

Clustered Seismicity in Southwestern Western Australia, July 2020 -June 2021

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Abstract

There were ~130 located earthquakes in southwestern WA in the 12 months July 2020 to June 2021 and they are examined in this report. As in previous years, the activity is highly clustered. Twenty-three probable cluster sites are identified, 18 of which may have been active prior to the current period. Two clusters are of note, southwest of Koorda and west of Quairading. The cluster southwest of Koorda is new, but activity west of Quairading may relate to cluster activity close to the same location in 1991-92. In total, five new cluster locations are proposed. It is suggested that recurring seismicity at cluster sites is the normal form of seismicity in southwestern WA. Some clusters in the wider region are also noted. The cluster centres identified in these reports may have extra significance in the analysis of regional seismic hazard

Keywords: Earthquakes, Clusters, Seismicity, Southwest Western Australia,

1 Introduction

The clustered nature of seismicity in southwestern West Australia (SWA) was first noted by Denham et al., (1987), while Leonard et al., (2012) described southwest Western Australia as exhibiting “hotspot” activity. Dent (2016) produced an initial map with about 50 cluster locations, and this has since been expanded. This report on SWA seismicity is the 7th in a series, covering seismicity since June 2012. These reports have defined 65 earthquake cluster locations. They include numerous earthquake relocations, which incorporate new phase data from the Australian Centre for Geomechanics (ACG) network. As many of the ACG stations are close to earthquake sources, these relocations are often considerably better than those that can be achieved from Geoscience Australia’s national-scale seismic network.

A cluster is defined as a group of earthquakes which does not have a clear “mainshock” followed by a series of aftershocks. Such groups may also be referred to as earthquake “swarms”. There may be many events in a single day, or events may be months apart. Thus, in this report for a 12-month period, a single event may be considered part of a “cluster” if it occurs within the area of a previously defined cluster. Particular attention is paid to events of ML 2.5 and above (red circles in Figs 1-7), and if such an event cannot be correlated with other events, it is termed “isolated”.

The clusters identified in SWA are named sequentially as they are identified, using the zonal divisions (Dent, 2014) shown on Figure 1. Twenty-eight cluster locations were identified as being active between June 2017 and June 2020 (Dent, 2020, tables 2 & 3), and these are shown on Figure 1 and indicated in Appendix 1. Groups of events which correlate with pre-defined clusters are listed in Table 1 and suggested new cluster locations are shown in Table 2. All cluster locations so far identified in SWA are listed in Appendix 1.

Of interest is how long a cluster may be active. Table 1 shows when activity at a given location was noted in this series of reports. This indicates three locations which were active in the early 2000's. Activity at some locations may well be traced back earlier than this. The cluster west of Quairading (E4) may possibly be traced back to 1992. Cluster activity at a location may be short an intense, with most events within a few days or weeks, or may be spread out over several months, or even years.

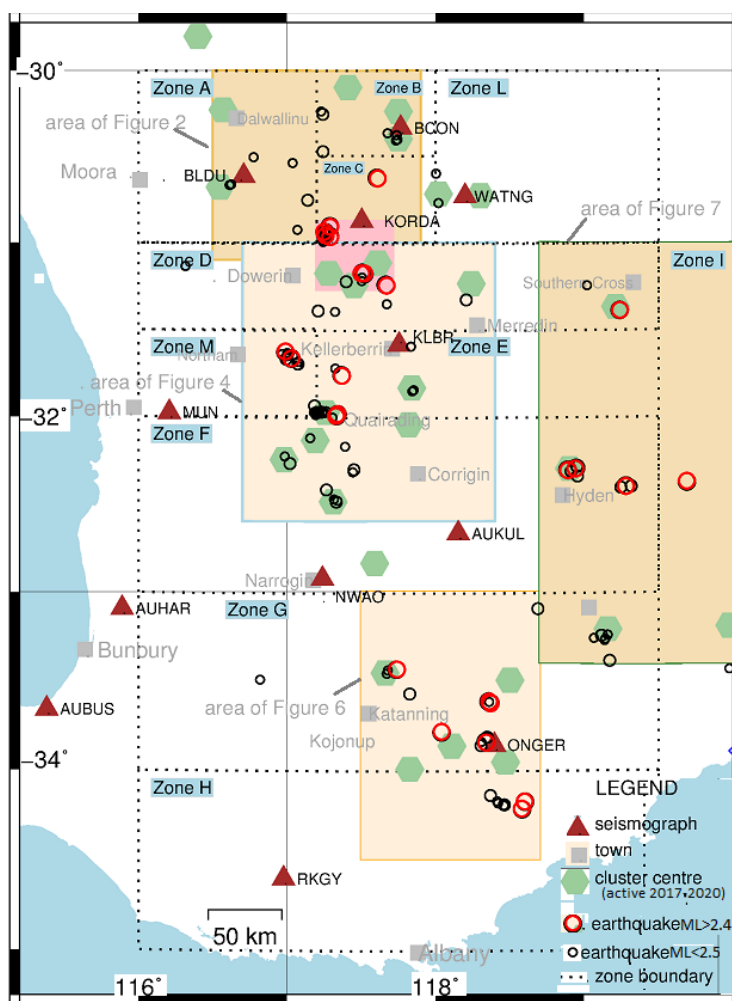


Figure 1. Seismicity in southwest WA, July 2020 – June 2021

2 Overview of seismicity in SWA July 2020 – June 2021

The year 2020-2021 was relatively quiet seismically in SWA. In the area of Figure 1, only 125 events (\geq ML 2.0) are listed in the Geoscience Australia (GA) catalogue. Twenty-six of these were \geq ML 2.5 and are plotted as red circles on Figure 1 and listed in Appendix 2. The largest event was only ML 3.0 (northeast of Koorda).

As with previous years, numerous clusters can be identified from the distribution of the seismicity. The two most obvious clusters in the area were southwest of Koorda (SWK), and west of Quairading (WOQ). The SWK cluster commenced late in the period (May 2021) and contained 13 GA-located events (to 30 June 2021), the largest being ML 2.9. Activity from the SWK cluster has continued, and increased, past the end of the reporting period (June 2021). Activity from the WOQ cluster occurred mainly in August-September 2020 and significantly, it may represent reactivation of a cluster centre which was active in 1992.

