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A Review of Seismicity in Southwest Western Australia for 24 Months from July 2022 to June 2024

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Abstract

The wheatbelt region of southwest Western Australia is an area of elevated intraplate seismicity. The seismicity is highly clustered, with 80 active clusters identified over the last 20 years. This report reviews the seismicity between July 2022 and June 2024, which includes continuing seismicity from the Arthur River region, and a damaging magnitude 5.0 event near Gnowangerup. Most of the seismicity in this period occurs in 21 clusters; 10 were previously active and 11 are new. Of interest is the contemporaneous seismicity of 5 neighbouring cluster pairs, suggesting a possible causative link.

Keywords: Seismicity, Southwest Western Australia, Clusters

1 Introduction

The wheatbelt region of southwest Western Australia (SWA) is a region of elevated intraplate seismicity, and commonly known as "The southwest seismic zone" (SWSZ) of Western Australia, a term coined by Doyle (1971) when reviewing earlier work by Everingham (e.g. Everingham 1968). Denham et al. (1987) noted that the seismicity in this region is highly clustered with events occurring in groups confined within a small area. However, this observation was not elaborated on for the following 20 years.

Following initial reviews of cluster groupings in SWA and elsewhere by Dent (2008a, 2012), a study was commenced to identify and name cluster locations. Leonard (2008) suggested a "South West Australia Region" of enhanced seismicity – one of

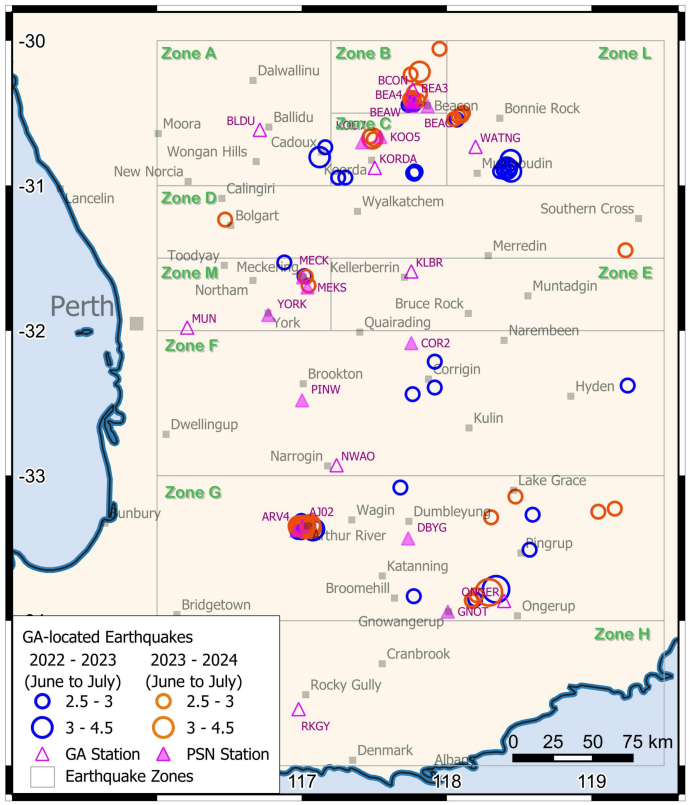

Figure 1. Location map. Earthquake Zones of Dent (2014; 2017). Earthquakes from July 2022 to June 2023 inclusive.

four such regions in Australia for which he discussed the seismicity. Leonard's South West Australia region was divided by Dent (2014) into 8 latitudinally-based sub-zones, and later revised (Dent 2017) to the 10-zone configuration shown in Figure 1. The seismicity of SWA between July 2012 and June 2022 has been analysed from a "clustered" viewpoint in 8 previous reports by Dent and co-workers (eg. Dent & Collins, 2018; Dent & Love, 2022). Seventy-five cluster locations had been proposed by the end of 2022 (70 clusters listed in Dent, (2021), and a further 5 in Dent & Collins, (2022)). They have been named according to the name of the zone within which they fall.

Clusters can be categorised as either "MainShock/Aftershock" sequences (MSAS), or "swarm-like", where there is frequently no "principal event". Seismicity in SWA is mainly of the latter variety, and where an event, or group of events is considered to be of the former category, it is not assigned a cluster location. However, the distinction between categories can become difficult and debatable at times.

In this report, earthquakes and groups of earthquakes are considered; most are assigned to previously identified cluster locations but some locations are new. The predominant source of events during the period studied here was a small region about 10 km SW of Arthur River. This sequence started with an ML 4.0 event on 8 January 2022, followed by an ML 4.8 event on 26 January 2022 (Murdie et al., 2022, Dent & Love, 2022).

2 Earthquake Locations

Most earthquake locations are derived by Geoscience Australia (GA), and they usually have uncertainties quoted of about +/- 5-10 km. Most of the events were also recorded on the Public Seismic Network (PSN), a network of seismographs supported by the Australian Centre for Geomechanics (ACG), which commenced in 2006 (Dent, Heal & Harris, 2006). Locations of the PSN stations operating in 2022-24 are shown on the larger-scale maps following Figure 1 and listed in Appendix 3. Data from these stations have been added to the GA data to derive new locations, usually with a lower RMS of residuals, and therefore probably lower uncertainties in location. These re-locations were made using the EQLOCL location program (© SRC, Melbourne) and the WA2 velocity model (Dent, 1989), and were used to assign locations to the cluster groups.

While the uncertainty in these locations varies from earthquake to earthquake, it is considered that in the majority of cases, relocations have uncertainties of < +/- 5 km.

The analysis here has been conducted in three sections: Events between 30-31°S (Zones A, B, C and L), events between 31-32°S (Zones D, E and M) and events between 32-35°S (Zones F, G and H) - see Figure 1.

3 Earthquakes between 30-31°S (Zones A, B, C, L)

3.1 Zone A, Cadoux region

Zone A (Figure 2) has been the site of intense seismic activity over the last 70 years, but was relatively quiet in this study period. A damaging ML 6.2 earthquake occurred at Cadoux in 1979 (Lewis et al., 1981), and an ML 5.5 event at Gabalong in 1955 (Everingham et al., 1982). A major group of events also occurred near Burakin between 2000 and 2002 (Leonard, 2002).

Three small events (MLs 2.2-2.4) in August and September 2022, occurred at location A2, the centre of the major Burakin series of 2001-2002 (Dent et al., 2021).

An ML 4.4 event occurred 4 km south of Cadoux in August 2022. The EQLOCL relocation for this event is about 7 km SW of the GA location and is shown in Figure 2 and listed in Appendix 2(a). It is close to 3 other smaller (ML~2.2) contemporaneous events. This group is classified as an MSAS group, rather than a cluster group (Table 4).

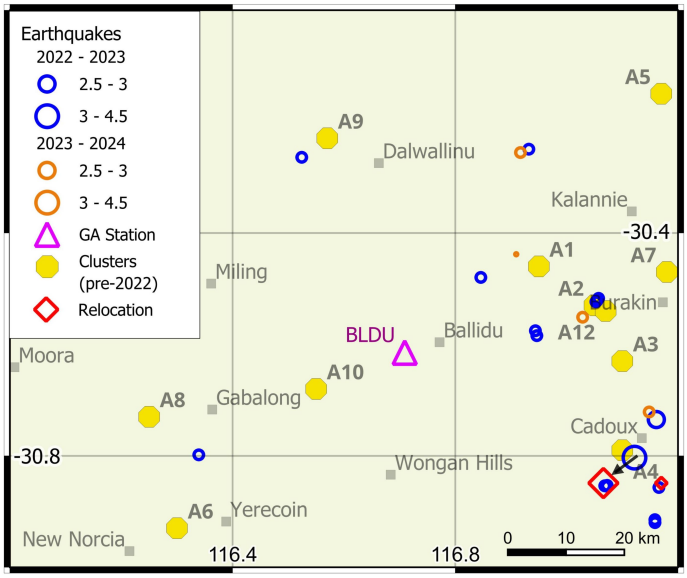

Figure 2. Seismicity in Zone A (Cadoux region)

3.2 Zone B, Beacon

During the 2-year study period, there were two periods of high seismicity NW of Beacon – in October/November 2023, and in May/June 2024 (Figures 3a, b). The group in May/June 2024 was the larger of the two, with 25 events in May 2024, and these plot to the south of the 2023 group. It is suggested that these events originated from location B2, and the earlier events from location B1, about 20 km to the north.

