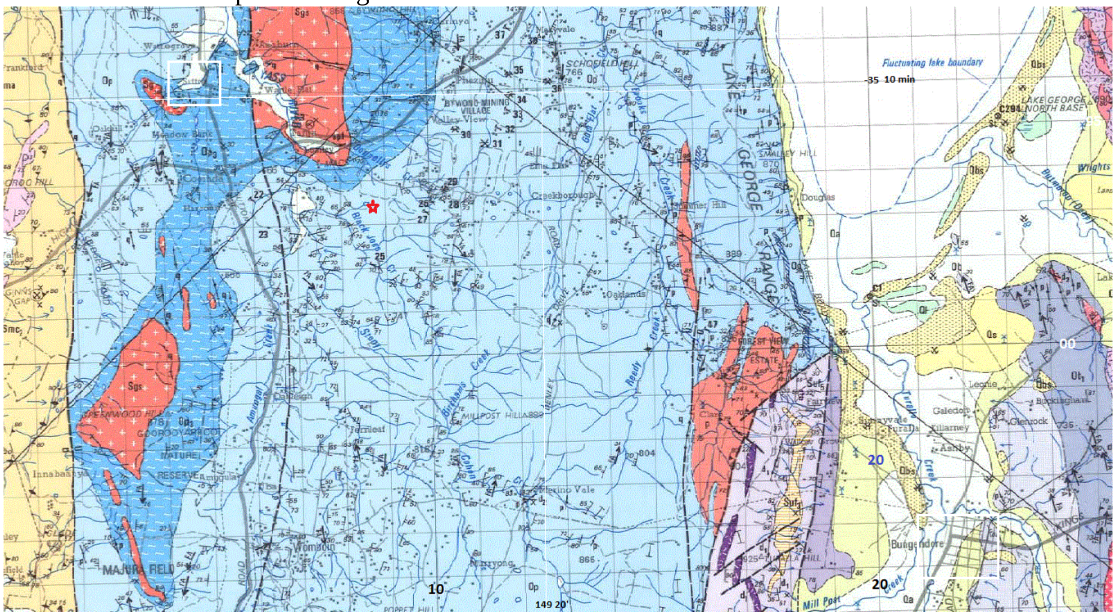
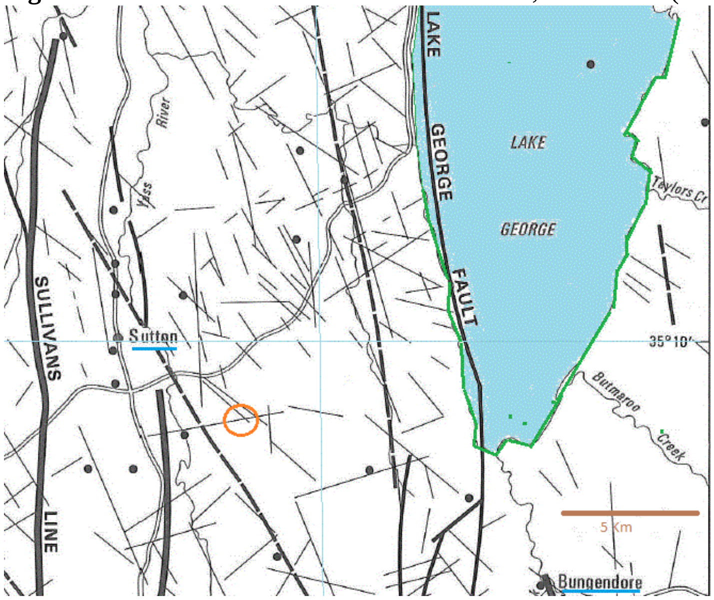