As reported by Murdie et al. (2021), GA's earthquake locations in SWA improved from mid - late 2020, when four new stations, KORDA, BCON, ONGER, and WATNG were added to the Australian National Seismograph Network (ANSN) network in SWA (Figure 1). However,

Mundaring (MUN) was out of service for much of the year. With the new stations operating, recent earthquake plots show clearer clustering of events. However, locations can still be further improved when ACG data is added. Forty-one events in this period have been

Table 1. Seismicity which has been correlated with existing cluster locations

Cluster location	No. of events	Name	Match	Fig.	ML max	When active	First noted activity (in this series)
W of Burakin	1	A2	good	2	2.2	9 Apr 2021	March 2002
N of Burakin	1	A7	good	2	2.4	18 Jan 2021	June 2016
SW of Ballidu	3	A10	fair	2	2.2	Jul 2020	May 2018
NW of Beacon	4	B2	close	2	2.2	Jul 2020	March 2012
NE of Kalannie	2	B3	fair	2	2.4	Nov 2020	Aug – Oct 2004
NE of Koorda	1	C3	close	2	3.0	6 Mar 2021	November 2004
Youndegin	2	E1	good	3	2.5	Aug 20 & Mar 2021	2011
W of Bruce Rock	2	E2	good	4	2.1	Aug & Dec 2020	2014
N of Hyden	5	F1	good	7	2.6	Oct 2020	February 2013
N of Brookton	2	F2	good	5	2.3	Sep 20 & Feb 2021	December 2013
ENE of Pingelly	3	F4	good	5	2.3	Jan 2021	May 2014
NE of Hyden	3	F6	good	7	2.5	Oct-Nov 2020	March 2013
NW of Marvel Lock	1	D11	fair?	7	2.8	11 Aug 2020	July-Oct 2017
SW of Dumbleyung	3	G1	good	6	2.6	Jul 2020	July 2013
SE of Newdegate	5	G3	good	7	2.4	Jul-Nov 2020	June 2015

relocated by the author using the EQLOCL location program (© SRC, Melbourne) and the WA2 earth model. They are listed in Appendix 3, and shown as magenta diamonds on Figs 2-7. GA's magnitude determinations (MLs) have been adopted for all relocations. The relocations have assisted greatly in defining of the cluster locations shown in Table 2.

Four sub-regions of the SWA region have been defined: 1 (north), 2 (central), 3 (south) and 4 (east), (Figure 1), and these contain the majority of the seismicity for the period. Clusters identified in these areas are described below. The proximity of these clusters to pre-defined

Table 2. Cluster locations which are new or of uncertain status.

Cluster location	Lat	Lon	Max ML	Events	When most active	Name	Comment
SW of Koorda	-30.95	117.25	2.9	13	Late May 2021	C5	
E of Wyalkatchem	-31.20	117.50	2.7	4	Mar-May 2021	D2 ^{NE}	10 km NE of D2
N of Cunderdin	-31.40	117.22	2.4	1	28 Jun 2021	D3 ^{NE}	10 km NE of D3
W of Quairading	-31.98	117.22	2.4	17	Aug 20 – Feb 21	E4 ^E	E of E4
W of Quairading	-32.01	117.25	2.7	3	Dec 2020	E4 ^W	(E4 active Sep 2012)
SW of Pingrup	-33.62	118.36	2.6	3	Oct-Nov 2020	G9	
NW of Ongerup	-33.86	118.32	2.5	4	4 events on 21 Aug 20	G10	
SE of Borden	-34.17	118.47	2.9	7	7 events in Aug 2020	H3	
NE of Holt Rock	-32.34	119.69	2.6	1	18 Nov 2020	I2	

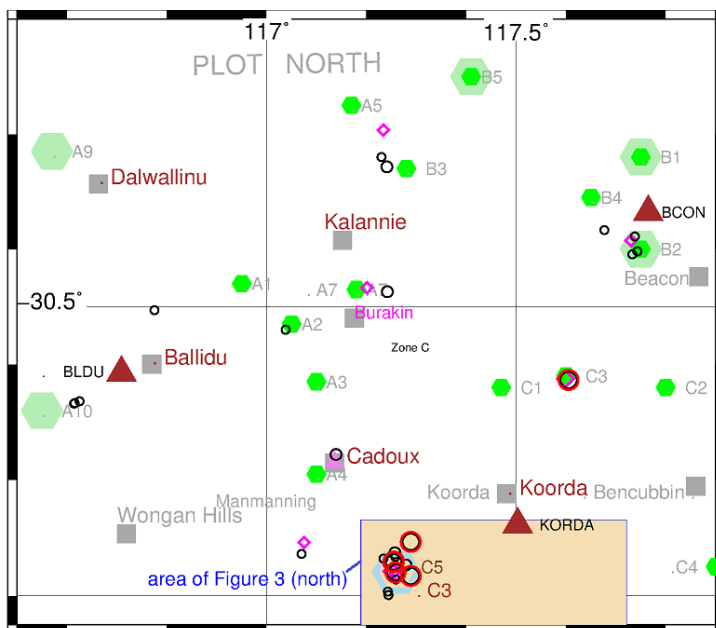
clusters is described as “close” (0-2 km), “good” (3-4 km) or “fair” (5-7 km).

Clusters which were noted as being active in 2017-2020 (Dent & Collins, 2020) are shown as large green hexagons on Figs 1-7. As cluster locations can be active for several years, it is expected that they will cross time boundaries used in these reports. Some may be found to correlate with earlier (pre-2017) cluster centres, which are shown as small green hexagons on Figs 2-7.

3 Analysis of seismicity

3.1 Seismicity in Area 1 (north) - Figure 2

As mentioned above, the most important cluster in the twelve-month period is that southwest of Koorda (SWK). It occurs within this area and is shown in more detail in Figure 3. Within this reporting period, the SWK cluster had 13 events, the first of which (ML 2.4) was on February 1 (although a precursory event is seen 12 months earlier, 28 Feb 2020, ML 2.3). The location was then quiet until a major resurgence in late May 2021, with 12 events from 18 April to 30 June 2021, including 3 events of ML 2.5+, the largest being ML2.9. The GA locations suggest they have an approximately N-S trend, over an area about 10x5 km, but relocations (Appendix 3) suggest they may all be concentrated close to 30.96°S, 117.26°E (Table 2). This location has not been noted as active in previous reports, and following the naming convention used in earlier reports, (it falls in Zone C) it is here defined as Location C5.



Legend: Hexagon = cluster centre (large = active 2017-20). Circle = earthquake (red if ML > 2.4). Diamond = earthquake relocation. Triangle = seismograph (pink = ACG station). Square = town

Figure 2. Seismicity, Area 1 (north)

Other clusters that can be seen in Figure 2 are:

W of Burakin (Table 1): One small event (ML 2.2, 9 April 2021) occurred near location A2 (correlation “good”). This location corresponds to ‘Location B’ as was originally defined by Leonard & Boldra (2002) and was the site of major seismicity in 2001-2002 (Dent & Collins, 2020, Dent et al., 2021) with three ML 5 events.