Relocations of the two largest events (October 2023 and May 2024, both ML 3.3) moves each of them about 5 km to the southwest, bringing them closer to cluster centres B1 and B2 (Figure 3b). Relocations of some of the other events also bring them closer to these locations. A small event (ML

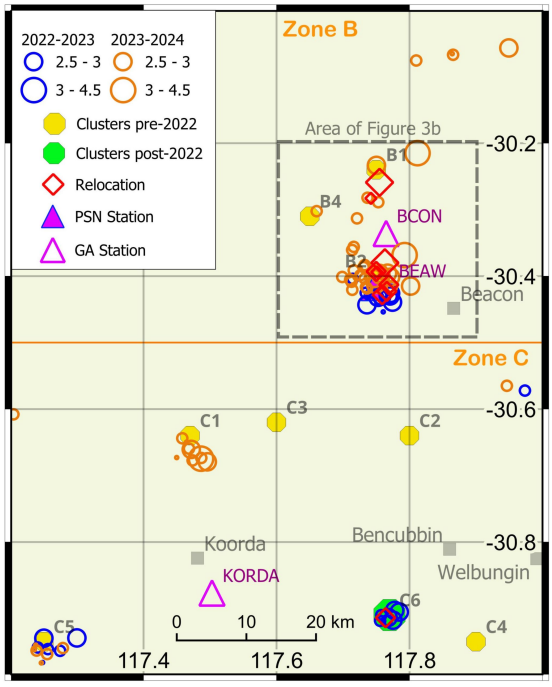

Figure 3a. Seismicity in Zones B & C

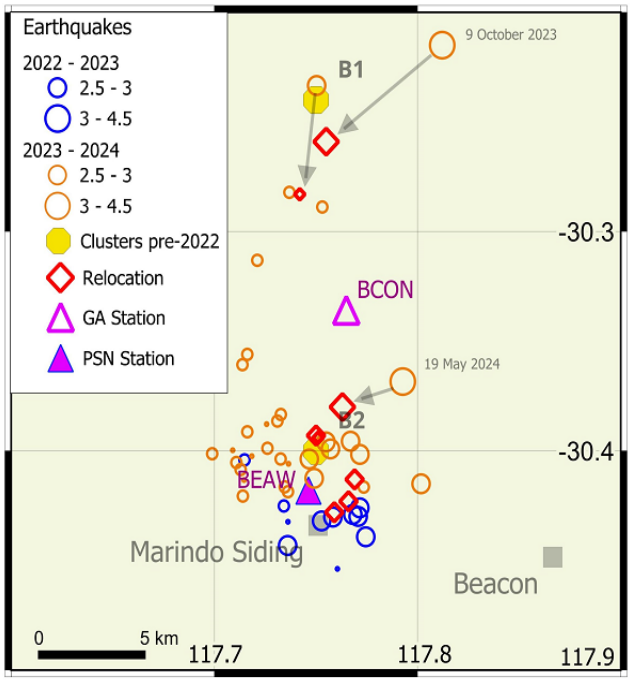

Figure 3b. Seismicity northwest of Beacon

2.2) which was located near cluster location B4 was a part of the November 2023 B1 sequence and is probably poorly located.

3.3 Zone C, Koorda region

The plot of seismicity in zone C (Figure 3a) shows three cluster groups. Cluster C5, about 30 km SW of Koorda, was first noted from relatively intense activity in April 2021, and activity has continued since then, though it has declined. There were 12 events from this location in the study period, with the majority, including the 2 largest events (both ML 2.7), occurring in the first 12 months.

The second cluster location is C1, about 20 km north of Koorda. This location exhibited intense cluster activity in 2011-2012, but showed only occasional activity until April-May 2024, when 9 events occurred (largest ML 3.3). C1 may represent the same location as two ML 4+ earthquakes which occurred in 2004 and 2005.

The third cluster in zone C is SW of Bencubbin. This is a new cluster location, with 7 events in the group, occurring between late November 2022 and January 2023, with the largest event (ML 2.9) at the beginning of the activity. This group is identified as (new) cluster group C6 (Table 2)

3.4 Zone L, Mukinbudin – Bonnie Rock

A cluster of events occurred east of Mukinbudin, mostly in November 2022, and is identified as a new cluster location L7. There were 24 located events, the largest ML 3.5. The assigned location of L7 (Table 2) takes into account the relocations of some of the larger events in the group. It is notable that there have been several other cluster sites active in the Mukinbudin area over the last 5 years (L3, L5, L6).

The group in the northwest of Figure 4, which occurred mainly in October 2023, has also been identified as a new cluster location L8. The location of L8 has been based largely on relocations of some of the larger events in this group.

It is noted that the clusters east of Mukinbudin (L7) and SW of Bencubbin (C6), about 60 km apart, were active contemporaneously in November 2022 (Table 5).

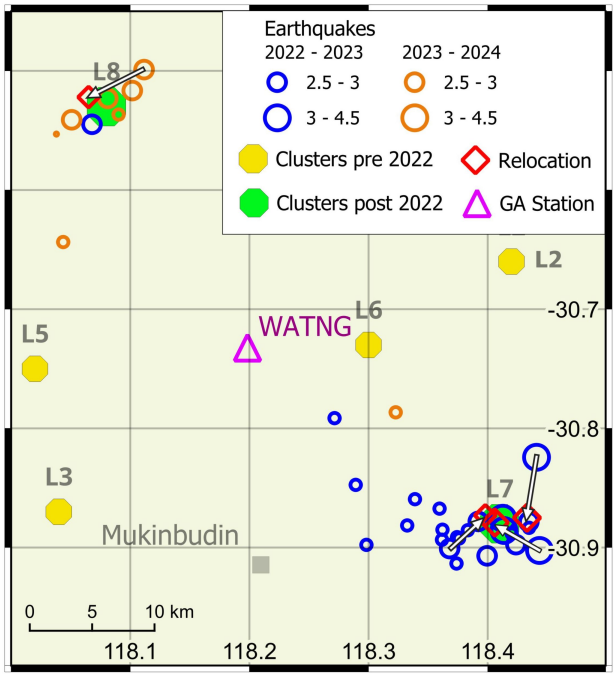

Figure 4. Seismicity in Zone L (Mukinbudin). Arrows link original GA locations with their relocations.

4 Earthquakes between 31°-32°S (Zones D, M & E)

Events in this region are shown on Figure 5a, with the Meckering, and "west of Quairading" regions shown in more detail in Figure 5b.