**Table 2** – GA database locations for earthquakes near Sutton, 2001 -2002

| Date | Time (UTC) | ML | Lat. | Long. | dep | R.M.S | Stn/pha | Q. | Closest Stn & distance | Comment |
|---|---|---|---|---|---|---|---|---|---|---|
| 19/09/2001 | 15:01:20.1 | 1.8 | -35.189 | 149.298 | 0G | .212 | 5/7 | C | CNB | |
| 27/12/2001 | 15:23:27.3 | 1.9 | -35.155 | 149.341 | 5G | .907 | 3/6 | E | CNB | |
| 14/01/2002 | 10:28:53.0 | 1.6 | -35.165 | 149.322 | 0G | .54 | 3/6 | C | CNB | |
| 16/01/2002 | 13:39:52.6 | 1.5 | -35.182 | 149.329 | 0G | .313 | 3/5 | F | CNB | |
| 20/01/2002 | 09:42:53.7 | 1.8 | -35.169 | 149.299 | 0G | .573 | 3/6 | F | CNB | |
| **23/01/2002** | **02:44:12.1** | **2.3** | **-35.162** | **149.309** | **0G** | **.541** | **3/6** | **E** | CNB 18k | |
| **23/01/2002** | **09:00:47.3** | **2.5** | **-35.174** | **149.278** | **0G** | **.428** | **6/10** | **B** | CNB | |
| 23/01/2002 | 09:03:28.5 | 1.2 | -35.174 | 149.355 | 0G | .424 | 3/5 | Z | CNB | |
| 29/01/2002 | 01:47:20.5 | 1.5 | -35.193 | 149.278 | 1.6 | .484 | 3/6 | E | CNB 16k | |
| 29/01/2002 | 13:39:46.7 | 1.4 | -35.177 | 149.304 | 0G | .435 | 3/6 | D | CNB | |
| 29/01/2002 | 16:01:54 | 1.7 | -35.172 | 149.292 | 0 | | | | | Soln not found |
| 31/01/2002 | 16:55:06.5 | 1.3 | -35.179 | 149.274 | 0.9 | .541 | 4/8 | E | CNB | |
| 01/02/2002 | 19:35:00 | 1.4 | -35.169 | 149.3 | 0 | | | | | Soln not found |
| **02/02/2002** | **07:07:05** | **2.2** | **-35.189** | **149.265** | **1** | | | | | Soln not found |
| 11/02/2002 | 13:54:56.4 | -- | -35.192 | 149.297 | 0.9 | .020 | 3/5 | | MP1 1.3k | vfd locn |
| 19/02/2002 | 11:53:52.4 | 1.0 | -35.189 | 149.290 | 0.7 | .010 | 4/6 | | MP4 1.4k | vfd locn |
| 13/03/2002 | 21:00:08.6 | 1.2 | -35.212 | 149.277 | 2.7 | .329 | 3/6 | F | MP4 3.2k | |
| 16/03/2002 | 12:57:19.7 | -- | -35.192 | 149.292 | .7 | .009 | 4/8 | | MP5 0.1k | vfd locn |
| 18/04/2002 | 00:51:55.5 | 1.7 | -35.167 | 149.301 | 0 G | .633 | 3/5 | Z | CNB 17k | |
| 10/08/2002 | 15:19:47.3 | 1.3 | -35.195 | 149.268 | 2.9 | .283 | 3/6 | D | MP4 1.6k | |
| 13/08/2002 | 04:51:06.1 | 1.4 | -35.200 | 149.274 | 1.7 | .18 | 3/6 | D | MP4 2.0k | |

Events ML ≥ 2.0 are bolded.  Legend : G = depth constrained by geophysicist
Q = quality assigned by analyst
RMS = root mean square of residuals