N of Burakin (Table 1): The relocation of an ML 2.4 event north of Burakin (18 January 2021) moves it close to Location A7 (correlation “good”).

SW of Ballidu (Table 1): Minor activity (3 events in July 2020, largest ML 2.2), apparently from a location active in May 2018 (defined as A10 in Dent & Collins, 2020). The 2020 events plot about 5 km east of A10, and the difference is here ascribed to location errors (correlation “fair”).

NW of Beacon (Table 1): Several events occurred at an important cluster location (B2), which was very active in 2011 (Dent, 2012), and which has seen significant periods of activity since then (correlation “good”). Activity at this location is continuing past June 2021.

NE of Kalannie (Table 1): Two small events in November 2020 occur near location B3 (correlation “fair”), however a relocation of one of them (Appendix 3), suggests a location approximately midway between locations B3 and A5.

NE of Koorda (Table 1): An apparently solitary event (ML 3.0, 6 March 2021, the largest in SWA in this period) occurred near location C3, a cluster centre active in 2011 (Dent, 2012), (correlation “close”).

3.2 Seismicity in Area 2 (central) – Figure 4

This area contains the second significant cluster mentioned in the introduction, about 20 km west of Quairading (WOQ). Area 2 also contains the Meckering area, which has seen intermittent activity, intense at times, since the ML 6.5 event of 1968 which levelled the original village of Meckering (Gordon & Lewis, 1981). The Meckering area is briefly discussed below.

E of Wyalkatchem: This region is shown in Figure 4, and in more detail in Figure 3. There were four events in March and May 2021, and relocations (see Appendix 3) of the two largest events suggests a common location at 31.20°S, 117.50°E (Table 2). This is approximately 10 km NE of Location D2 which was defined from seismicity in 2011 (Dent, 2012). Locations at that time were not as good as they are now, and it is suggested that the location shown in Table 2 might be a better location of D2. In Table 2 it is here called D2^{NE}. Note a solitary event on 7 June 2021 (ML 2.6) to the southeast of D2. The relocation confirms this location.

N of Cunderdin: One event occurred in late June 2021 (ML 2.4), followed by an ML 2.9 event in early July 2021, and another small event in August 2021 (Figure 4). This location (31.40 °S, 117.22 °E) is approximately 10km NE of location D3, and is here called D3^{NE} in Table 2.

Youndegin: Two events occurred southeast of Cunderdin (August 2020, ML 2.2; March 2021, ML 2.5), shown in Figure 4 (detail in Figure 5). The larger event is near the Youndegin (E1) cluster (correlation “good”).

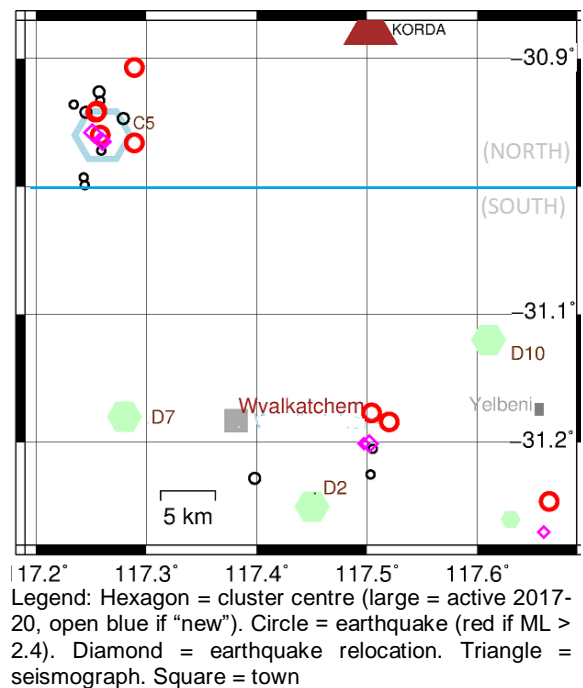


Figure 3. Seismicity, Koorda & Wyalkatchem

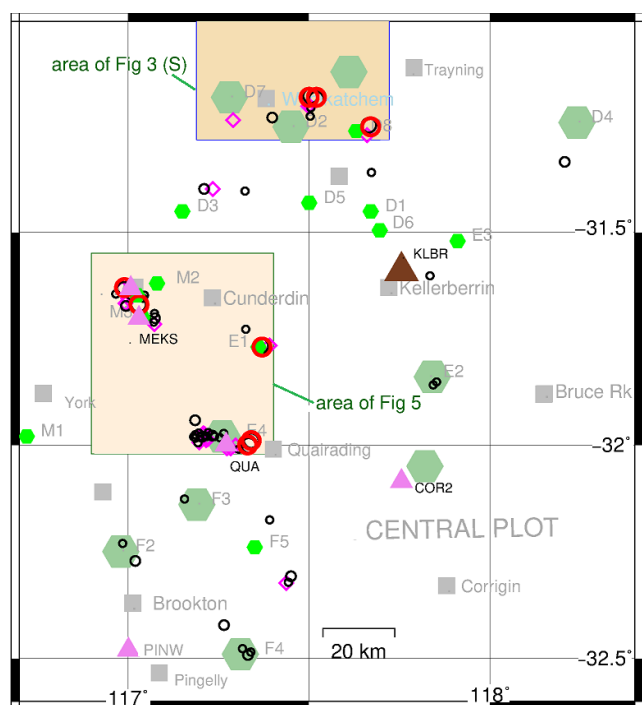


Figure 4. Seismicity, Area 2 (central)

W of Bruce Rock: Two small events occurred south of Kellerberrin (Figure 4, Table 1), both ML 2.1. These events represent a continuation of cluster activity from the previous period, the largest of which was ML 2.6 in June 2020, at location E2 (correlation “good”).