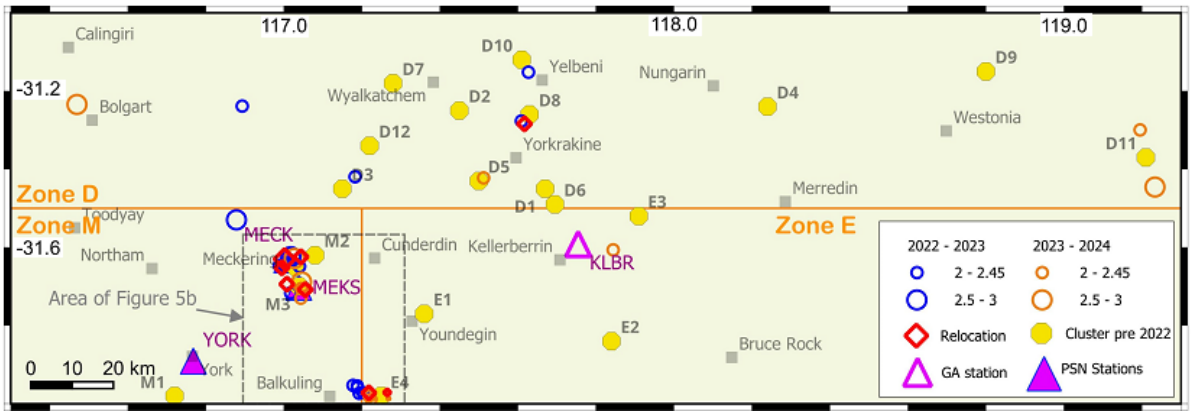

Figure 5a. Seismicity in Zones D, M & E

4.1 Zone, D Bolgart – Westonia (31.0 – 31.5 °S)

The only event of ML 2.5+ was a solitary event north of Bolgart (Figure 5a). While the seismicity has been low in the Bolgart region for the past 50 years or so, it contains the ML 5.1 Bolgart earthquake of March 1952 (Everingham et al., 1982), and was a region of high seismicity between 1968 and 1971, culminating in the Calingiri event (ML 5.7) of March 1970 (Gordon & Lewis, 1980).

A single ML 2.3 event near cluster location D8 on 1 August 2022 appears unremarkable, but this location became the focus of a brief period of high seismicity (58 located events, largest ML 4.5) in July & August 2024 (ie, immediately after the period studied here). Relocations by the author suggest the centre of the 2024 activity is close to 117.61°E, 31.28°S, only about 1 km from the GA location of the 2022 event. Location D8 has been added to Table 1, which shows previously identified clusters showing activity in the 2022-2024 period.

4.2 Zone M, Meckering

The 11 events near Meckering are shown in Figure 5b, and they can be considered as continuing aftershocks of the damaging ML 6.8 event in 1968 (Gordon & Lewis, 1980). They are on the hanging wall side of the surface-rupturing reverse fault and seem to define a north group (mostly in November 2022) and a southern group (mostly in June 2024), roughly correlating with the identified cluster locations of M4 and M3.

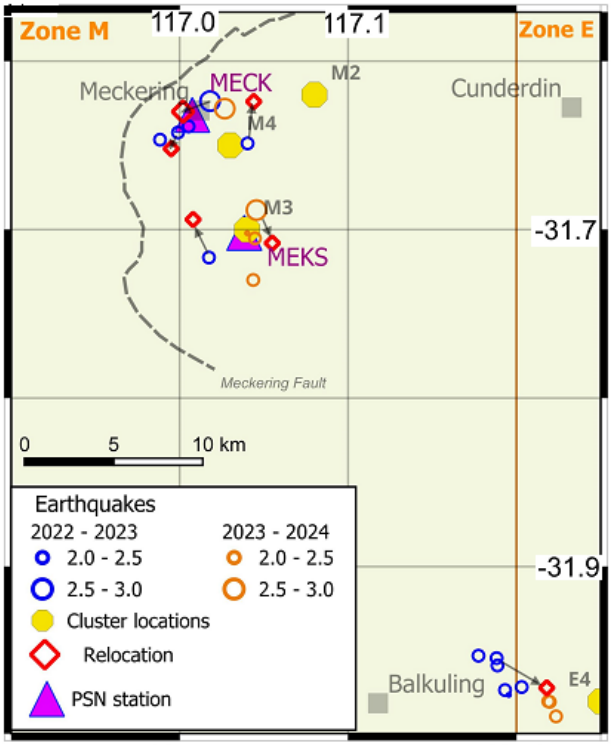

Figure 5b. Seismicity Meckering to Balkuling

Table 1. Cluster locations identified prior to 2023 and deemed active during this study

Place	Name	Location	Max ML	Number	Date	Comment
Burakin	A2	117.05 -30.53	2.4	3	Aug-Sep 2022	Site active, 2001
N of Beacon	B1	117.75 -30.24	3.3	5	Oct-Nov 2023	Site active, 2009
NW of Beacon	B2	117.75 -30.40	3.3	38	May 2024	Site active, 2012
N of Koorda	C1	117.47 -30.64	3.3	10	May 2024	Site active, 2012
SW of Koorda	C5	117.25 -30.95	2.7	12	Spread over time	
SE of Wyalkatchem	D8	117.63 -31.26	2.3	1	1 Aug 2022	Site active, 2024
W of Quairading	E4	117.25 -31.98	2.4	10	May 2023	Site active, 1992
SE of Newdegate	G3	119.16 -33.21	2.6	3	Oct 23-Jan24	
Arthur River	G11	116.97 -33.37	4.1	158	Feb 2023	
NW of Wagin	G12	117.14 -33.25	2.4	3	July 2022	

4.3 Zone E

The only group of significance in Zone E is the group west of Quairading. This group, which crosses westwards into Zone M, is shown in more detail in Figure 5b, and represents a continuation of activity which began about 2 years earlier. This location was named E4 in Dent and Collins (2018), based on a group of events in (2012). The plot of events in Figure 5b suggests a possible NW trend, as was also noted for events in 2020-2021, when it was suggested (Dent, 2021) that the E4 location might be better regarded as two locations, E4 (east) and E4 (west). An alternative possibility is that there may be an elliptical or linear structure present. More precise earthquake locations (ie, locations using well-sited arrays of close seismometers operating at high sampling rates) are required to resolve this.

More significantly, it is suggested that events at this location represent a renewal of activity which was first noted as a significant swarm location in 1991 – 1992, when a cluster of 35 located events occurred (largest ML 3.3, Dent & Collins, 2018). Other than one small event ENE of Kellerberrin (ML 2.3, July 2023), there do not seem to be any other events in Zone E.

Table 2. New cluster locations identified in this report (ie, since Dent & Collins (2023)

Place	Name	When	Max	Num	Location
SW of Bencubbin	C6	Nov 22 – Feb 23	2.9	7	117.77 -30.91
E of Mukinbudin	L7	Nov 22	3.5	24	118.41 -30.88
SE of Beacon	L8	Oct 23	3.0	7	118.08 -30.53
W of Brookton	F11	Aug 2022	2.4	4	116.92 -32.37
S of Narembeen	F12	Jan- Mar 2023	2.2	3	118.40 -32.18
SW of Corrigin	F13	Dec 2022	2.7	4	117.75 -32.46
SE of Corrigin	F14	Jan-Feb 2023	2.5	4	117.91 -32.39
N of Kulin	F15	Nov 2023	2.4	2	118.15 -32.62
SW of Lake Grace	G13	Jun-Aug 2023	2.6	7	118.24 -33.29
E of Gnowangerup	G14	Jun 2024	2.4	5	118.29 -33.95
SW of Gnowangerup	H4	Oct 2022	2.4	4	117.94 -34.04

5 Earthquakes between 32°-35°S (Zones F,G and H)

5.1 Zone F, Brookton to Hyden (32°-33°S)

Seismicity in this zone was relatively minor and is shown in Figure 6. Five small cluster groups can be seen, all of which are new.