**Figure 7** Faults and lineaments in the Sutton area, from Abell (1992)

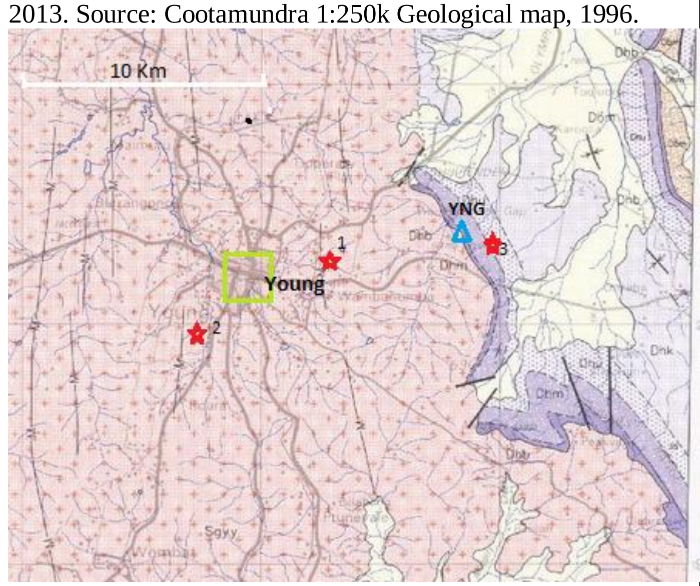



# 3 Events with fair locations

## 3.1 Near Young, August – September 2013

This is a group of just three, relatively small events near Young (Figures 4 and 6), on 24th and 28th August 2013, and 4th September 2013 (ML's of 2.5, 2.6 and 1.7). The group has been chosen for examination because it is quite close (~ 7 km) to the GA seismic station at Young (YNG), which gives the potential for above-average quality locations. The GA catalogue locations are shown on (Table 3 and Figure 8), and have an approximately linear, northeast orientation, over about 12 km. Relocations of the events are also shown in Table 3.

**Figure 8** Geology and earthquakes near Young, Aug. – Sep. 2013. Source: Cootamundra 1:250k Geological map, 1996.




However, the extreme similarity of the waveforms of the events on the YNG seismograph (Figure 9) indicates that the events are much more closely spaced than the catalogue solutions suggest. In Figure 9 (a and b), the waveforms for the three events at YNG have been normalised, and overlain. Figure 9(a) shows the vertical component and 9(b) the north-south component. The difference between the P and S arrival times is a reliable indicator of hypocentral distance, and Figure 9 indicates that the S-P time at YNG is about 0.8 secs. This indicates that the hypocentral distance of the earthquakes from the YNG seismograph is ~7 km (±2km approximately).

The similarities in the waveforms shown in Figure 9 (a and b) imply that the events are within 1 km of each other.

The first of the three events (ML 2.5 on 24th August 2013) is roughly central to the three locations. It is also about 7 k from the YNG seismograph, matching the observed S-P time, assuming a focal depth near 0 km. This location (34.31°S, 148.33°E) has therefore been chosen as the preferred location for the group of three events. The epicentre would approach that of the YNG seismograph were the event to be deeper, and at 7 km depth, it would be directly under the seismograph. In that case the P arrival would be very large on the vertical relative to the horizontals.

The EW components of the earthquake waveforms (not plotted) show large P wave amplitudes relative to the S phase, supporting the conclusion that the events are west of the YNG seismograph.

At the preferred location, the geology map (1:250,000) suggests a relatively uniform granitic environment around Young. East of Young, and near the YNG seismograph, is an apparently faulted contact with metamorphic rocks. This contact may dip to the west, and the earthquakes may lie on this postulated west-dipping fault plane.