W of Quairading: Events in this area are close to location E4, which was defined in Dent & Collins (2018a) based on four small events (largest ML 2.1) between September 2012 and April 2013. Approximately 20 events occurred in this area in this study period, and formed two groups, one of 17 events to the west of E4, between August 2020 and May 2021 (largest ML 2.4), and three to the east in December 2020 (largest ML 2.7). These events are shown in Figure 4, and in more detail in Figure 5. The western group is here called E4^w, and the eastern group is E4^e. A temporary ACG station was installed in mid-February 2021 (re-occupying the 1992 field recorder site QUA), and some events from E4^w were well recorded. The location suggested for the group is at 31.98°S, 117.22°E (Table 2), which is about 5 km west of E4. No close data were recorded

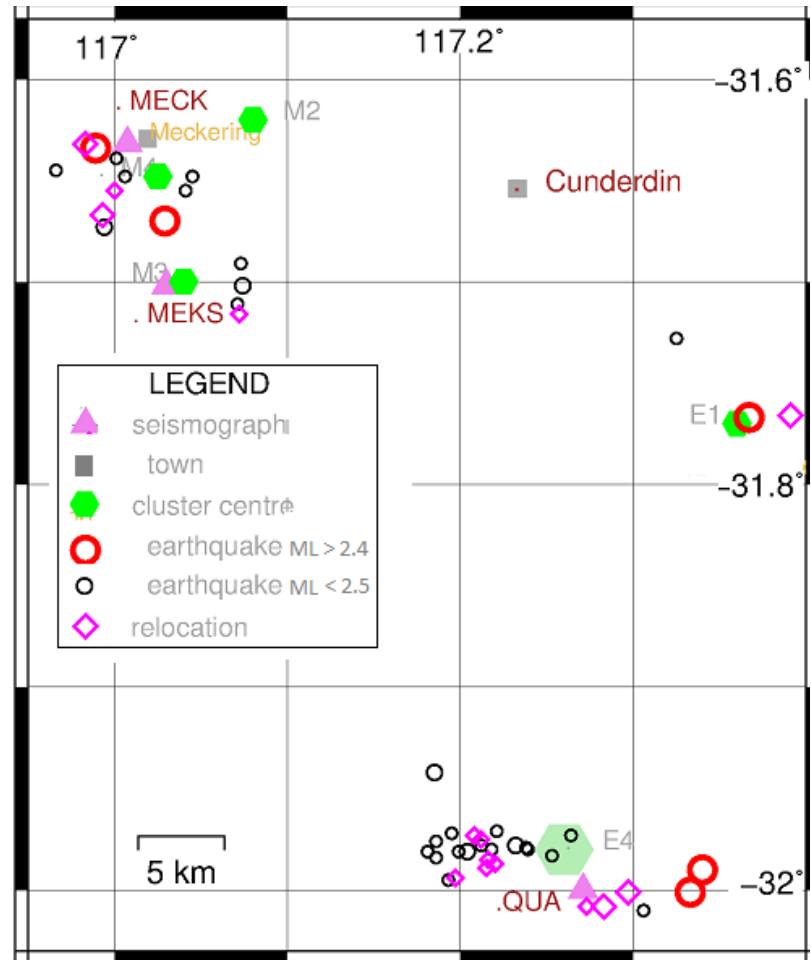


Figure 5. Quairading cluster and the Meckering region

for the eastern group (E4^e), but relocations suggest a common location at approximately 32.01°S, 117.28°E (Table 2), which is almost exactly the location suggested for a cluster of about 30 located events in 1991-1992, the largest being ML 3.3, some of which were quite well located (Dent and Collins, 2018b). It is here suggested that the same source is responsible for both cluster groups.

The seismicity of the western group (E4^w) is approximately contemporaneous with the eastern group (E4^e), and is here called “sympathetic” seismicity, i.e., where two close groups show seismicity which is closely spaced in time, but there is no apparent structural connection between the two.

N of Brookton: Two events occurred (ML 2.2, ML 2.3) near the Kokeby cluster (F2) (Figure 4, Table 1) (correlation “good”).

ENE of Pingelly: There were three events in January and February 2021 (Figure 4, Table 1), the largest being ML 2.3. These represent continuing activity at F4 (correlation “good”).

Meckering area: The number of events (11) near Meckering between May and June 2021 is somewhat higher than the average year. Three cluster locations (M2, M3 and M4, **Figure 5**) have previously been defined near Meckering. Given the extent of surface faulting in 1968 (approximately 30 km in a N-S direction), it might be expected that epicentres could be widely distributed, and no attempt will be made to divide them into cluster groups, although

three events east of the seismograph MEKS are probably related. A new field station was installed north of Meckering in June 2021, and this area will be reported on in more detail later.

3.3 Seismicity in Area 3 (south) – Figure 6

This southerly region (**Figure 6**) was relatively quiet for many years, and 34° South is the approximate southern boundary of the region commonly known as the “southwest seismic zone” or SWSZ. The region seems to have been somewhat re-activated by the Lake Muir seismicity of late 2018 (Clark et al., 2020; Dent & Collins, 2020). There was only one cluster centre in Zone H (H1, north of Rocky Gully) until 2019, when the second (H2, NE of Tambellup), was defined.

Relatively large uncertainties in epicentres can be expected before the installation of ONGER in mid-2020 because of the poor seismograph distribution. However, the ACG network has had at least one station near Gnowangerup since 2008, meaning relocations can be significantly better. The Gnowangerup station was closed after ONGER opened and was moved to Tambellup. There are 4 cluster groups discernible in Figure 6.

SW of Dumbleyung: There were three events in July 2020 (Table 1), the largest being ML 2.6, near location G1 (correlation “good”), where a significant cluster was noted in July 2013 with about 20 events at that time, the largest being ML 2.9 (Dent, 2014).

SW of Pingrup: There were three events between 24 October and 1 November 2020 (Table 2), the largest being ML 2.6. These define a new cluster location G9 at 33.62°S, 118.36°E.

NW of Ongerup: There were four events in August 2020, the largest being ML 2.5 (Table 2). These events do not match any defined clusters but do correlate well with an intense swarm of small events noted in 1990-1991. This was monitored at the time with a network of four field recorders (Dent 2008). The August 2020 locations are used to define a new cluster location G10 at 33.86°S, 118.32°E.

SE of Borden: There were seven events between 6 and 12 August 2020, the largest being ML 2.9 (Table 2). These are scattered over about 10 km, but relocations of the most westerly and easterly events bring them together, suggesting a group location at 34.17°S, 118.47°E. This is defined as a new cluster location H3.