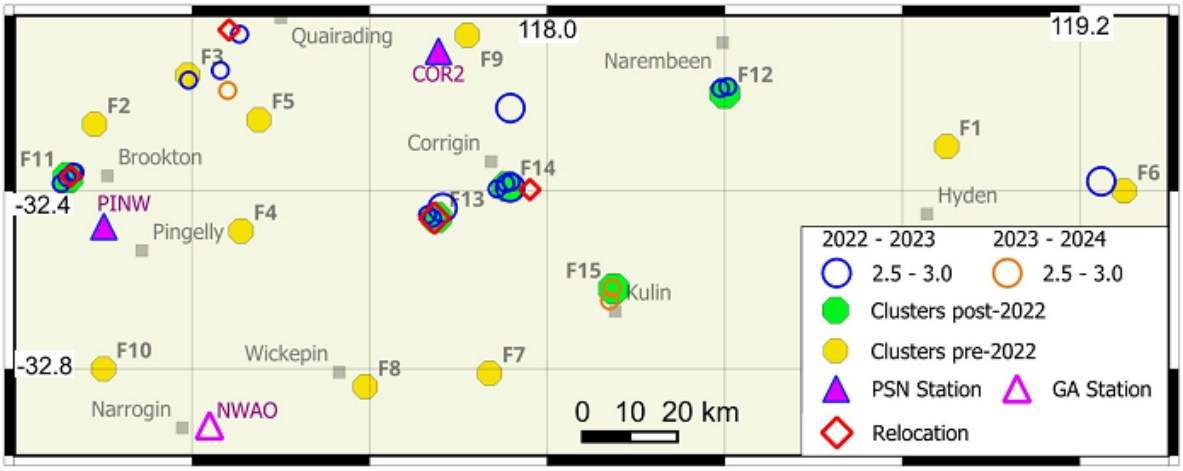

Figure 6. Seismicity in Zone F

A group of 4 small events (all in August 2022, largest ML 2.4) occurred W of Brookton (Figure 6). There is no other recent seismicity near this location, and the approximate central point is here defined as a new cluster location F11 (Table 2). Very few events occur west of this location, and these events may represent the approximate western boundary of the "SWSZ".

Two small events are seen S of Narembeen in early 2023 and a third occurred 2 days before the study period began. All events were ML 2.2, and this location is here given the identity of F12 (Table 2).

Seven events, comprising two cluster groups, about 20 km apart, can be seen southwest, and south, of Corrigin, mostly between December 2022 and February 2023. The largest event of the southwest group was ML 2.7, and for the southeast group, ML 2.5. Relocations of these two events using additional (PSN) data shows no significant errors present, and the events are assigned to two cluster locations, F13 and F14 (Table 2) at the GA locations for the largest events respectively. Significantly, these two clusters are basically contemporaneous, and listed in Table 5, with the seismicity within each of them occurring between December 2022 and February 2023. However, any causal relationship between the centres is not known.

There were two events north of Kulin (ML 2.2 and 2.4) in November 2023; this is also a new cluster location, and is given the identity of F15 (Table 2).

5.2 Zone G, (33°-34°S, Katanning region)

Figure 6 shows an apparently isolated ML 2.7 event in April 2023, about 50 km east of Hyden. It is listed in Table 4 as an isolated event, although it falls close to cluster location F6.

Two very significant groups of events occurred in Zone G (Figure 7a). The first, about 10 km SW of Arthur River is continuing activity from an ML 4.8 event in January 2022, and the second, an ML 5.0 event east of Gnowangerup occurred in August 2023. The Arthur River event produced a clear InSAR

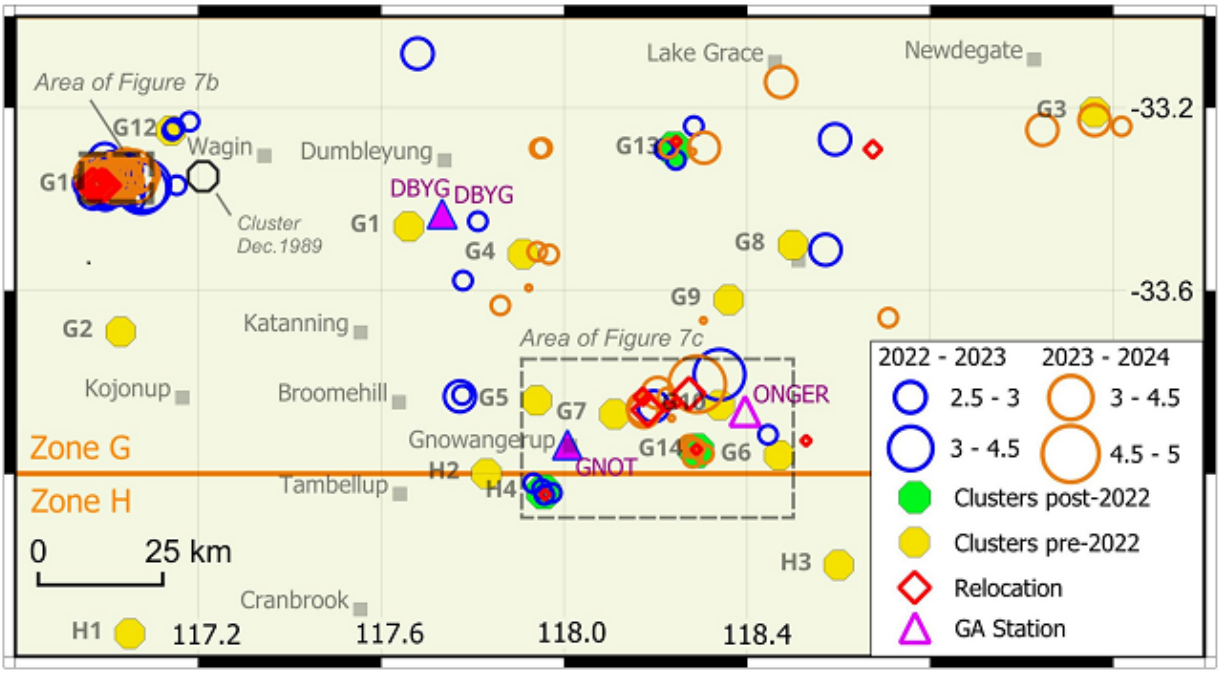

Figure 7a. Seismicity in Zone G

(Interferometric Synthetic Aperture Radar) signal (pers. comm., S. Valkaniotis, 2022, and reproduced in Murdie et al., 2022), while only a vague signal resulted from the 2023 Gnowangerup event (pers. comm., Dan Clark 2023). Note that an ML 4.8 event in October 2007, southwest of Broomehill, known as the "Katanning" earthquake (Dawson et al., 2008) and shown in Figure 7a, also produced a good InSAR signal and visible ground deformation.

5.2.1 The Arthur River seismicity

The activity during this period is a continuation of the seismicity following an ML 4.8 event on 26 January 2022 (Murdie et al., 2022). Events between July 2022 and June 2024 are shown in more detail in Figure 7b. The largest events in this period were in February 2023 (ML 4.1), September 2023 (ML 3.6) and February 2024 (ML 3.6).

Up to 10 temporary seismographs were deployed in the area, and the seismicity for the first 9 months of activity was discussed by Murdie et al., (2022) and Dent & Love (2022). Seismicity for the following year was discussed by Dent & Collins (2023). As mentioned in Murdie et al. (2022), relocations of GA solutions have often resulted in large shifts in location, some shifts approaching 10 km. Generally, the new locations are west to SW of the GA locations. While trends within the local seismicity were hard to determine, the seismicity broadly matched a tabular region identified by InSAR where an approximately 2 cm ground uplift had occurred (Figure 7b), (pers. comm., S. Valkaniotis, 2022).