**Figure 9** Normalised waveforms of the three 2013 Young earthquakes

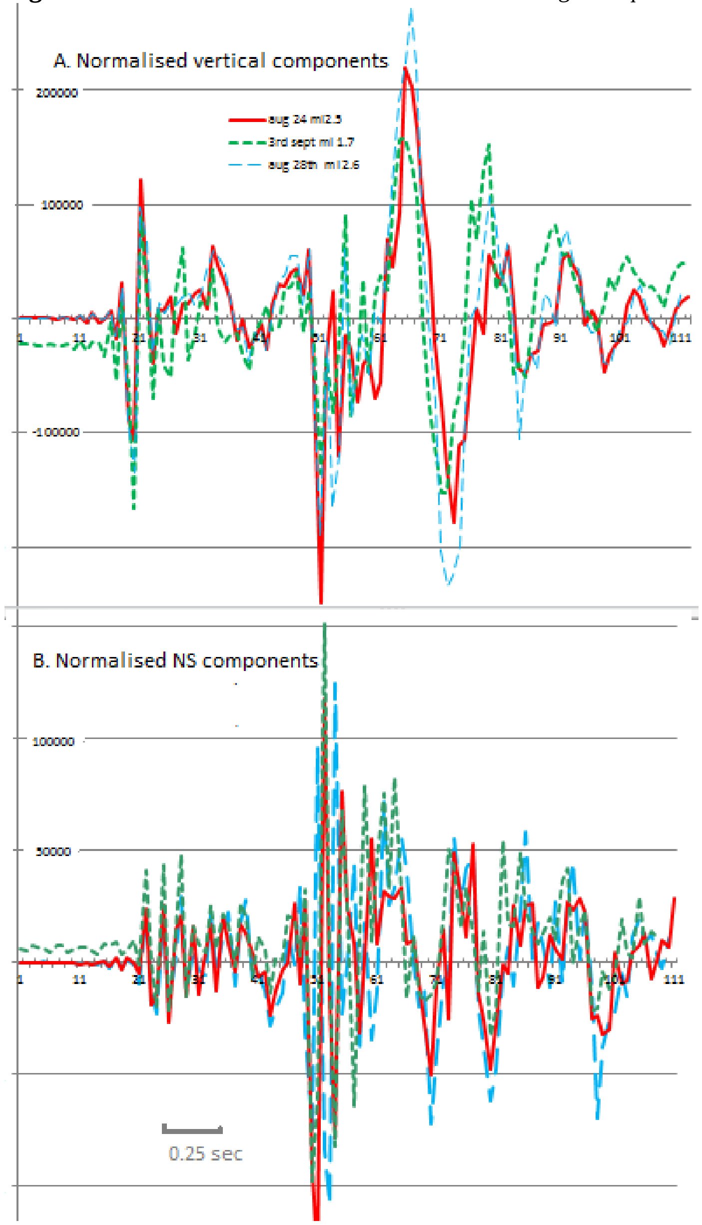



**Table 2** – Locations and relocations for earthquakes discussed in text: near Cowra (2006) and Young (2013)

| Date | Time (UTC) | ML | Lat. | Long. | Dep Km | RMS secs. | GAP | Stn/ pha | Comment 1 | Comment 2 |
|---|---|---|---|---|---|---|---|---|---|---|
| 21/10/2006 | 09:51:49.6 | 4.2 | -34.036 | 149.161 | 15G | .521 | | 17/25 | Cowra | GA database |
| 21/10/2006 | 09:51:50.0 | 4.2 | -34.049 | 149.198 | 14 | .118 | 141 | 8/8 | Cowra | Relocation |
| 24/08/2013 | 20:27:48 | 2.5 | -34.307 | 148.333 | 3 | 0.40 | 125 | 8/12 | Young | GA database |
| 24/08/2013 | 20:27:48.5 | 2.5 | -34.313 | 148.332 | 0.3 | .205 | 252 | 5/5 | Young | Relocation |
| 28/08/2013 | 09:15:19 | 2.6 | -34.332 | 148.280 | 0 | 1.59 | 156 | 7/11 | Young | GA database |
| 28/08/2013 | 09:15:19.2 | 2.6 | -34.266 | 148.299 | 1 G | .138 | 169 | 7/7 | Young | Relocation |
| 03/09/2013 | 19:48:47 | 1.7 | -34.300 | 148.409 | 4 | 0.71 | 126 | 4/7 | Young | GA database |
| 03/09/2013 | 19:48:46.2 | 1.7 | -34.259 | 148.352 | 1 G | .457 | 331 | 3/4 | Young | relocation |

Legend : G(depth column) = depth constrained by geophysicist
RMS = root mean square of residuals

**3.2 Southeast of Cowra, 21 October 2006**

This event about 40 km southeast of Cowra (Table 3 and Figure 4) in October 2006 is “non-clustered” or solitary. It has been selected from the database because it is relatively large (ML 4.2), and relatively recent. The data used to originally locate the earthquake is available, and the quality of the location can be assessed. Small to moderate, non-clustered events in the Central West are not frequent in the database – at least since the 1970s, when the increase in seismic stations made it possible to detect and locate relatively small events. The depth GA computed was constrained to 15 km - if not constrained, the depth increases to about 20 km. Because there were no close stations to the event (YNG was ~75 km distant), it is impossible to compute the focal depth accurately.

The residual of the P phase arrival at YNG is quite large – about 0.7 secs, suggesting the location could be improved. Ideally the residuals at all the stations used should be of the order of 0.1 seconds or less.

The event has been relocated (Table 2), using the same phase data and the same program (EQLOCL) as used by GA, but many of the more distant arrivals ( > ~ 300 km) were not used in the computation (ie, they were “deferred”). The new solution (blue star on Figure 10) was 4 km to the east of the original, and the depth was 14 km. The RMS of residuals was much smaller, and the uncertainty in the coordinates is now probably about +/- 5 km.

