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A review of seismicity in the southwest region of Western Australia, July 2021–June 2022, with special reference to event clustering

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Abstract

Previous reports on southwest Western Australia (SWA) seismicity have identified 80 cluster locations, mostly from activity in the last 10 years. Earthquakes in the region in 2021–22 are reviewed here and allocated to cluster locations where considered appropriate. Most of the seismicity can be assigned to one of 18 cluster locations considered active during the year. The most significant seismicity for the year was southwest of Arthur River, from January 2022 onwards. This was one of the more significant seismic episodes in SWA for the last 50 years and is identified as a new cluster location. All but three of the cluster locations identified in this year were identified in previous studies. A four-tier rating system for clusters is introduced here, and the Arthur River cluster is rated “A”. Characterising the clustered nature of SWA seismicity is important to help us to understand the underlying geological causes of this behaviour, and to better inform the assessment of local earthquake hazard.

Keywords: Southwest Western Australia, seismicity, earthquake clusters

1 Introduction

Southwest Western Australia (SWA) is possibly the most active seismic region in mainland Australia. Around 1,300 earthquakes with a magnitude ML greater than 2.5 are listed for this region in the Geoscience Australia (GA) catalogue over the last last 30 years. For the same period, the only comparable region is the Flinders Ranges of South Australia and its surrounds, where GA lists around 500 earthquakes of similar magnitude. The seismicity in SWA is generally concentrated into clusters of events, and previous papers in this series (eg Dent 2016, Dent & Collins 2018, Dent 2021) have endeavoured to emphasise the clustered nature of earthquakes in SWA. In a report on an earthquake cluster north of Cadoux in October 2000 (Leonard & Boldra, 2001), Gibson is quoted as suggesting “clusters occur every 1–2 years in southwest Western Australia”. This frequency may be true if considering only “significant” (or large) clusters, but the eight reports in this series so far suggest that the majority of seismic events in SWA each year are “clustered”. About 10 to 20 cluster groups are active each year, some of which are continuing or recurring, and some of which appear to be new. Figure 1 shows earthquakes ML ≥ 2.5 in the region during 2021–22 from the (GA) earthquake catalogue, and the 80 cluster centres so far identified. In this report, the seismicity of the 12-month period from July 2021–June 2022 is reviewed to assess its clustered nature. To do this (as with previous reviews), seismic events are divided into three classes:

mainshock/aftershock events, cluster events, and isolated events—although the boundaries between these classes is gradational. Putting events into these categories can be assisted by careful analysis of existing data. In some cases, new phase data has been added and the events relocated. These relocations often reinforce the connections between events, which beforehand would have been questionable.