An apparently solitary ML 2.5 event occurred about 20 km N of

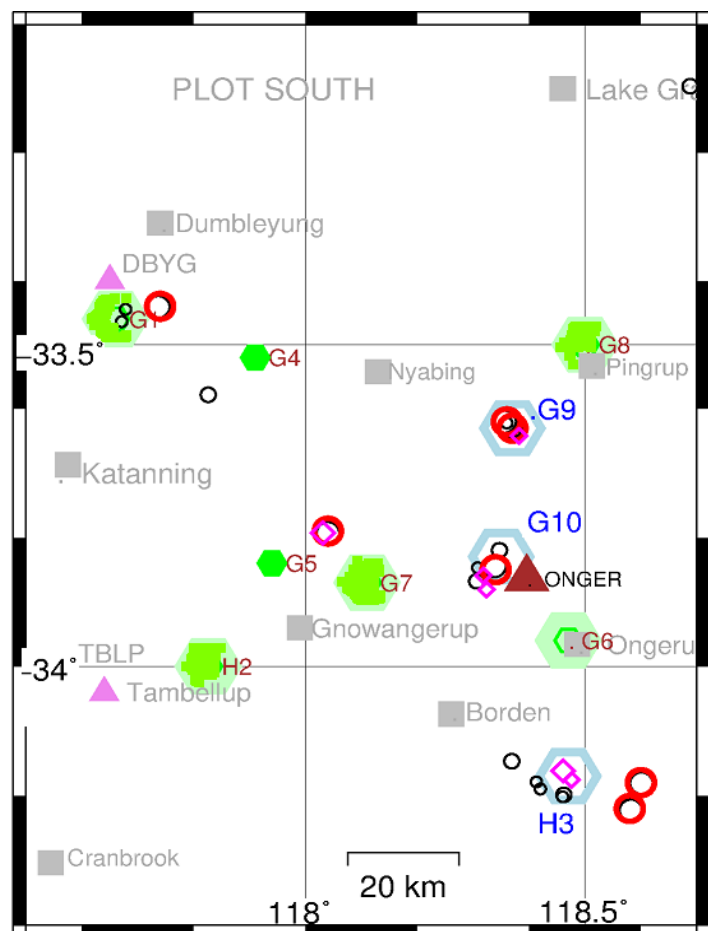


Figure 6. Seismicity. Area 3 (south)

Gnowangerup on 14 November 2020. It is relatively close (about 5 km) to locations G5 and G7. Whether it can be related to either of these two cluster centres is uncertain. It should be remembered that the location uncertainties in this area flow through to uncertainties in cluster locations as well.

3.4 Seismicity in Area 4 (east) – Figure 7

Events in this area (Figure 7) in the eastern regions of SWA, are hard to locate because of poor seismograph distribution. Figure 7 clearly shows three clusters: (1) N of Hyden (five events), (2) NE of Hyden (three events) and (3) SE of Newdegate (five events). These clusters show “good” correlation with locations F1, F6 and G3 respectively, and are listed in Table 1. They occurred in October and November of 2020.

Zone I was added to the list of zones in Dent (2020) to accommodate an important cluster north of Ravensthorpe in August 2017 (I1). Figure 7 shows a solitary event (ML 2.6) in November 2020 east of F6. Examination of prior activity shows four other events nearby, and of similar magnitude, since August 2017, and this location is here defined as a new cluster location, I2. It is approximately co-linear with F1 and F6, suggesting they may be linked in some way.

NW of Marvel Loch: A single, relatively large event (ML 2.8) occurred on 11 August 2020 (Table 1) and may represent continuing activity from a cluster location D11 active in September 2017. A small (ML ~2.2) ACG-located event (19 Feb 2021) also seems to have come from this location.

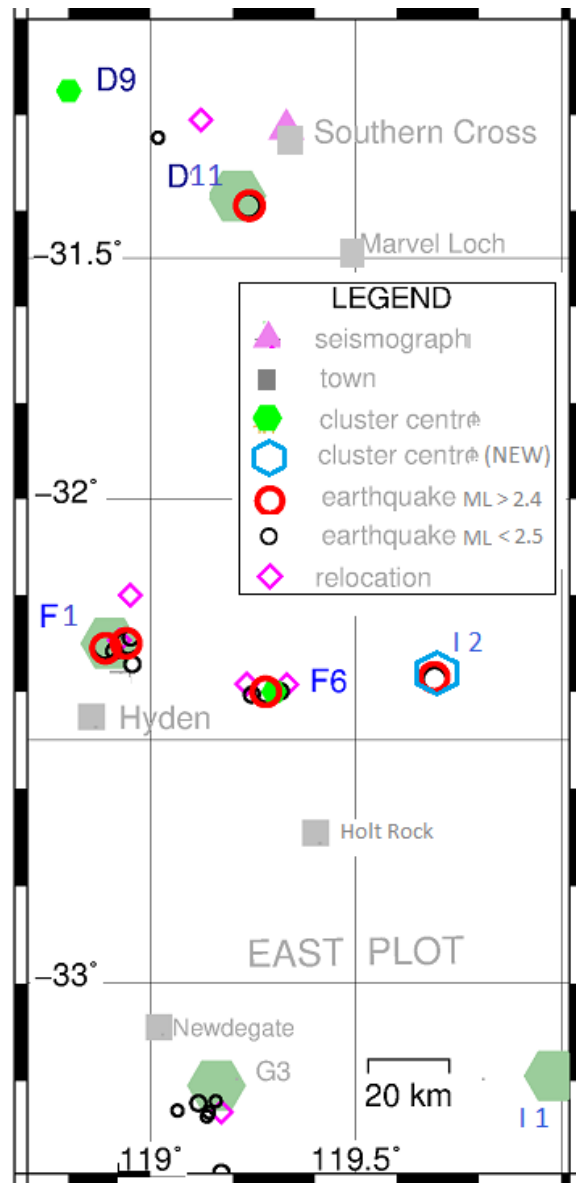


Figure 7. Seismicity, Area 4 (east)

4 Discussion

As discussed in Section 3.2, the events west of Quairading represent an instance where events may occur in two or more closely spaced clusters, rather than at a single location. However, there is an important caveat to consider, in that the locations are poor and all may emanate from a single location. This is more of an issue for older events where there is limited data. However, in cases such as west of Quairading, and west of Beacon, location accuracy is considered reliable enough to suggest that there really are separate clusters. For

grouped clusters in other areas, it is less certain. These include the groups in the vicinity of Ongerup and north of Hyden.

Some groups identified are close to an existing cluster location, and they may prove to be at the same location if locations can be improved. These are shown in Table 2 as belonging to that cluster, but with a “ne”, “e” or “w” qualifier depending on their relative location.

Assuming the groups of clusters are real (we might call them “super clusters”), it would be nice to ascertain if there was “structure” within the clusters. This could suggest a causative fault, and may allow an estimate of its orientation, and, if the data was high quality, perhaps a dip to the fault. If the cluster locations were linked in some way, it could explain the “sympathetic” seismicity seen here in neighbouring cluster locations, e.g. W of Quairading, N-NW of Hyden, and in the past, NW of Beacon.