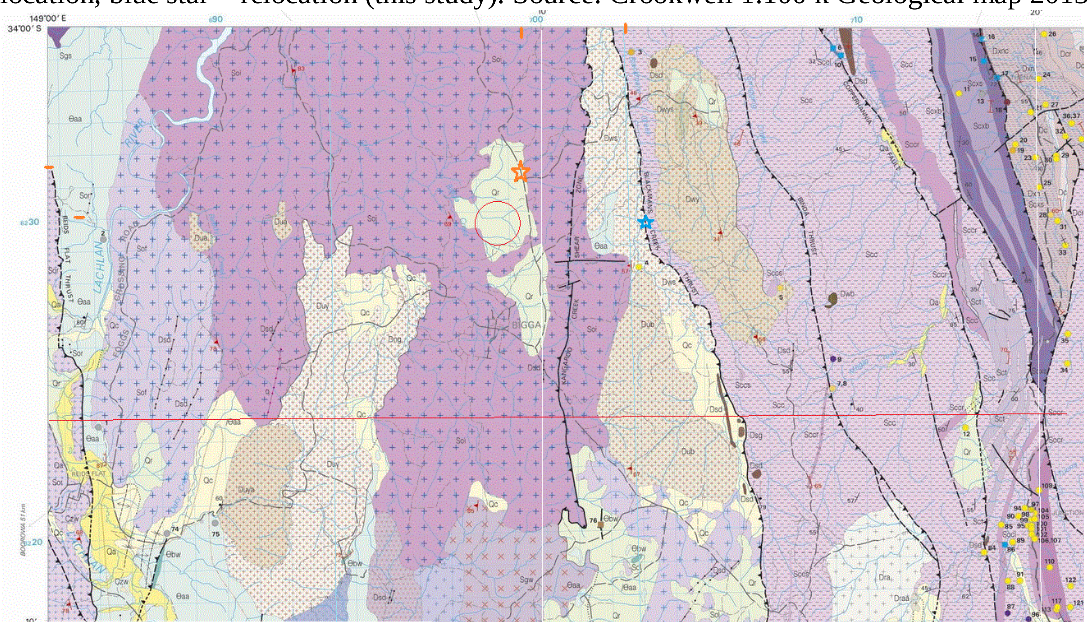


**Figure 10** Geology near the Cowra event of 21st October, 2006. Orange star = original GA location, blue star = relocation (this study). Source: Crookwell 1:100 k Geological map 2013

The GA location puts the event in a granitic terrane, not far west of a group of westerly dipping faults and shear zones (Figure 10). The relocation puts the event on the outcrop of the Blackman’s Creek Thrust. However, recalling that the event may be 14 km deep or more, it may well fall on one of the westerly dipping faults to the east of that thrust – ie, the Binda Thrust, about 5 km to the east, or the Copperhannia Fault, about another 5 km east of the Binda Thrust. These faults/thrusts lie in a region of Silurian sediments, adjacent to the granite intrusions.

This demonstrates that, even with a relatively accurate location, it still may not be possible to confidently assign a causative fault to an earthquake.

## 4 EVENTS WITH POOR LOCATIONS

### 4.1 West Wyalong 1982

The West Wyalong region was very active during 1982 and into 1983. There were several hundred events in this extended cluster, many of which were felt by local residents, and minor damage was caused (Denham et al., 1984). Many of them were quite small, and because there were no close seismographs, only 26 of the events were instrumentally located. Denham et al. (1984) suggested that the uncertainties in locations were probably about ± 10 km, but considering the distance to the seismic stations, and their heavy concentration in one azimuthal direction (to the south east of the events), the work of Bondar et al. (2004) suggests this is probably an optimistic assertion.

Denham et al., (1984) suggested the seismicity may have correlated with the boundaries of the Bland Creek drainage system (Figure 11), but also pointed out the possible connection with granite outcrops, although acknowledging that exposures were very poor.