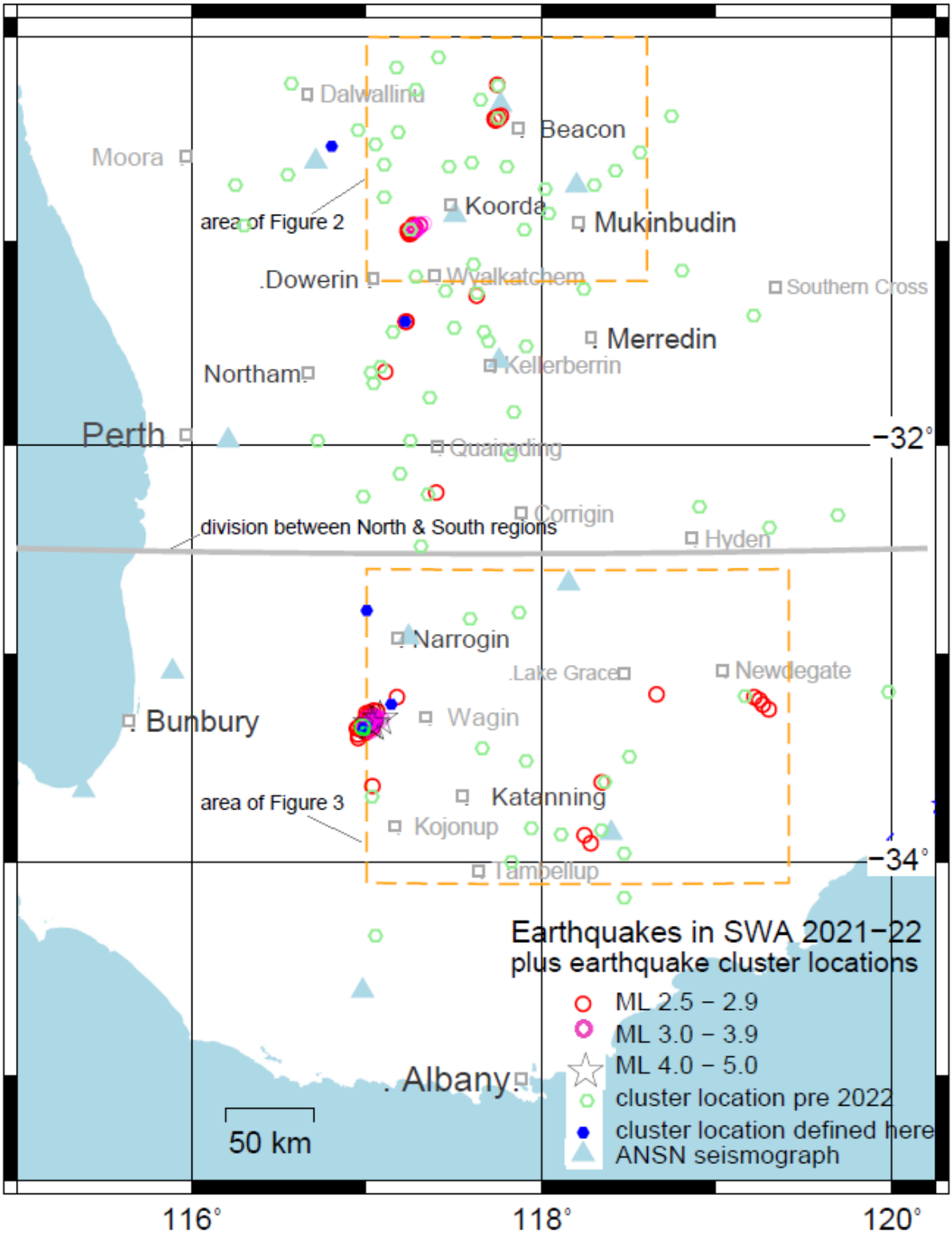

Figure 1. All events (133) of ML ≥ 2.5 in SWA in 2021-22. Table 1 shows the larger events from Arthur River (ML ≥ 4.0) and southwest of Koorda (ML ≥ 3.0), and the remaining events in SWA of ML ≥ 2.5.

1.1 Overview of seismicity in 2021–22

There were 457 events (ML ≥ 2.0) located by Geoscience Australia in SWA in 2021–22. Of these, four were of ML 4.0 or greater, all of which were part of the Arthur River sequence (the largest being ML 4.8). One hundred and thirty three of the 457 were ML ≥ 2.5, the largest annual number of such events in SWA since 1979, the year of the ML 6.3 Cadoux earthquake when 138 events ML ≥ 2.5 were recorded. Eighty-seven of the 133 ML ≥ 2.5 events were from the Arthur River area**.** The largest events for the year are shown in Table 1. These data show how seismicity in the year was dominated by the Arthur River activity.

Table 1. Large events of 2021-22 (Arthur River ML ≥ 4, SW of Koorda ML ≥ 3.3, the rest ML ≥ 2.5)

Date & Time	ML	Location	Lon	Lat	Cluster	N/S	Relocated lon/lat	
2021 07 04 0041	2.9	N of Cunderdin	117.228	-31.399	D12	N	117.236	-31.395
2021 07 18 2134	2.6	NW of Ongerup	118.244	-33.873	G10	S	118.325	-33.873
2021 07 19 0812	3.5	SW of Koorda (1)	117.277	-30.951	C5	N	117.247	-30.948
2021 07 27 1152	3.3	SW of Koorda (2)	117.327	-30.920	C5	N	117.247	-30.944
2021 08 07 0627	2.9	NW of Beacon	117.745	-30.236	B1	N	117.747	-30.250
2021 08 09 0930	2.6	N of Cunderdin	117.222	-31.401	D12	N		
2021 08 26 1758	2.6	NW of Kojonup	117.030	-33.610	Isolated	S	116.956	-33.628
2021 09 23 1034	2.7	SE of Newdegate	119.213	-33.215	G3	S		
2021 10 31 1655	2.5	SE of Lake Grace	118.655	-33.202	Isolated	S		
2021 11 14 2315	2.6	NW of Beacon	117.754	-30.404	B2	N	117.766	-30.379
2021 11 29 2002	2.5	NW of Beacon	117.767	-30.389	B2	N	117.758	-30.400
2022 01 05 1137	4.0	Arthur River (1)	117.020	-33.340	G11	S	116.991	-33.376
2022 01 10 1253	2.5	NW of Ongerup	118.279	-33.912	G10	S	118.533	-34.079
2022 01 24 2124	4.8	Arthur River (2)	117.076	-32.322	G11	S	117.013	-33.361
2022 02 01 1041	4.3	Arthur River (3)	117.034	-33.345	G11	S	116.980	-33.367
2022 02 01 1945	2.5	SE of Wyalkatchem	117.628	-31.273	Isolated	N	117.660	-31.274
2022 03 02 1514	2.5	S of Quairading	117.397	-32.231	F5	N	117.421	-31.235
2022 03 06 1301	3.4	SW of Koorda (3)	117.285	-30.939	C5	N		
2022 04 07 0622	2.7	NW of Wagin	117.173	-33.215	G12	S	117.144	-33.251
2022 05 10 1752	2.8	NW of Beacon	117.736	-30.412	B2?	N		
2022 05 11 0308	2.8	NW of Beacon	117.749	-30.394	B2?	N		
2022 05 12 1642	2.7	SW of Pingrup	118.342	-30.622	G9	S		
2022 05 17 1727	2.5	NW of Beacon	117.730	-30.402	B2?	N		
2022 05 18 0215	2.7	NW of Beacon	117.732	-30.407	B2?	N		
2022 05 28 1324	2.8	SE of Newdegate	119.296	-33.274	G3	S		
2022 06 05 0329	2.9	SE of Newdegate	119.262	-33.251	G3	S		
2022 06 05 0335	2.9	SE of Newdegate	119.242	-33.229	G3	S		
2022 06 24 1626	2.8	Meckering	117.105	-31.644		N		