This analysis has attributed 23 of the 26 largest events (Appendix 2) in 2020-2021 to eleven cluster locations. Overall, about 90 of the approximately 130 events, (i.e., about 70%) can be assigned to cluster centres based on the GA locations. Relocating many of the smaller “unassigned” events using additional data could see them assigned to existing, or perhaps new, cluster locations. In reports on preceding years, commonly >80% of events have been assigned to cluster locations.

Relocations of events in the two major clusters (SWK, WOQ) support the conclusion (as seen for events near C3 in 2011 and west of Beacon in 2012) that event distribution is much tighter than GA solutions suggest. Dent (2017) suggested that clustered events may fit within a 2x2 km area.

The data above show the necessity for the best possible earthquake locations. The average uncertainty for earthquakes located using stations of the ANSN alone is about 5-10km, making the resolution of closely spaced clusters very difficult. This is more of an issue for events before 2020, since the four new stations installed by the GSWA (Murdie et al., 2021) have resulted in considerably improved locations in SWA. A joint project between GA, the ANU and the Geological Survey of W.A. currently underway has seen the installation of an additional 25 temporary seismographs in SWA (Murdie et al., 2020), and this should result in a data set of very accurately located events in the region.

Earthquakes in cluster groups are the most common form of seismic expression in the western Yilgarn Craton. However, they are also found in the central and eastern regions of WA, as well as off the west coast, e.g., west of Margaret River in July 1989 where there were 14 events, with maximum ML 3.2 (Dent, 2008). Another example to the east is a group of about a dozen events about 150 km south of Warburton between 1986 and 2001 (largest ML 4.8, August 1988).

In a review of cluster groups active between 2017 and 2020, Dent (2020) plotted cluster locations against the local geology, as well as against gravity anomaly data. No clear association was noted, but a possible correlation between a NNW trend in seismicity with a NNW trend in the gravity field was noted. Dent et al. (2021) plotted seismicity in the Cadoux region against anomalies in the geomagnetic field. A possible correlation between N-S trending earthquakes, and a N-S trending geomagnetic anomaly was noted. However, no clear correlation of features on the map with seismicity sources A, B, C or D (cluster locations A1 to A4, Appendix 1) is evident.

In seismic hazard analysis, one of the first steps is the production of a “de-clustered” seismic catalogue, in which fore-shocks and after-shocks (“dependent” events) have been removed, and sophisticated algorithms have been written to achieve this. However, the swarm-like earthquake clusters seen in southwest Australia suggest that often “master events” can be

hard to define. Also of importance is the apparent long duration of some cluster centres. This work is a start to understanding the clusters of south-west Australia, so that eventually a more accurate assessment of seismic hazard may be produced. It also suggests that some locations of high seismic risk are already apparent, and should become the focus of more detailed examinations.

5 Conclusions

The concept of continuing or renewed activity at specific cluster sites is consistent with activity seen in this 12-month period. Earthquake activity within this period occurred at locations of fifteen previously defined clusters (Table 1). Three other groups of earthquakes may possibly have association with previous clusters, but this remains uncertain, and four occurrences are considered to be new cluster sources (Table 2). These locations of recurring seismicity are significant for the prediction of future seismic activity in the region.

6 Acknowledgements

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7 References

- Clark, D. J., Brennand S., Brenn G., Garthwaite M. C., Dimech J., Allen T. I., and Standen S., 2020. Surface deformation relating to the 2018 Lake Muir earthquake sequence, southwest Western Australia: new insight into stable continental region earthquakes. *EGU Solid Earth*, 11, 691–717.
- Denham, D., Alexander, L.G., Everingham, I.B., Gregson, P.J., McCaffrey, R., Enever, J.R., 1987. The 1979 Cadoux earthquake and intraplate stress in Western Australia. *Aust. J. Earth Sci.* 34, 507– 521.
- Dent, V. F., 2008. Improved hypocentral estimates for two recent seismic events in south-western Western Australia using temporary station data. In *Proc. AEES 2008 Conference*, Canberra, ACT.
- Dent, V. F., 2012. Evidence for shallow focal depths and denser locations for three southwest seismic zone earthquake clusters, 2011. *Proc. AEES 2012 Conference*, Gold Coast, Queensland.
- Dent, V. F., 2013. Using the “PSN” network in southwest Australia to improve earthquake locations in the region. *Proc. AEES 2013 Conference*, Hobart, Tasmania.
- Dent, V.F., 2014. Earthquake clusters in southwest Australia in 2013-14. *Proc. AEES 2014 Conference*, Lorne, Victoria.
- Dent V.F., 2016. A preliminary map of cluster locations in southwest Western Australia, 1990 – 2016. *Proc. AEES 2016 Conference*, Melbourne, Victoria.
- Dent V.F., & Collins, C., 2017. A new interpretation of the seismicity of the Mukinbudin/Bonnie Rock area of Western Australia. In *Proc. AEES 2017 Conference*, Canberra, ACT.
- Dent, V.F. & Collins, C.D.N., 2018(a). Clustered seismicity in southwest Australia, June 2012 – May 2013. In: *Proc. AEES 2018, Conference*, Perth, WA.

- Dent, V.F, & Collins, C.D.N., 2018(b). Seismicity of the Quairading area, Western Australia, with special reference to an earthquake cluster in 1992. In: Proc. AEES 2018 Conference, Perth, WA.
- Dent V., Love D. & Collins C., 2019. Possible clustering in space and time of aftershocks of the ML 5.7 Lake Muir earthquake, southwest Australia, 16 September 2018. Proc. AEES 2019 Conference, Newcastle, NSW.
- Dent V.F, & Collins, C.D.N., 2020. The extent of the epicentral zone for events associated with two ML 5 events in March 2002 near Burakin, Western Australia - a review of field and epicentral data. In: Proc. AEES 2020 Virtual Conference.
- Dent V.F, 2020. Additions to the list of cluster centres in southwest Western Australia seismicity from 2017 to 2020. In: Proc. AEES 2020 Virtual Conference.
- Dent V.F, Collins, C.D.N., & Murdie, R., 2021. 20 years of earthquakes near Burakin in the Western Australian Wheatbelt: A timeline of events in the Burakin seismic cluster of 2001 – 2002 and subsequent seismicity in the region Proc. AEES 2020 Virtual Conference.
- Gordon F.R. and Lewis J.D., 1980. The Meckering and Calingiri earthquakes: October 1968 and March 1970. Geological Survey of Western Australia Bulletin 126.
- Leonard M. & Boldra P., 2001. Cadoux swarm September 2000 – an indication of rapid stress transfer? In: Proc. AEES 2001 Conference, Canberra, ACT.
- Leonard, M., Clark, D., Collins, C. & McPherson, A., 2012. The 2012 Australian Seismic Hazard Map – Source Zones and Parameterisation. In: Proc. AEES 2012 Conference, Gold Coast, Queensland.
- Murdie, R., K. Gessner, M. Miller, M. Salmon, H. Yuan, J. Whitney, S. Gray and T. Allen, 2020. Geological Survey of Western Australia: SWAN takes off - a new seismic monitoring project in Western Australia, Preview 208, 28-29, doi: 10.1080/14432471.2020.1828423.
- Murdie, R., Brisbout, L., Glanville, H., Allen, T. & Dent, V. 2021. Earthquake monitoring in the Southwest Seismic Zone, Western Australia. ASEG, Queensland, 2021

Appendix 1. Cluster locations.