**Table 4** – **Proposed locations for the ML 4.6 West Wyalong event of 26 November1982**

| Source | Time (UTC) | Lat. | Long. | depth | # Stns | RMS(sec) | Comment |
|---|---|---|---|---|---|---|---|
| ANU | 0011 13.5 | -33.89 | 147.18 | 10 | 13 | -- | |
| BMR | 0011 16.7 | -34.016 | 147.329 | 4 | 17 | -- | |
| MACR | 00 11 ---- | -33.94 | 147.25 | ~4 | n/a | n/a | GA " preferred" locn. |
| ISC | 0011 13.64 | -33.855 | 147.086 | 4 | 16 | 1.03 | |

Denham et al., (1984) presented three solutions for the largest event (Table 4). The first two were the instrumentally derived solutions by the ANU and the BMR, and the third, relatively different from the first two, was derived from felt reports. They stated that the third solution was the preferred location, and is the solution stored in the GA database of Australian earthquakes. To this collection of epicentres has been added the ISC relocation of the event.

The uncertainties in location means that the possibility that most of the earthquakes came from a quite confined source zone (diameter ~ 2km), similar to that of the 1994 Eugowra swarm, cannot be precluded. The location has been added to Table 1, but the uncertainties are large (~± 20 km)

Lesser periods of activity in the area have occurred at times in the ~30 years since the 1982 activity. Ten events in the area of Figure 1 since 1983, of magnitude ML $\geq$ 3.5 are listed in Table 5, three of which are near West Wyalong (1989, 1999 and 2005). These are only the largest of numerous events near these times. The solutions are of the order of 20 km from the preferred solution in Table 5, but considering the probable uncertainties in the locations, it is feasible that the events emanated from a location close to the preferred location of the 26$^{th}$ November 1982 event.

**Figure 11** Geology and earthquakes in Cootamundra-West Wyalong area 1959 – 1982 adapted from Denham et al., (1984). Legend : Pink = granite, blue = volcanics, stippled = sediments. Uncoloured = overburden. 1982 earthquakes = larger circles. Source: Macquarie 1:500k geology map, 1969.