The second important earthquake source in the year (but far minor to Arthur River) was southwest of Koorda, where 89 events were recorded (21 of ML ≥ 2.5), Both of these active areas, along with other cluster activity, will be discussed in more detail below. For this report, the seismicity can be conveniently divided into Northern and Southern regions, with the division at 32.5S degrees. The more significant seismic events and clusters in each region will

be briefly discussed. The very significant Arthur River cluster is currently under closer investigation (Murdie et al., 2022; Dent & Love, 2022) and more detailed reports can be expected later.

1.2 Cluster Classification

As the number of clusters defined increases (now > 80), it is becoming important to try and classify them to indicate their significance relative to other clusters. This needs to be based not only on maximum magnitudes, but also the number of events. Accordingly, we are here introducing a 4-tier Significance ("S") scale – see Table 2: A) is used for the most significant, B) for a large/significant cluster, C) for a "normal" cluster and D) for a minor cluster. These definitions will be based on activity in the current study period (2021–22), and not on activity in previous years. Events need to be closely spaced geographically, but the time interval between events is a point for further consideration. This is obviously a quite subjective scale at present, but hopefully can be refined in the future.

Table 2. Proposed cluster classification (significance) scale

Significance	Largest event (ML)	2nd largest event (ML)	Number of events	Description
A	4.5+	3.5+	50+	Very significant cluster
B	4.0+	3+	20+	Large cluster
C	3.0	2+	10+	"Normal" cluster
D	2.0	1	5 or less	Minor cluster

2. Seismicity in the Northern region

There were ~183 GA-located events, of which 34 were ML 2.5 or more. Most can be allocated to nine cluster centres (Table 3), based simply on the GA-catalogue locations As discussed later, relocations of selected events have supported these allocations. The two main centres were 1) southwest of Koorda (mentioned above), and 2) northwest of Beacon, and these are discussed in more detail below**.** The SW Koorda cluster is given a significance rating of B.

Other cluster centres have been identified and are listed in Table 3. All are given a significance rating of D (i.e., minor). The larger of these are 1) SE of Bonnie Rock, and 2) west of Quairading. The Bonnie Rock events may be at the same location (L1) as a group of seven events, which occurred in 2000 (largest ML 2.9, Dent & Collins, 2017). There has been little activity since 2000. The "west of Quairading" location may be related to an important cluster in 1991 (E4). Other minor clusters identified are 1) west of Dalwallinu, 2) north of Cunderdin, 4) SE of Bonnie Rock, and 4) north of Koorda. The few other remaining (small) events have not been examined closely and can be expected to have relatively poor locations. They may also belong to defined cluster locations. The Meckering area, where a number of events are noted, is not so much a location where some clusters are noted, but a relatively broad region which has been intermittently active ever since the 1968 activity (Gordon & Lewis, 1981).

Table 3. Active Cluster areas (northern region)

Area	ID	Num	Sign. Cat	Max ML	Most Active	Comments
SW of Koorda	C5	~84	B	3.5	Jul–Aug 2021	Continuation of previous year
N of Beacon	B1	~30	C	2.9?	Jul–Aug 2021	Renewal of activity from 2009?
NW of Beacon	B2	~10	C	2.9?	Nov 2021	Intermittent activity since 2011
SE of Bonnie Rock	L1	3	D	2.4	Oct 2021	Active area in 2000
NW of Dalwallinu	A9	2	D	2.3	April 2022	Active in 2018 and 2019
NW of Quairading	E4	7	D	2.4	Feb 2022	Return of activity from 1991
N of Koorda	C1	2	D	2.3	Mar 2022	
NW of Kellerberrin	D1	2	D	2.3	Aug 2021	
SE of Wyalkatchem	D8	1	D	2.4	Feb 2022	
Nth of Cunderdin	D12	4	D	2.9	Aug 2022	-31.40 117.22 (NEW locn)
S of Quairading	F5	2	D	2.5	Mar 2022	

2.1 Cluster descriptions (northern region)

2.1.1 Southwest of Koorda cluster (C5). This cluster was first noted in the previous report (Dent 2021) as the intense period of activity began in May 2021. Several of the events from the May-June 2021 activity were relocated, and a common location was suggested in that report at -30.95, 117.25 (C5).