Two stations installed in the epicentral area shortly after the sequence commenced (AJ02, ARV4, Figure 7b) have continued to operate into 2024. When their data are added to data from the GA network, locations can be significantly improved. About 40 events since July 2022 have been relocated in this manner, and relocations for the 12 events of ML 3.0 or greater (Table 3) are shown in Figure 7b. The largest event (ML 4.1) on 5 February 2023 relocates about 12 km westwards, to a location close to G11, the approximate centre of seismicity identified in Dent & Collins (2022). The other ML 3-plus events also relocate to within 2 km of this location. While good relocations of smaller events are

distributed over the entire uplifted region, the majority of the seismicity seems to occur in the southern portion.

Table 3. Arthur River events greater than ML 3.0, July 2022 – June 2024

Date/time	GA computed values					Relocation			
	Lon°E	Lat°S	ML	Dep.	RMS	Lon°E	Lat°S	Dep.	Pha.
2022-09-15_20:00:28.965	117.000	-33.337	3.0	2.1	0.68	116.984	-33.368	2.0	7
2022-12-25_17:47:56.144	117.032	-33.331	3.0	5.0	0.77	116.970	-33.363	3.3	7
2023-02-03_05:16:22.087	117.076	-33.376	3.2	5.3	0.83	116.972	-33.378	1.8	7
2023-02-05_00:39:57.733	117.084	-33.369	4.1	5.6	0.96	116.987	-33.372	1.9	8
2023-02-06_10:44:18.181	117.010	-33.352	3.0	5.0	0.78	116.971	-33.377	3.7	6
2023-09-01_06:07:36.36	116.989	-33.350	3.1	1.6	0.70	116.970	-33.360	3.4	8
2023-09-02_08:49:10.208	117.057	-33.340	3.6	5.0	0.93	116.995	-33.370	2.1	10
2023-11-10_05:09:19.747	116.978	-33.349	3.2	5.0	0.79	116.987	-33.362	3.7	5
2024-02-10_10:18:37.413	117.045	-33.360	3.0	5.0	0.84	116.989	-33.374	2.2	5
2024-02-10_10:20:11.956	117.061	-33.359	3.6	5.0	0.68	116.967	-33.369	3.3	5
2024-06-19_10:39:38.871	117.019	-33.361	3.1	1.7	0.95	116.989	-33.361	3.2	7
2024-06-21_20:31:58.128	117.011	-33.347	3.1	1.1	1.02	116.984	-33.365	3.3	9

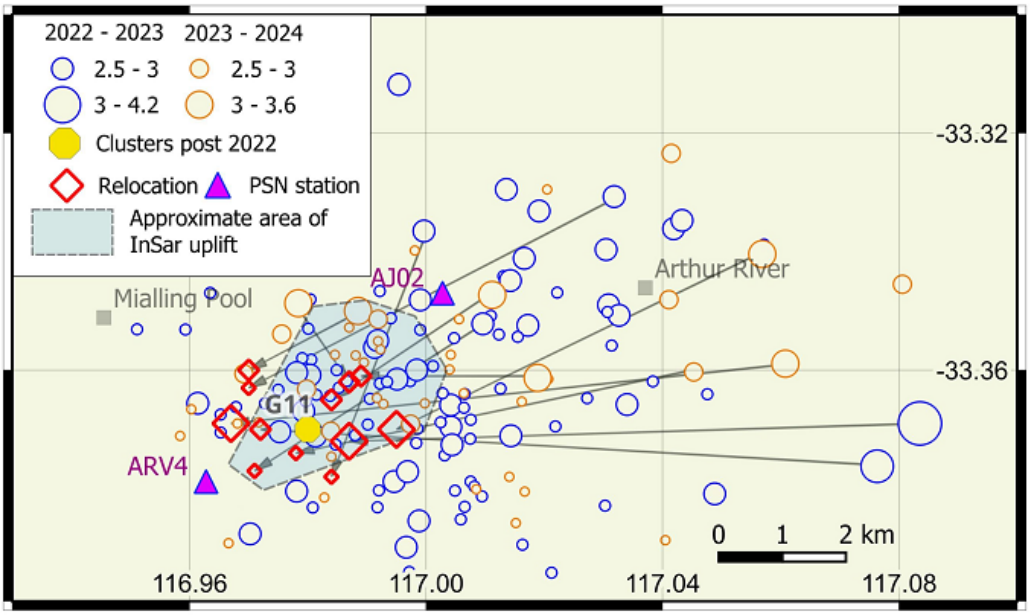

Figure7b. Seismicity near Arthur River, with relocations of events greater than ML 3.0

Because there are insufficient data from close stations, the focal depths computed are unreliable. However, the short S-P times at stations AJ02 and ARV4 indicate that the events are shallow, at about 3 km deep or less. Much of the seismic data collected in this region is still to be analysed, and refined focal depths and epicentral trends may be published in the future.

As noted in Dent & Collins (2022), a cluster of 12 located events occurred in December 1989, about 15 km to the east of the 2022-2024 activity. The largest was ML 2.6, with a central point for the cluster at 33.35°S, 117.21°E, about 11 km SW of Wagin (Figure 7a). This location is approximate because the closest seismograph at the time was NWAO, about 80 km north of the epicentres.

5.2.2 Gnowangerup area seismicity

The other group of important events in Zone G are those around an ML 5.0 event which occurred near Mindarabin, about 30 km NE of Gnowangerup, on 5 August 2023. This region is shown in more detail in Figure 7c. The earthquake caused major structural damage to the only farmhouse in the area. GA did not locate any aftershocks of the event in the 5 months following the ML 5.0 event, although two events in the previous month (both ML 2.6) could be foreshocks. However, the PSN station near Dumbleyung (DBYG), ~70 km to the NW Figure 7a), detected 6 events in the following two days, with the largest estimated at ~ML 2.3. These 6 events cannot be located with any reliability, because they were not recorded by other stations - the GA station ONGER, (~15 km from the epicentre), was not brought back into service until 22nd Aug., 17 days after the ML 5.0 event.