	Name	Lon	Lat	Location	Com.		Name	Lon	Lat	Location	Com.
1	A1 [!]	116.95	-30.46	NW of Burakin		36	E4	117.25	-31.98	W of Quairading	20(2)
2	A2 [!]	117.05	-30.53	W of Burakin	'locB'	37	F1	118.90	-32.30	N of Hyden	20(2)
3	A3 [!]	117.10	-30.63	SW of Burakin	'locC'	38	F2	116.98	-32.25	N of Brookton	20(2)
4	A4 [!]	117.10	-30.79	W of Cadoux		39	F3	117.19	-32.14	Morbinning	20(2)
5	A5	117.17	-30.15	Kalannie		40	F4	117.31	-32.49	E of Pingelly	20(2)
6	A6	116.30	-30.93	New Norcia		41	F5	117.35	-32.24	S of Quairading	
7	A7	117.18	-30.47	N of Burakin		42	F6	119.30	-32.40	N of Holt Rock	
8	A8	116.25	-30.73	SW of Miling		43	F7	117.87	-32.81	SW of Kulin	
9	A9	116.57	-30.23	W of Dalwallinu	20(3)	44	F8	117.59	-32.84	SW of Wickiepin	20(3)
10	A10	116.55	-30.68	SW of Ballidu	20(3)	45	F9	117.82	-32.05	N of Corrigin	20(3)
11	A11	116.40	-29.80	S of Latham	20(3)	46	G1	117.66	-33.46	SW of Dumbleyung	20(2)
12	B1	117.75	-30.24	N of Beacon	20(2)	47	G2	117.03	-33.69	NW of Kojonup	
13	B2	117.75	-30.40	NW of Beacon	20(2)	48	G3	119.16	-33.21	SE of Newdegate	20(2)
14	B3	117.28	-30.26	NE of Kalannie		49	G4	117.91	-33.52	W Nyabing	
15	B4	117.65	-30.31	NW of Beacon		50	G5	117.94	-33.84	NW of Gnowangerup	
16	B5	117.41	-30.10	NE Kalannie	20(2)	51	G6	118.47	-33.96	W of Ongerup	20(3)
17	C1	117.47	-30.64	N of Koorda		52	G7	118.11	-33.87	NE of Gnowangerup	20(3)
18	C2	117.80	-30.64	N of Bencubbin		53	G8	118.50	-33.50	N of Pingrup	20(3)
19	C3	117.60	-30.62	NE of Koorda		54	G9*	118.36	-33.62	SW of Pingrup	
20	C4	117.90	-30.95	S of Bencubbin		55	G10*	118.34	-33.85	NW of Ongerup	
21	C5*	117.25	-30.95	SW of Koorda		56	H1	117.05	-34.35	N of Rocky Gully	
22	D1	117.67	-31.45	SE of Yorkrakine		57	H2	117.826	-34.00	NE of Tambellup	20(3)
23	D2	117.45	-31.25	SE of Wyalkatchem	20(2)	58	H3*	118.47	-34.17	SE of Borden	
24	D3	117.15	-31.45	N of Cunderdin		59	L1	118.56	-30.57	E of Bonnie Rock	
25	D4	118.24	-31.24	SE of Nungarin	20(2)	60	L2	118.42	-30.66	SE of Bonnie Rock	
26	D5	117.50	-31.43	SW of Kellerberrin		61	L3	118.04	-30.87	W of Barbalin	
27	D6	117.70	-31.50	N of Kellerberrin		62	L4	118.74	-30.39	Mt. Jackson	
28	D7	117.28	-31.18	W of Wyalkatchem	20(2)	63	L5	118.02	-30.75	N of Welbungin	20(3)
29	D8	117.63	-31.26	SE of Wyalkatchem		64	L6	118.30	-30.73	N of Mukinbudin	20(3)
30	D9	118.80	-31.15	NE of Westonia		65	M1	116.72	-31.98	SW of York	
31	D10	117.61	-31.12	NW of Yelbeni	20(3)	66	M2	117.08	-31.62	E of Meckering	
32	D11	119.21	-31.37	NW of Marvel Loch	20(3)	67	M3	117.04	-31.70	S of Meckering	
33	E1	117.36	-31.77	NE of Youndegin		68	M4	117.03	-31.65	Meckering	
34	E2	117.84	-31.84	W of Bruce Rock		69	I1	119.98	-33.19	N of Ravensthorpe	20(3)
35	E3	117.91	-31.52	N of Doodlakine		70	I2*	119.69	-32.34	NE of Holt Rock	

Clusters marked with a "*" are defined for the first time in this report

Clusters marked with a "!" first defined by Leonard & Boldra (2001)

20(2) – refers to Table 2 in Dent (2020)

20(3) – refers to Table 3 in Dent (2020)