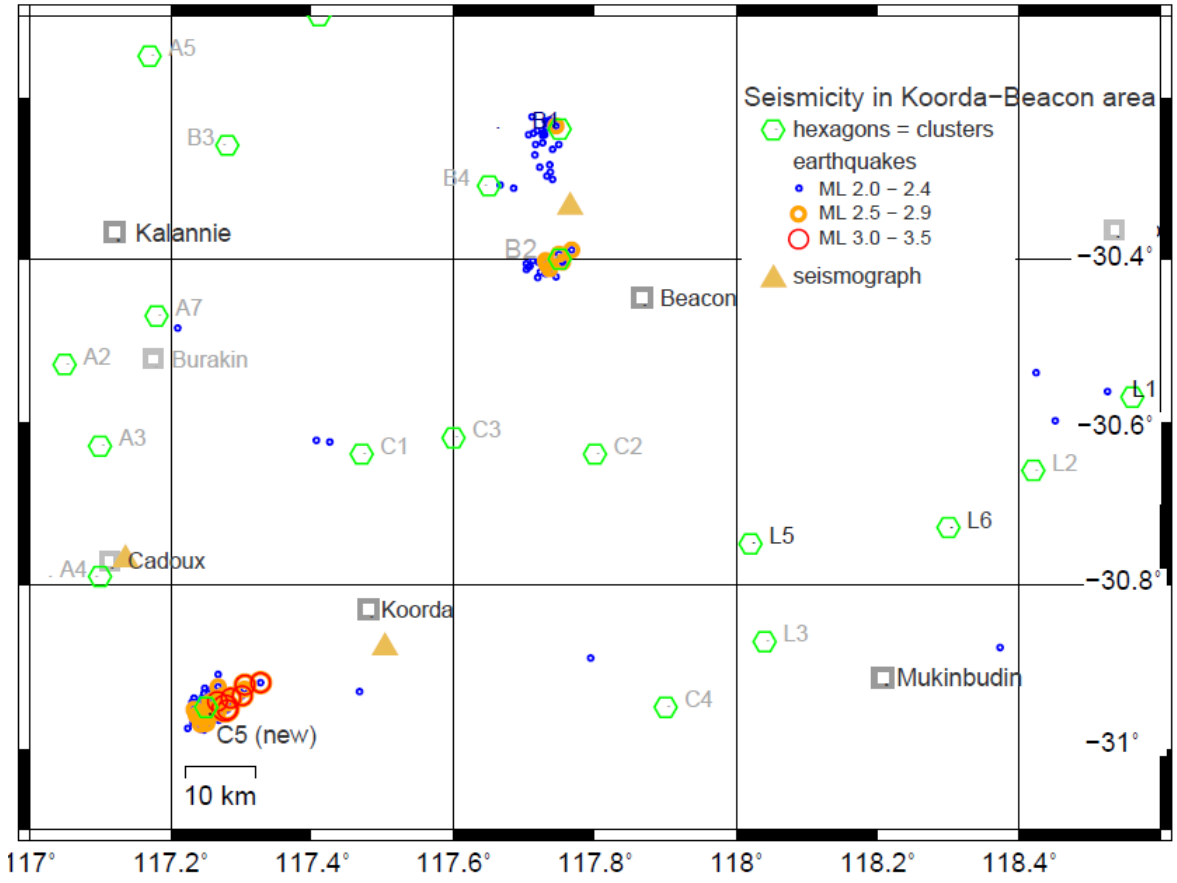

Figure 2. Seismicity southwest of Koorda and in the Beacon area

Figure 2 shows the larger events (ML ≥ 2.5) in this cluster in July 2021 – June 2022, and also all events (i.e., ML ≥ 2.0) in the area in 2021 prior to July. Activity in July/August 2021 was greater than the initial activity of May/June 2021. It also suggests a NE trend to the events, with the larger events on the eastern side of this trend. However, relocations bring some of the larger events in the east (Table 4) back towards 117.25, i.e. the location of cluster C5. It is suggested that the apparent NE lineation is an artefact of the asymmetric station distribution.