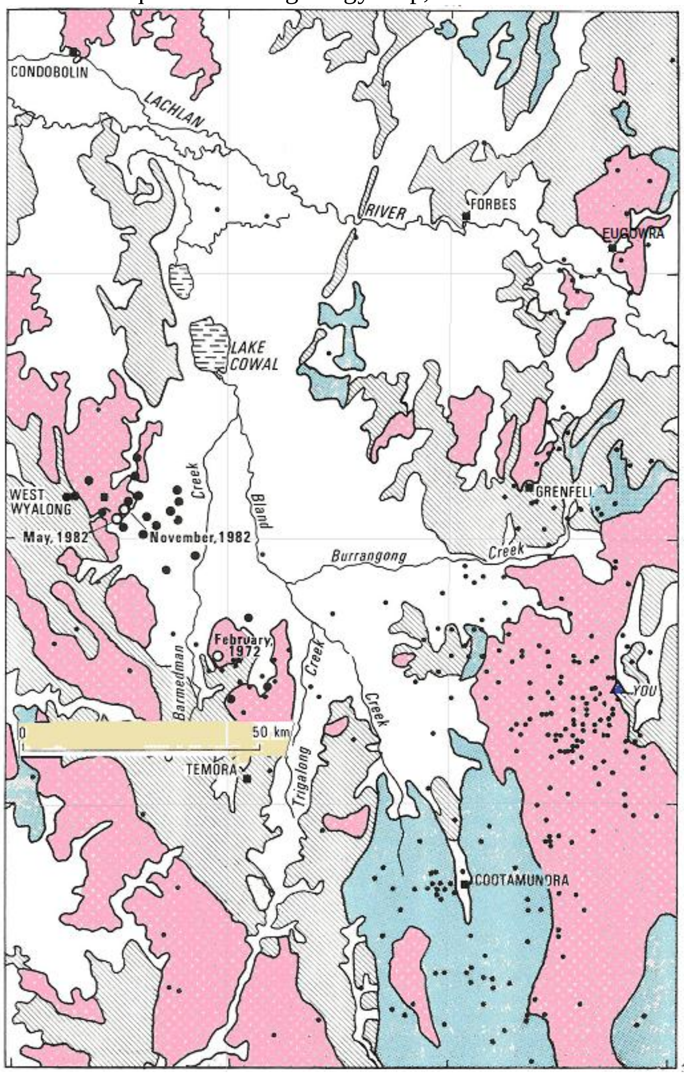



**Table 5** – Significant earthquakes in the region of Figure 8 since 1983

| ML | Date | Time | latitude | longitude | depth | Near Town | RMS | stns | gap | Q |
|---|---|---|---|---|---|---|---|---|---|---|
| 3.9 | 05 Jan 89 | 20:48:27 | -33.820 | 147.120 | 0 | West Wyalong | | | | |
| 3.7 | 11 Oct 92 | 02:03:26 | -34.352 | 147.463 | 17 | N of Temora | | | | |
| 4.1 | 21 Aug 94 | 05:53:51 | -33.421 | 148.364 | 1 | Eugowra | | | | |
| 3.9 | 16 Oct 98 | 13:46:14 | -34.669 | 147.385 | 16 | Temora | | | | |
| 4.4 | 14 Mar 99 | 00:13:31 | -34.001 | 147.077 | 2 G | West Wyalong | .795 | 19 | 75 | C |
| 3.8 | 23 Nov 01 | 03:33:32 | -33.870 | 148.390 | 3.8 | Grenfell | .645 | 19 | 61 | B |
| 3.6 | 21 Dec 01 | 03:07:43 | -33.893 | 148.330 | 2.5 | Grenfell | .594 | 14 | 75 | B |
| 3.9 | 22 Aug 02 | 21:23:03 | -33.865 | 148.354 | 3.4 | Grenfell | .609 | 20 | 72 | A |
| 3.9 | 28 Feb 04 | 11:32:09 | -34.996 | 147.675 | 12.3 | Junee | .369 | 17 | 67 | B |
| 3.7 | 18 Jan 05 | 10:09:12 | -33.845 | 147.191 | 12.7 | West Wyalong | .564 | 8 | 144 | D |
| 2.5 | 13 Aug 12 | 07:54:42 | -33.488 | 148.316 | 1 | Eugowra | .470 | 7 | 49 | |
| 2.5 | 13 Aug 12 | 07:54:42 | -33.460 | 148.370 | 1.1 | Eugowra (relocation) | .135 | 7 | | |

RMS = root mean square of residuals
Gap = largest azimuthal gap between recording seismographs
Q = location quality assessment by analysts

### 4.2 Narromine, 1932

The sequence near Narromine in the early 1930s contains 17 identified events, although newspaper reports at the time indicate that there were probably many more (McCue, 2014). In the GA catalogue, it is only represented by two events (21$^{st}$ May and 7$^{th}$ June 1932), located at the time by single station locations by Riverview Observatory, Sydney. From McCue's work, the sequence appears to have commenced on 19$^{th}$ March 1930, with a single event (ML ~ 3.6). There was then a quiescent period until 2$^{nd}$ March 1932 when the next noted event, ML ~2.8, occurred. It was then quiet for another 11 weeks, when a period of high activity about 3 months long, commenced on 19$^{th}$ May with an event of magnitude ~ 3.0. The largest event in the series, ML ~ 5.0 occurred 2 days later on 21$^{st}$ May.

McCue (2014) assigns all events to the location of 32.3°S, 148.4°E, which is about 15 km southeast of Narromine, and 10 km east of the RIV location. It is in the southwest quadrant of the MM V isoseismal contour in his isoseismal map for the main event. This contour has an approximate diameter of 50 km, and considering the scattered nature of the felt report data used to construct the map, this location can be expected to have an uncertainty of the order of ±40 km.

On the 1:250k geology map this location falls on the approximate location of an inferred fault which separates the granite from Ordovician sediments. It must be remembered however that there are large uncertainties in this location, and while it is possible that this is the causative fault for the Narromine cluster, it is still possible that future mapping might present alternative explanations.