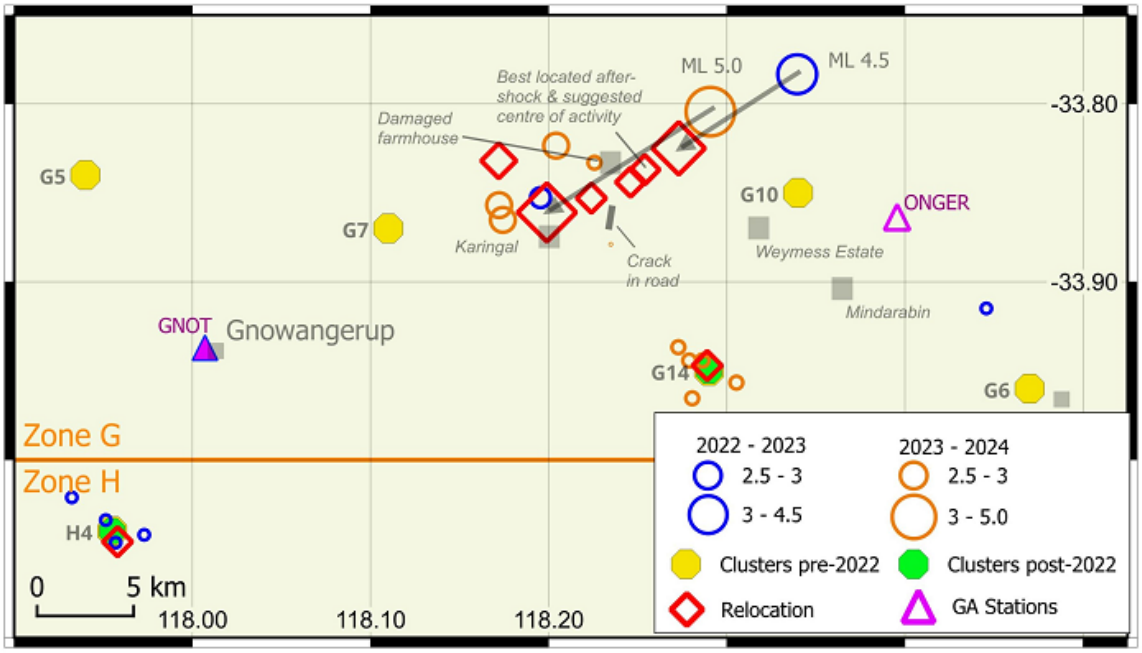

Figure 7c. Seismicity in the Gnowangerup area

The PSN station at Gnowangerup (GNOT, Figure 7c) was reoccupied from 11 August 2023, 5 days after the main event, and detected about 4 aftershocks in the first week of its operation. These all had S-P times of close to 2.9 secs at GNOT. The largest of these, on 16 August at 18:26 hrs UTC, had an estimated magnitude of ~ ML 2.2, and was also recorded on PSN stations at DBYG and PINW, and so a location can be determined. This location (118.254°E, 33.837°S) is plotted on Figure 7c, and listed in Appendix 1, and is within 1 km of the damaged farmhouse. It is probable that the main shock and aftershocks all originated at close to this location. This location is within the stated margin of error for the GA and Seismological Assoc. of Australia (SAA) locations of the main event, listed in Appendix 1.

There must have been many more small events as the farmer, whose house was damaged, reported “almost non-stop” seismicity for about a week following the ML 5.0 event. A NNE orientated crack in a gravel road, about 2 km south of the farmer’s house, was found by the farmer after the event. This feature traversed the road and probably continued into bush areas either side of it (Figure 8).

This group of events is considered to be a Mainshock/Aftershock sequence and listed in Table 4. It is not considered a cluster location. Occasional events well after the main shock (e.g. two events in May 2024, and another in July 2024) are probable aftershocks.

Significant clusters of small events (largest ML 2.3) have been noted near this location in the past – ie, at the Wemyss Estate in 1991 and Karingal in 2007 (Dent, 2008b).

A group of 5 events can be seen on Figure 7c, approximately 40 km ESE of Gnowangerup. They occurred between April and June 2024 and are assigned to a new cluster location G14 (Table 2).

5.2.3 Events southeast of Newdegate

Three events SE of Newdegate (ML 2.6, 2.5 & 2.3) may represent continuing activity from cluster location G3 (Figure 7a). The largest previous event at this cluster location was an ML 4.3 event in June 2019, and there have since been occasional events near there, sometimes relatively large. This sequence, which is classified as a "cluster", has some similarities with the 2023 Gnowangerup event (classified MSAS), i.e., there was one large event, while other events were infrequent and spread out over many months.

Figure 8. Crack in north-south road east of Gnowangerup

Five events in June and August of 2023, about 30 km SW of Lake Grace, are allocated to a new location called G13 (Table 2). The largest event was ML 2.6 and was the second of 3 events on 27 August 2023.

5.3 Zone H, (34°-35°S) Tambellup, Cranbrook – Rocky Gully

Seismicity in this region, south of 34°S, is shown in Figure 7c. It is a region of low seismicity, although the Lake Muir events of 2018 were an exception to this. Only 3 cluster locations have been located in this zone so far – H1 (N of Rocky Gully, Dent, 2014), H2 (NE of Tambellup, Dent, 2020), and H3 (SE of Borden, Dent, 2021). In this study period, four small events SW of Gnowangerup occurred in October 2022 (Figure 7c). The largest was ML 2.4, and the average location is 34.04°S 117.95°E which is defined here as a new cluster location H4 (Table 2).

6 Solitary events and Mainshock/Aftershock sequences

Events which may belong in this category are listed in Table 4. At times it can be hard to determine into which category a group of events may belong. The most important factor is the difference in magnitude between the "main" event, and the majority of the "coda" events. If the difference is 1 magnitude unit or greater, it will generally be classified as an MSAS sequence because "swarm" sequences generally have several "main" events of similar size. In this report, the Arthur River sequence is classified as a "swarm" as the two largest events were ML 4.8 and ML 4.1, and there were a very high number of subsequent events. The 5 August 2023 ML 5.0 Gnowangerup event is classified as an MSAS event. There were no located aftershocks at the time it occurred. However, approximately

6 months beforehand, there was an ML 4.5 event close to the mainshock location.

The point to be taken is that, even if an event appears to be "solitary", it may be related to a previous event, which may have occurred months, years, or even decades beforehand.

Table 4. "Isolated" and MSAS earthquakes July 2022 – June 2024 (ML >= 2.5)

Place	When	Max ML	Comment
Off Augusta	17/08/2022	3.3	Off southwest coast
Cadoux	21/08/2022	4.4	Has 3 small aftershocks?
Gnowangerup	05/08/2023	5.0	Suggested epicentre is 118.25 -33.84
SW of Southern Cross	08/11/2023	2.6	Similar to ML 2.8 event, November 2023
S of Goomalling	11/01/2023	2.6	
N of Bolgart	04/01/2024	2.5	Near location of ML 5.1 event, March. 1952
NE of Holt Rock	18/03/2024	2.7	Near cluster location F6

7 Discussion

In the above analysis, events were determined to have originated from 10 cluster locations which were previously recognised, and from 11 locations that have not been previously noted. The most significant cluster groups (from Arthur River and NW of Beacon) belong to the former category – although the seismicity recorded at Arthur River actually represents one continuing (but declining) sequence. The most significant of the "new" cluster locations is probably that found east of Mukinbudin (L7, Figure 4), which comprises about 24 located events, mainly in November 2022, the largest ML 3.5.

It has been noted that contemporaneous seismicity is sometimes observed at neighbouring clusters. While some connection could be envisaged for clusters within ~ 20km of each other, what could be described as contemporaneous activity has been observed at separations of 60 – 70 km. An example from the current study (Table 5) is the cluster pair E of Mukinbudin (L7) and SW of Bencubbin (C6), where the separation is ~ 60 km. It is also seen between the NW of Beacon (B2) and north of Koorda

Table 5. Suggested pairs/times of contemporaneous or related seismicity

Cluster pair	Separation (km)	Date	Region	Comment
F13, F14	20	Dec 2022 – Feb 2023	S of Corrigin	
C1, B2	40	May 2024	N of Koorda & NW of Beacon	Also in 2012
F1, F6	40	Mar 2013	N of Hyden & E of Hyden	Ref. Dent (2018)
C6, L7	60	Nov – Dec 2022	SW of Bencubbin & E of Mukinbudin	
G11, G12	15	Mar – Jul 2022	SW of Arthur R. & NW of Wagin	
A2, A3	18	Sep 2000 & Sep 2001	NW of Cadoux	Leonard 2001

(C1) clusters, and between the Arthur River (G11) and NW of Wagin (G12) clusters. Similar contemporaneous seismicity between the north of Hyden cluster (F1) and north of Holt Rock cluster (F6) was noted by Dent (2021). A reason for contemporaneous seismicity is not clear. There do not appear to be any geological structures which could potentially link the events. Perhaps the best explanation is that continued shaking from one location has destabilised the equilibrium which may exist in a neighbouring fault or fault complex.