Table 4. Locations/relocations of some larger SW Koorda events

Day/Time	ML	GA lat	GA lon	Rms stn/ph	New lat	New lon	RMS stn/pha
July 27 1152	3.3	30.920	117.327	0.96 17/25	-30.944	117.247	0.146 6/9
July 27 1336	3.1	30.923	117.305	0.72 13/19	-30.928	117.249	0.122 5/6
Aug 07 1505	3.0	30.952	117.280	0.83 18/27	-30.945	117.257	0.162 7/10

Activity from this cluster commenced in May 2021 (although there was some precursory activity), and continued through June and, to a lesser degree, until March 2022. Activity from June–early September 2021 was more significant than the previous two months with seven ML ≥ 3 events (largest ML 3.5), vs two ML 2.9 events in the earlier period. There were three ML 3 events on 27 July, and 11 lesser-magnitude events. Activity declined from September 2021 onwards, and the last events appear to occur in March 2022. The defined location is not well constrained, because no field stations were deployed to collect near-field data. A single point is suggested, probably coinciding with cluster C5, but if Arthur River data represents a "typical" cluster, there may be some structure not yet resolved from the data set.

2.1.2 Northwest (B1) & West-Northwest of Beacon (B2). Figure 2 shows all events in the Beacon area (53 of ML ≥ 2.0). There are two clear groups, with 28 events in the north, and 25 in the south. It is suggested these two groups correspond with the already defined cluster centres, B1 and B2. Significant activity was first noted from B1 in early 2009 (Dent, 2009), and from B2 in 2012 (Dent & Collins, 2018). Activity from the region in the previous year (July 2012-June 2022) was restricted to four relatively small events near B2 (largest ML 2.2). Relocations of several events in the cluster confirm a common location close to 117.74, -30.24. The remaining two events occurred on 14–15 November 2021 (largest ML 2.6), and were about 15 km south of the earlier events, near 117.77, -30.38 and are assigned to the B2 cluster (117.75, -30.40).

2.1.3 West-Northwest of Quairading. The seven events in this cluster were spread out throughout the year, and it is suggested they are a continuation of the cluster activity noted at cluster E4 in last year's report when ~18 events were located in the area. It is suggested that activity at E4 can be traced back to 1992, and perhaps even earlier (Dent, 2018).

2.1.4 Bonnie Rock. There were three events in this group (largest ML 2.4 in October 2021). They occurred near to the location of cluster L1, which was the site of significant activity in the second half of 2000 (largest event ML 2.9, 5 June 2000 (Dent & Collins, 2017)). Relocations of 2021 events move them towards the year 2000 events, and they are here allocated to that location.

2.1.5 West-Northwest of Dalwallinu. Two events 10 minutes apart in April 2022 (ML 2.1, 2.3) are close to a significant cluster of events (A9) in August 2019.

2.1.6 North of Cunderdin. Four events have occurred in this area, two of these with ML ≥ 2.5 are shown in Table 1. It was suggested that a June 2021 event near this location was

related to cluster D3, about 10 km to the SW. However, it now seems apparent that this group represents a **new** location, here defined as D12, at 117.22, -31.40.

2.1.7 North-Northwest of Koorda. Two small events (ML 2.3 and ML 2.0) in March and April 2022 are allocated to cluster location C1

2.1.8 Southeast of Wyalkatchem. A single event (ML 2.5) on 1 February 2022, shows a close match with location D8, defined in Dent & Collins (2017) on the basis of two events near this location.

2.1.9 South of Quairading. There were two events (ML 2.3 and ML 2.5) relatively close to cluster location F5.

Meckering area events. There were four events in the Meckering area, an ML 2.8 event in June, and three events of ML < 2.5 between August 2021 and May 2022. Although several cluster centres have been defined in the Meckering area, it is not yet clear what is really going on here, and it is hoped to study the area in more detail later.

3. Seismicity in the Southern region

There are 274 located events in the southern region, with seismicity from the Arthur River area dominating (248 located events). This is a new cluster (G11) and is assigned here as category A (see Figure 3). A smaller cluster nearby (G12) northwest of Wagin is also new, and their proximity suggests a possible connection (they are about 15 km apart). Four other clusters, all previously named, were active (Table 5, Figure 3) with a small number of events. These were southwest of Dumbleyung (eight events), southeast of Newdegate (four events), west-northwest of Ongerup (three events) and southwest of Pingrup (two events). All of these four clusters, as classified, are “continuing” as they were noted as being active in the *previous 12 month period.*

Table 5. Earthquakes and Cluster centres in the Southern region

Place	ID	Number	Category	Max ML	Comment
Arthur River	G11 (new)	~250	A	4.8	Began 5 Jan 2022, continuing
SE of Newdegate	G3	4	D	2.9	All 4 events are ML 2.5+
SW of Dumblyung	G1	8	C	2.4	Including one remote event 1.9
WNW of Ongerup	G10	3	D	2.6	Jul 2021 to Jan 2022
NW of Wagin	G12 (new)	5	C	2.7	Apr 2022. Other smaller events
NW of Kojonup	G2	1	D	2.6	Aug 2021. Only one event.
SW of Pingrup	G9	2	D	2.7	Jul 2021 to May 2022

3.1 Cluster descriptions southern region

3.1.1 Arthur River region. This cluster is the subject of other reports and will not be treated in detail here. Activity from this location has not been reported before, and it is allocated a new cluster ID of G11. The active area is apparent in Figure 1 and Figure 3. A precursory event occurred on 28 November 2021, and it is probable there were other undetected events below ML 2.0 prior to activity in this area commencing with an ML 4.0 event on 5 January 2022. The largest event (ML 4.8) occured on 24 January and was felt in Perth. In the epicentral area it was felt at a Modified Mercalli level of at least V.