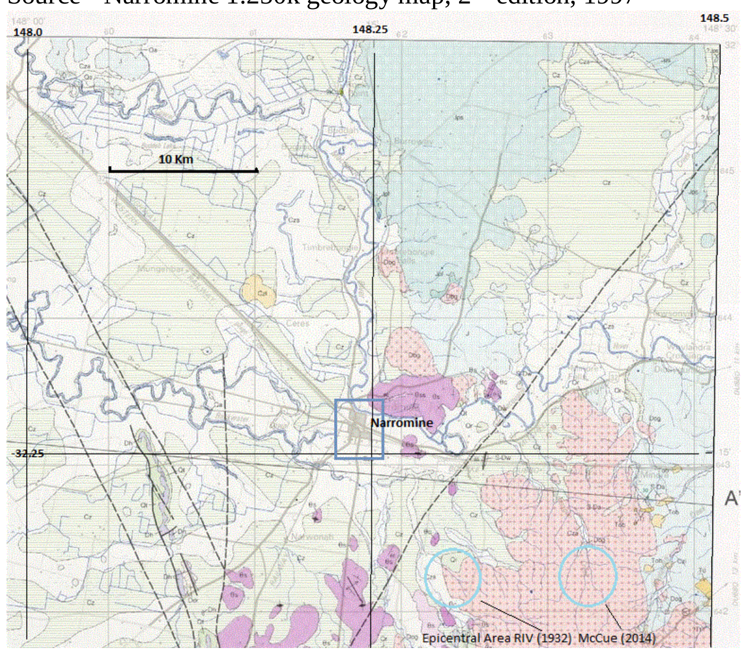



**Figure 12** Narromine Geology, and suggested cluster locations. Source - Narromine 1:250k geology map, 2$^{nd}$ edition, 1997

There has been little seismicity near Narromine since the 1932 activity, and the seismicity that has occurred was not apparently close to the 1932 activity. However, this lack of correlation is not very meaningful, given the poor constraints on the 1932 location, and the probable poor quality of locations since then anyway.

## 5 DISCUSSION

In order to establish a credible connection between earthquakes and their host geology, both good earthquake locations, and good geological mapping are required. With the current density of seismographs in western NSW, good locations (uncertainties ≤ 7 km) are not often achieved. More detailed geological mapping is also required, although deep weathering/ lack of outcrop, and overlying Cainozoic sediments can make mapping difficult. The events discussed here do not unequivocally support or discredit Love's observation that Australian earthquakes do not appear to occur on fault lines.

The events discussed here tend to support the suggested correlation between seismicity and granitic intrusions. Only the events near Sutton appear to be remote from any such intrusion.

Five of the six groups discussed are clustered, and two (Eugowra and West Wyalong) are swarm-like. The Narromine, Sutton and Young clusters also have some swarm-like characteristics. Only the Cowra event is isolated or solitary. The bias of these six groups towards clustering may be a genuine feature of the seismicity of the central west, and the subject warrants a more in-depth statistical analysis. Larger events in the region appear to be frequently clustered. With smaller events it is harder to tell because they are often poorly located, and/or smaller related events may be missed because they are below the earthquake detection threshold in the area.

Focal depths are difficult to determine accurately, but the two groups which are well located can be confidently stated to have very shallow focal depths – of the order of only 1 km. The only isolated event studied, the ML 4.2 event in 2006 near Cowra, had an estimated focal depth of approximately 15 km but the uncertainty is large (~ ±15km!).

The size of the source zones for cluster groups is also not clear because of uncertainties in location accuracy. However, the two well-located clusters suggest source zones about 2 km wide, or less. This is consistent with observations of cluster groups in the southwest of Western Australia, e.g. Dawson (2008) and Dent (2014). In recent years, about a dozen cluster groups of various sizes have been noted in this region each year.

The lifetime of cluster groups also is not clear. Seismicity at Eugowra seems to have continued since 1994, though at a much lower level. Gibson et al. (1994) also noted that some residents had recollections of similar swarm activity about 50 years earlier. The West Wyalong area also seems to have exhibited recurring activity since the major cluster of 1982. The important earthquake centre near Gunning seems to have exhibited recurring activity since the 1850s, when the first European settlers arrived in the area.

Outside of the NSW region, two localities in Victoria where clusters of shallow earthquakes have been frequently noted are at Bradford Hills southwest of Bendigo, and at Pyramid Hill about 80 km north of that location. Both of these locations are close to granite intrusions. No fault is apparent near Pyramid Hill, but the Bradford Hills events are considered to be from the north-south trending Muckleford Fault, which cuts through a granite intrusion near Bradford (G. Gibson, pers. comm.).

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