One interesting event was the “isolated” ML 2.5 event north of Bolgart, as it is close to the location of an ML 5.1 event in 1950, and also relatively close to the Calingiri event of March 1970. As aftershocks of large events can occur decades later, it is possible that this event is related to the 1950 Bolgart event.

A possible related phenomenon is “rapid stress transfer”. This mechanism was suggested by Leonard & Boldra (2001), to relate a sustained period of high seismicity from a location north of Cadoux (now named location A3) in September 2000, with the onset of a sustained period of high seismicity west of Burakin, beginning with an ML 5.2 event in Sept. 2001, (Leonard, 2002, Dent et al., 2021) at a location now named location A2. A2 is ~ 20 km NW of A3, and this pair of clusters is also listed in Table 5.

Relocations of events suggest that, in most cluster groups, all events could be placed at one central location, considering the epicentral uncertainties. However, with some cluster groups, this is not the case. For events in the Arthur River region, many of the events can be more accurately located because of extra field stations deployed in the area, and the locations suggest an epicentral zone about 5 km wide. There are suggestions of a NNE trend to epicentres within the zone, but more research is needed. The fact that these events are contemporaneous suggests a single fault system causing the seismicity. As it has not been possible to accurately locate events in most cluster groups, it is not possible to identify epicentral trends within them, if they are indeed present. A recent well monitored earthquake sequence from Jamestown, north of Adelaide (Love & Lade, 2024), provides an example where this is possible. The largest event was ML 4.1, and the sequence defined an apparent NW striking fault line about 1 km long, with events between zero and 1.2 km depth. Although the geological setting is different, similar dimensions may apply to many of the SWA cluster groups noted here.

There are other examples where cluster locations are closely spaced, and it is possible that they represent end points of a single structure. An example is the cluster pair B1 and B2 NW of Beacon. B1 and B2 are separated by about 10 km, with a north-south trend. The most recent activity at B2 at the southern margin of the cluster suggests it may be extending southwards. Another possible location that is not a “point source” is E4, west of Quairading, where Dent (2021) suggested there may be an E4 (east) and E4 (west), about 5 km apart. Better locations are needed to resolve this issue.

A potential problem arises when proposed cluster locations are close to the extent of uncertainties in earthquake locations. This problem may be partly resolved if a sub-catalogue of relatively well-located events arises from the SWAN (South West Australia Seismic Network) survey currently being conducted by the Geological Survey of WA, in conjunction with the Australian National University (Miller et al., 2023)

The observation that seismicity in the SWSZ generally occurs in well-defined clusters raises the question as to whether there is a limit to the number of seismically active locations, or whether anywhere in the region may host earthquakes in the future. While new cluster locations will likely be identified in the coming years, given time it may become apparent that some areas never host clusters and are essentially aseismic. At present it is not possible to say one way or the other, without a better understanding of the underlying reasons why clustering of earthquakes is a feature of this part of southwest Western Australia.

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Appendix 1. Relocations presented in this report (excluding the Arthur River region)

Relocated		ML	Date / Time (UTC)	Cluster or Zone	GA		Comment
Lon	Lat				Lon	Lat	
117.751	-30.394	2.2	2022-07-10_0330	B2	117.715	-30.404	NW of Beacon
117.769	-30.413	2.8	2022-07-25_2228	B2	117.736	-30.443	NW of Beacon
116.604	-32.462	2.4	2022-07-30_2141	Zone F	116.649	-32.405	N of Boddington
117.619	-31.284	2.3	2022-08-01_0046	D8	117.609	-31.277	SE of Wyalkatchem
118.675	-33.291	2.6	2022-08-04_2130	Zone G	118.592	-33.269	SE of Lake Grace
117.170	-30.849	2.2	2022-08-20_1115	Zone A	117.166	-30.857	Manmanning
117.066	-30.849	4.4	2022-08-21_0437	Zone A	117.122	-30.803	W of Manmanning[3]
116.926	-32.367	2.4	2022-08-26_1207	F11	116.936	-32.358	W of Brookton
117.044	-31.624	2.2	2022-09-12_1711	M4	117.040	-31.649	Meckering
117.958	-34.046	2.4	2022-10-24_0152	G14	117.951	-34.034	E of Gnowangerup
118.245	-33.274	2.3	2022-11-06_1302	G13	118.284	-33.240	Lake Grace
118.398	-30.873	2.8	2022-11-14_0335	L7	118.284	-33.240	Mukinbudin
116.995	-31.652	2.3	2022-11-16_2026	M4	116.999	-31.642	Meckering
118.406	-30.879	3.2	2022-11-17_2134	L7	118.444	-30.902	E of Mukinbudin
118.433	-30.875	3.5	2022-11-21_2347	L7	118.441	-30.824	E of Mukinbudin
117.764	-30.914	2.9	2022-11-29_0444	C6	117.778	-30.903	SE of Koorda
117.283	-32.038	2.2	2022-12-07_2046	Zone F	117.307	-32.048	ESE of Quairading
117.746	-32.461	2.7	2022-12-18_0414	F13	117.764	-32.438	SW of Corrigin
118.225	-33.837	4.5	2023-01-05_0512	Zone G	118.340	-33.783	East of Gnowangerup[1,3]
118.273	-33.825	4.5	2023-01-05_0512	Zone G	118.340	-33.783	East of Gnowangerup
117.961	-32.397	2.5	2023-02-05_2236	F14	117.917	-32.392	SE of Corrigin
117.002	-31.630	2.7	2023-02-21_0928	M4	117.018	-31.624	Meckering
118.224	-33.853	2.5	2023-02-27_1130	Zone	118.195	-33.853	E of Gnowangerup[1]
118.246	-33.844	2.5	2023-02-27_1130	Zone	118.195	-33.853	E of Gnowangerup
117.766	-30.423	2.7	2023-03-03_1441	B2	117.774	-30.439	NW of Beacon
117.759	-30.428	2.9	2023-03-03_1442	B2	117.753	-30.432	NW of Beacon
116.676	-32.078	2.1	2023-03-30_2200	Zone F	116.692	-32.058	west of Beverley
118.529	-33.928	2.4	2023-04-22_1238	G14	118.446	-33.915	east of Gnowangerup
117.008	-31.694	2.3	2023-05-05_0912	M3	117.017	-31.717	S of Meckering
117.218	-31.972	2.4	2023-05-15_0234	E4	117.188	-31.954	WNW of Quairading
118.172	-33.832	2.6	2023-07-27_2137	Zone G	118.174	-33.865	E of Gnowangerup
118.183	-33.861	5.0	2023-08-05_2134	Zone G	118.291	-33.804	E of Gnowangerup[1]
118.199	-33.861	5.0	2023-08-05_2134	Zone G	118.291	-33.804	E of Gnowangerup
118.254	-33.837	2.3	2023-08-16_0826	Zone G	—	—	E of Gnowangerup[2]
117.755	-30.259	3.3	2023-10-09_0845	B1	117.812	-30.215	NW of Beacon
117.742	-30.283	2.5	2023-10-09_1840	B1	117.750	-30.233	NW of Beacon
117.265	-31.971	2.0	2023-10-10_2000	E4	117.268	-31.987	W of Quairading
118.065	-30.522	3.0	2023-10-19_0150	L8	118.102	-30.517	SE of Beacon
117.763	-30.380	3.3	2024-05-19_0351	B2	117.793	-30.368	W of Beacon
117.75	-30.393	2.9	2024-05-19_0824	B2	117.767	-30.396	W of Beacon
118.234	-33.830	2.8	2024-05-20_0611	Zone G	118.204	-33.824	E of Gnowangerup
117.055	-31.708	2.5	2024-06-14_0147	M3	117.046	-31.688	Meckering
118.289	-33.947	2.4	2024-06-21_0000	H4	118.279	-33.944	S of Gnowangerup