Table 6. Comparison of Arthur River cluster to some other clusters

Place	NW of Narrogin	Nth. of Ballidu	Nth. of Kellerberrin	Nth. of Beacon	Lk. Muir	SW of Koorda	Arthur Rv.
year	1966	1990	1997	2009	2018	2021	2022
Sign. rating	B	C	A	A		B	A
Duration	1 week	3 mon.	3 years	3 weeks	3 mon		8 months
Largest ev. ML	4.0	3.2	4.6	4.6	5.3	3.5	4.8
Num ML 4+	1	-	2	6	3	-	3
Num ML 3+	9	2	25	51	11	7	26
Num ML 2+	21	19	217	234	56	99	237
Num ML < 2		26	232	48	664	1	?

Temporary instruments were deployed by a team from the Geological Survey of WA and Macquarie University less than a week after seismicity commenced (Murdie et al., 2022), and several Public Seismic Network (PSN) recorders were also deployed over the following weeks (Dent & Love, 2022). Although definitive results are not yet available, preliminary results show that the epicentral zone is much smaller than a map of GA epicentres might suggest. A zone of approximately 20 km diameter reduces to a zone of about 5 km diameter, and to the southwest of what was apparently the most active area. The assigned cluster location (-33.37, 116.97) is the approximate mid-point of two suggested active locations (Dent & Love, 2022).

Although this activity is here classified as being “clustered” because of the large number of events and the fact that the largest events are towards the centre of the group (in time), it could possibly also be called a foreshock-mainshock-aftershock series, in a more “classical” description of the seismicity.

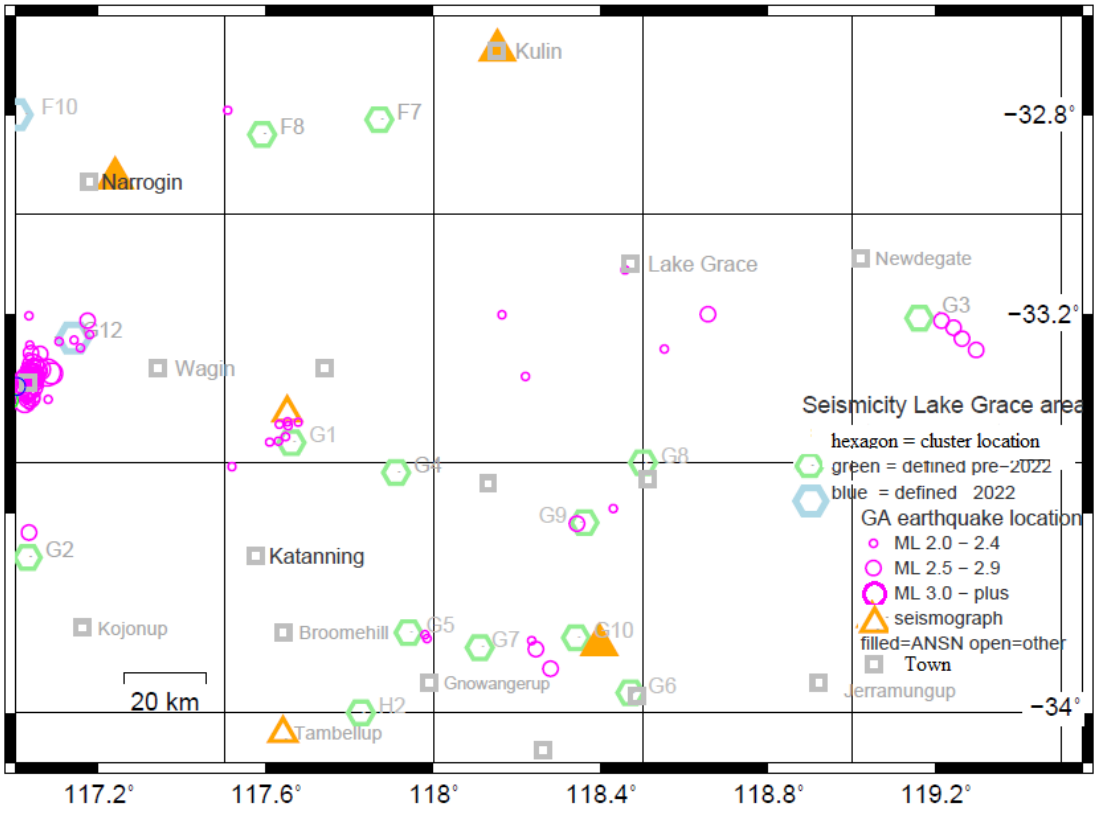

Figure 3 Seismicity in the Lake Grace, Dumbleyung, and Newdegate areas

3.1.1.1 Historical seismicity near Wagin/Arthur River. The largest early event was in May 1986, a solitary ML 4.0 event at a location about 20 km east of the 2022 activity. Three years later, near the same location (14–17 December 1989), there was a cluster of 17 events, the largest being ML 2.6. Two small events (both ML 2.2) were located about 10 km northeast of Arthur River in late 1997 and early 1998. None of this activity seems to positively correlate with the 2022 activity southwest of Arthur River. However, the 1997–98 activity may correlate with a second, minor cluster in March 2022, as noted below.

3.1.1.2 Comparison of Arthur River cluster to similar events in SWA. A comparison of this cluster with other recent large clusters (north of Kellerberrin (Dent 2011), north of Beacon, (Dent, 2009)) is shown in Table 6. Significance ratings have been applied to the clusters listed in Table 6. This table suggests that the North of Beacon (NOB) sequence was a little larger in terms of event numbers, even though the biggest event was a little smaller than the largest Arthur Rv. event (4.6 vs 4.8). The duration of the NOB cluster was also much shorter (i.e., about three weeks); the Kellerberrin swarm was roughly similar in terms of numbers of events, but that was over a period of about three years. The Arthur River. cluster also seems more significant that the Lake Muir event, which contained two ML 5.0 events, but many fewer events overall.

3.1.2 Seismicity northwest of Wagin. Five events in late March to early April 2022 (largest ML 2.7) were located by GA about 10 km east of Arthur River. They are listed in Table 7 and shown in Figure 3. A common location is indicated by the very similar S-P times at the PSN station AJ02. The assumed location is -33.25, 117.14, the relocated position of the 7 April event (ML 2.7, Table 1). They are of particular interest because of their proximity to the major Arthur River cluster (~ 20 km to the southwest), and the fact that the seismicity was contemporaneous. Four small events in Table 7, (ML < 2.0) were not identified by GA but were detected by the PSN network. There does not appear to be any geological connection between the two clusters. It may be close to the small cluster of events, noted above, in 1997–98. It is a new cluster location and has been labelled G12.

Table 7. Events in cluster northwest of Wagin (G12)

Date/time	ML	S-P at AJ02 (s)	Lat (GA)	Long (GA)	Lat (PSN)	Long (PSN)	Comments
18/3 1418	2.2	2.0	-33.27	117.16			SP 2.32 at AJ01
24/3 1658	--						SP 4 at AJ02 may be elsewhere?
24/3 1856	--	2.0					Not GA SP 2.30 at AJ01
24/3 1901	--	2.02					Not GA SP 2.35 AJ01
24/3 2213	2.1	2.0	-33.26	117.10			SP 2.37 at AJ01
25/3 1500	2.1	2.2	-33.25	117.14			SP 2.31 at AJ01
28/3 1311	2.2	2.0	-33.24	117.18			SP 2.30 at AJ01
28/3 1401	--						SP 2.3 at AJ01
07/4 0622	2.7	2.02	-33.21	117.17	-33.25	117.14	SP 2.31 at AJ01

3.1.3 South-southeast of Lake Dumbleyung. Eight events, mostly in late 2021, the largest being ML 2.4, followed three events in the previous 12 months. These are allocated to cluster location G1, which was the site of a cluster in 2013 (approx. 30 events).

3.1.4 Southeast of Newdegate. There were four events between late May and September, and all between ML 2.7 and 2.9. No smaller events were detected. They are allocated to cluster location G3, where an ML 4.3 event occurred in 2019. Their apparent

northwest lineation (based on GA locations) is probably due to poor station distribution. There were four events in the same area in the previous twelve-month period, all less than ML 2.5.

3.1.5. Southwest of Pingrup. This site (G9) and the site below (G10) were identified for the first time in last year's report (Dent, 2021). G9 had two events, (largest ML 2.7) in this reporting period.

3.1.6 West-Northwest of Ongerup. This site (G10) had three events spread through the year, the largest being ML 2.6.

3.1.7 North-northwest of Gnowangerup. Two small events (ML 2.2 and ML 2.3) are about 4 km east of location G5 (defined in Dent & Collins, 2018) from activity, which occurred in 2013 and 2017–18).

3.1.8 North-Northwest of Kojonup. An event in August (ML 2.6) occurred approximately 10 km northwest of cluster G2, which was the site of a cluster of events in late 2014 (largest event ML 2.7).

3.2 Other events

3.2.1 Lake Grace. This appears to be a solitary event in October 2021 (ML 2.5), but there are other smaller events in the vicinity (i.e., up to 30 km distant), and there may be a relationship, but masked by poor epicentral locations.