1 Solution by Seismological Soc. of Aust. (SAA)

2 Not located by Geoscience Aust. (GA)

3 Solution in Appendix 2

Appendix 2(a) EQLOCL solution for the Cadoux event, 21 August 2022

Date 2022-08-21 **Origin Time** 0437 1.93 +- 0.88 **Zone** 50
Easting 506.29 +- 5.77 **Longitude** 117.066
Northing 6587.14 +- 12.16 **Latitude** -30.849
Depth 7.09 +- 21.27

Arrival times = 9 **S.D.** = 0.144 **Seismographs** = 6
Nearest recorder = 41.9 km **Gap** = 135.9 deg **Accuracy** = B
Earth Model WA2 Run by: VFD

168 km NE (44 deg) of PERTH 3 km W (272 deg) of Manmanning **Assign ML** 4.4

DATA USED

Code	Wave	AT	+-	WT	CT	DT	Dist	Azim	Ad	Ae
KORD	P	8.72	0.10	1.35	8.86	-0.15	41.9	94	9.7	9.7
KORD	S	13.74	1.00	0.77	13.67	0.07	41.9	94	9.7	9.7
BLDU	P	9.00	0.10	1.35	9.06	-0.06	43.1	307	9.8	9.8
BLDU	S	14.20	1.00	0.77	14.00	0.20	43.1	307	9.8	9.8
KLBR	P	19.00	0.20	1.09	19.14	-0.14	105.3	141	4.0	4.0
KLBR	S	31.40	1.00	0.71	31.07	0.33	105.3	141	4.0	4.0
WATG	P	19.90	0.10	1.25	19.77	0.13	109.1	83	3.8	3.8
AKUL	P	35.20	0.20	1.02	35.22	-0.02	226.6	153	-42.2	42.2
NWAO	P	35.75	0.20	1.02	35.73	0.02	230.8	176	-42.2	42.2
Deferred Data										
WATG	S	33.60	1.00	0.71	32.14	1.46	109.1	83	3.8	3.8
AKUL	S	63.80	1.00	0.67	60.10	3.70	226.6	153	-40.3	40.3
NWAO	S	64.80	1.00	0.66	60.98	3.82	230.8	176	-40.3	40.3
ONGR	P	51.70	0.30	0.90	50.97	0.73	356.9	159	-42.2	42.2

Appendix 2(b) SAA solution for the Gnowangerup event, 05 August 2023

EQ Date: 2023-08-05 2134 43.20 ± 0.27 Gnowangerup 18km NE **Mag:** MLv 5.4

Longitude: 118.1830 ± 1.65 km
Latitude: -33.8608 ± 1.10 km **Depth:** 5.00 ± 1.75 km(Const.)

Arrivals: 16/22 **StdDev:** 0.404 **Sites:** 9/11
Nearest: 64.0 km (DBYG) Gap: 138.9° **Quality:** P Accuracy: C

Run by: DL **Run Date:** 2023-08-08 **eqFocus** 4.5.1 **Earth Model:** WA2

Active Arrivals:

site	phase	time	wt	calc	residual	dist	travTime	res/tt
DBYG	P	2134 53.75 ± 0.0	2.7	53.68	0.07	64.03	10.55	0.634
DBYG	S	2135 02.06 ± 0.0	2.7	61.35	0.71	64.03	18.86	3.760
ARV5	P	2135 03.22 ± 0.0	2.6	63.78	-0.56	127.33	20.02	-2.797
ARV5	S	2135 18.64 ± 0.0	2.6	79.13	-0.48	127.33	35.45	-1.359
AUALB	P	2135 03.99 ± 0.0	2.6	63.98	0.01	128.89	20.79	0.071
AUALB	S	2135 19.62 ± 0.0	2.6	79.48	0.14	128.89	36.42	0.393
AUKUL	P	2135 04.50 ± 0.0	2.6	64.45	0.05	132.13	21.30	0.235
AUKUL	S	2135 19.57 ± 0.0	2.6	80.31	-0.74	132.13	36.37	-2.037
NWAO	P	2135 04.90 ± 0.0	2.6	65.01	-0.11	136.17	21.70	-0.502
NWAO	S	2135 21.32 ± 0.0	2.6	81.30	0.03	136.17	38.13	0.086
RKGY	P	2135 05.44 ± 0.0	2.6	65.31	0.13	138.46	22.24	0.599
RKGY	S	2135 21.71 ± 0.0	2.6	81.82	-0.11	138.46	38.51	-0.295
KLBR	P	2135 21.33 ± 0.0	2.5	80.53	0.81	254.84	38.14	2.117
KLBR	S	2135 48.92 ± 0.0	2.5	108.67	0.25	254.84	65.72	0.385
KMBL	P	2135 43.64 ± 0.0	2.4	103.84	-0.19	443.82	60.45	-0.313
AUKAL	P	2135 46.17 ± 0.0	2.4	106.18	-0.01	462.85	62.97	-0.023

Deferred Arrivals:

site	phase	time	wt	calc	residual	dist	travTime	res/tt
PINW	P	2135 13.16 ± 0.0	2.5	72.01	1.15	186.75	29.96	3.823
PINW	S	2135 35.54 ± 0.0	2.5	93.64	1.91	186.75	52.35	3.640
COR2	P	2135 14.86 ± 0.0	2.5	73.88	0.99	200.91	31.67	3.122
COR2	S	2135 38.02 ± 0.0	2.5	96.97	1.05	200.91	54.82	1.922
KMBL	S	2136 28.39 ± 0.0	2.4	149.67	-1.28	443.82	105.19	-1.215
AUKAL	S	2136 31.19 ± 0.0	2.4	153.80	-2.61	462.85	107.99	-2.414

Appendix 3. Public Seismic Network stations in operation during 2022 - 2024

Code	Latitude	Longitude	Opened	Location, remarks
AJ01	-33.3582	116.9756	2022-02-19	Arthur Rv. -Rifle Range – intermittent only
AJ02	-33.3470	117.0028	2022-02-20	Arthur Rv. -Pascoe's - closed 06 Aug. 2024
AJ03	-33.3769	116.9929	2022-02-21	Arthur Rv. -Burgess' – closed 19 July 2022
ARV4	-33.3788	116.9628	2022-03-10	Arthur Rv. -Bird's
ARV5	-33.3528	116.9526	2022-06-08	Arthur Rv. -Rocky Ridge closed 19 July 2022
CADX	-30.7692	117.1360	2014-02-11	Cadoux
COR2	-32.0857	117.7457	2017-08-05	Corrigin – Caporn's
DBYG	-33.4231	117.7333	2021-07-27	Dumbleyung
GNOT	-33.9384	118.0071	2017-04-27	Gnowangerup Town (reopened 2023-08-11)
MEKS	-31.7018	117.0384	2018-12-11	Meckering South
MECK	-31.6316	117.0074	2015-12-03	Meckering
PINW	-32.4798	117.0010	2019-11-13	Pingelly Woolshed (replaces PING)
STHX	-31.2305	119.3263	2021-06-16	Southern Cross
TMBL	-34.0430	117.6380	2017-04-27	Tambellup – closed Feb. 2023