3.3 Events in far northwest of SWA. There are three small (ML < 2.5) but isolated events in the Moora/Eneabba area, which is close to the region where the Darling Fault separates the Yilgarn Craton from the Perth Basin. Preliminary investigations by the author suggest events in this region may be deep. For example, an ML 3.0 event on 29 Dec. 2018, location ~ 29.8°S, 115.7°E, appears to have a depth ~25 km on relocation. Future events in this region need to be carefully monitored to see if this may really be the case.

4. Additions to the cluster list from historical seismicity

Most of the 70 clusters defined to 2021 occurred in the 10 years 2012–2021, and are tabulated in the appendix to Dent (2021). However, some of the larger clusters which had been investigated with the assistance of temporary networks were included, e.g., Kellerberrin (1994) and Beacon (2009). The first four clusters defined in the present list were initially identified by Leonard & Boldra (2001) in their study of seismicity north of Cadoux in 2000 -2001 (they were called points A, B, C and D – now locations A1 – A4).

Many clusters can be identified from the Mundaring Geophysical Observatory (MGO) records for the time prior to 2011, and many are listed in Dent (2016). However, they have not been added to the list of clusters because it is considered the event locations were not good enough to give good cluster locations. One exception is a cluster near Ballidu in April/May 1990, which was well-monitored with the help of temporary stations. Its location was -30.53 116.80, and is here added to the list as A12, and also shown in Table 6 (significance rating C).

A cluster ~20 km northwest of Narrogin, in January/February 1966 was noticed in the GA earthquake catalogue, and has some similarities to the 2022 Arthur River cluster, ~80 km south. The largest event (ML 5.0 on 23 February 1966) has been determined to be an error, occurring in the Indian Ocean (Everingham, 1969), but the other events present (largest ML 4.0) still make it a significant cluster. Although the cluster location cannot be considered precise, it is here added to the list, as F10, at an approximate location of -32.80 117.00, and it is also shown in Table 6, and given a sign rating of B.

5. Discussion

In all, 18 cluster groups are identified as being “active” in 2021-22. The largest (Arthur River) is one of the most significant clusters in SWA for the last 20 years (category A). The cluster southwest of Koorda is given category B. Eight clusters had been active in the 12 months prior (i.e., “continuing” activity). Three groups (including that southwest of Arthur River) have not been noted before (i.e., “new”). This is a relatively small number. In the report for 2020–21, five new clusters were identified, and analyses of activity over the last 10 years have commonly reported 10 or more new clusters each year. However, such a reduction is to be expected as the probably-finite number of cluster sites in SWA are gradually identified.

If such repeating cluster sites are a genuine geological feature, then the identification of these sites would need to be taken into account in assessing the earthquake hazard at a local scale.

Data from studies so far indicates that activity at a single location over a period of about 10 years is not uncommon. In a few instances (e.g., west of Quairading), seismicity may be traced back about 40 years. However, for some of the largest cluster groups, recurring long-term seismicity is yet to be observed. Examples are: north of Kellerberrin (very active 1994–1996, but little since), and northwest of Narrogin (very active 1967–1968, but also little since). Data from this report strengthen the observation that certain locations are sources of sporadic, and usually minor, seismicity over a period of many years. The nature of the source of this activity is yet to be determined. It is possible that larger events have occurred at these locations in the past.

This observation, i.e., that the majority of seismicity emanates from sites of previous activity, suggests that the practice of “declustering” an earthquake catalogue (i.e., removing “dependent” events), for seismic hazard and risk purposes, probably needs re-evaluation—in the case of SWA activity at least. Almost all events recorded in SWA could be considered “dependent” in some way or another, i.e., they are closely related to previous seismicity at the same location, some of which may be, or more probably *is,* from prehistorical times. That is, there are fundamental geological causes at each cluster site that have not yet been identified through a lack of sub-surface mapping of geological structures.

Locations active this year that can possibly be traced back furthest in time include L1 (first noted as being active in June 2000), and E4, west of Quairading. Activity at E4 may represent renewed activity at a centre active in 1991–92 (largest ML 3.3).

Point source vs distributed events

It has been largely assumed in reports so far that clusters can be represented as “point sources”. It was stated that epicentres could probably be placed into a 2 km diameter sphere. For this year, the apparent linear distribution of events southwest of Koorda appears unlikely where relocations are considered. However, from last year’s report, an E-W group of cluster centres to the northwest of Quairading seems a real possibility.While Proterozoic mafic dykes in the region trend E-W, no correlation between the seismicity and these features can be made at this stage.

This year, for possibly the first time, a large collection of well-located events—from the Arthur River cluster—is being obtained. The data seem to confirm that events are spread out over an area possibly 5 km x 5km, but structure within this area is yet to be revealed revealed (Dent and Love, 2022). As the maximum sized event was ML 4.8, it might be expected that the fault system causing the events is relatively large, and therefore the earthquakes will be spread over a wide area.

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