Appendix 2. Events in SWA, July 2020 – June 2021 and ML ≥ 2.5

	Date & Time	ML	Location	Lat	Lon	Associated Cluster	Comment
1	2020-07-11T12:32:35.6	2.7	S of Dumbleyung	-33.44	117.74	G1	
2	2020-08-10T03:26:55.2	2.9	SE of Borden	-34.22	118.58	H3	new
3	2020-08-10T15:40:00.7	2.8	SE of Borden	-34.18	118.60	H3	new
4	2020-08-11T11:26:46.0	2.8	SW of Southern Cross	-31.39	119.24	D11	
5	2020-08-21T20:58:53.5	2.5	NW of Ongerup	-33.85	118.34	G10	
6	2020-10-02T21:32:25.7	2.5	N of Hyden	-32.31	118.89	F1	
7	2020-10-06T10:36:21.3	2.6	NE of Hyden	-32.30	118.94	F6	
8	2020-10-24T09:59:08.9	2.5	SW of Pingrup	-33.63	118.37	G9	new
9	2020-10-31T03:02:37.3	2.6	SW of Pingrup	-33.62	118.36	G9	new
10	2020-11-05T14:46:22.2	2.5	NE of Hyden	-32.40	119.28	F2	
11	2020-11-14T20:43:37.4	2.5	Gnowangerup	-33.79	118.04	Isolated?	
12	2020-11-18T18:20:12.5	2.6	Goldfields	-32.37	119.69	I2	new≥
13	2020-12-04T23:45:48.8	2.7	Quairading	-32.00	117.33	E4 ^E	
14	2020-12-28T17:40:42.1	2.5	Quairading	-31.99	117.34	E4 ^E	
15	2021-03-06T00:57:01.9	2.5	NE of Wyalkatchem	-31.18	117.52	D2	
16	2021-03-06T03:51:32.8	3.0	NE of Koorda	-30.63	117.61	C3	
17	2021-03-11T04:39:05.5	2.7	NE of Wyalkatchem	-31.18	117.50	D2	
18	2021-03-18T00:49:19.8	2.6	Meckering	-31.63	116.99		
19	2021-03-26T06:28:36.8	2.5	SE of Cunderdin	-31.77	117.37	E1	
20	2021-04-18T11:00:12.7	2.8	SW of Koorda	-30.96	117.26	C5	
21	2021-05-24T13:43:04.5	2.6	SW of Koorda	-30.94	117.25	C5	
22	2021-05-24T15:17:52.9	2.6	SW of Koorda	-30.97	117.29	C5	
23	2021-05-24T15:20:32.5	2.9	SW of Koorda	-30.94	117.25	C5	
24	2021-05-24T17:57:44.1	2.9	SW of Koorda	-30.91	117.29	C5	
25	2021-06-07T09:05:30.1	2.6	SE of Wyalkatchem	-31.25	117.67	Isolated?	
26	2021-06-10T18:22:39.6	2.6	Meckering	-31.67	117.03		

Appendix 3. Relocation of Geoscience Australia's locations

	Date/Time	Area	ML	Lat	Lon	Depth	Near Stn	Cluster
01	2020-07-17 1701	W of Beacon	2.0	-30.385	117.730	1.6	BCON	B2
02	2020-08-10 1540	SE of Gnowangerup	2.8	-34.162	118.461	2N	ONGER	H3
03	2020-08-11 1234	W of Quairading	2.3	-31.994	117.197	5.1	MEKS	E4*
04	2020-08-12 2026	SE of Gnowangerup	2.3	-34.176	118.476	2.6	ONGER	H3
05	2020-08-14 1400	SE of Gnowangerup	2.3	33.859	118.318	1.4	ONGER	G10
06	2020-08-16 1544	W of Quairading	2.4	-31.975	117.212	4.1	MEKS	E4*
07	2020-08-21 2058	SE of Gnowangerup	2.5	-33.881	118.324	6.3	ONGER	G10
08	2020-09-07 0550	SE of Meckering	2.4	-31.716	117.072	5.2	AUKUL	
09	2020-10-02 2132	N of Hyden	2.5	-32.294	118.923	5.2	AUKUL	F1
10	2020-10-06 1036	NE of Hyden	2.6	-32.303	118.947	3.0	AUKUL	F1
11	2020-10-14 2203	S of Newdegate	2.1	-33.264	119.171	2.9	ONGER	G3
12	2020-10-24 0959	SE of Gnowangerup	2.5	33.642	118.382	0.9	ONGER	G10
13	2020-10-30 1503	E of Hyden	2.4	-32.385	119.331	5.4	HYDN	F6
14	2020-11-05 1446	NE of Hyden	2.5	-32.39	119.258	14	AUKUL	F6
15	2020-11-14 2043	NW of Ongerup	2.5	-33.793	118.031	5.3	ONGER	G9
16	2020-11-16 2034	NE of Kalannie	2.4	-30.193	117.234	7.8	BCON	B3
17	2020-11-18 1820	Goldfields	2.6	-31.211	119.122	12.5	STHX	
18	2020-12-04 2345	W of Quairading	2.9	-32.001	117.297	5.4	MEKS	E4!
19	2020-12-09 0213	W of Quairading	2.2	-32.008	117.273	2.9	COR2	E4!
20	2020-12-15 0820	SW of Wyalkatchem	2.3	31.234	117.290	6.6	KORDA	
21	2020-12-18 1822	W of Southern Cross	2.2	-31.211	119.122	2N	STHX	Has hyd
22	2020-12-28 1740	W of Quairading	2.5	-32.008	117.283	4.8	MEKS	E4!
23	2021-01-12 0954	W of Quairading	2.0	-31.985	117.216	2N	COR2	E4*
24	2021-01-18 1518	7 k NE of Burakin	2.4	-30.467	117.201	7.5	CADX	A7
25	2021-01-27 1335	34 km S of Quairading	2.3	-32.324	117.437	2.7	COR2	
26	2021-02-05 2237	S of Manmanning	2.0	-30.908	117.073	3.1	CADX	
27	2021-02-19 2147	80 Km ENE of Hyden	(2.0)	-32.164	119.644	2N	HYDN	I2
28	2021-03-06 0057	NE of Wyalkatchem	2.5	-31.201	117.497	2.5	KORDA	D3*
29	2021-03-06 0351	NE of Koorda	3.0	-30.625	117.599	3.3	KORDA	C3
30	2021-03-11 0439	NE of Wyalkatchem	2.7	-31.201	117.502	3.5	KORDA	D3*
31	2021-03-13 2221	W of Quairading	2.2	-31.987	117.220	-0.3	QUA	E4*
32	2021-03-13 2229	W of Quairading	2.4	-31.989	117.215	0.9	QUA	E4*
33	2021-03-18 0049	Meckering	2.6	-31.632	116.983	12.1	MECK	
34	2021-03-19 1113	W of Quairading	2.0	-31.973	117.208	3.0	QUA	E4*
35	2021-03-26 0628	SE of Cunderdin	2.5	-31.766	117.391	4.3	QUA ?	E1
36	2021-04-18 1100	SW of Koorda	2.8	-30.958	117.251	-0.8	CADX	C5
37	2021-05-24 1757	SW of Koorda	2.9	-30.965	117.260	-0.3	CADX	C5
38	2021-05-27 2128	SW of Koorda	2.2	-30.964	117.261	5.1	CADX	C5
39	2021-06-07 0905	SE of Wyalkatchem	2.6	-31.262	117.658	5.1	KORDA	
40	2021-06-08 1350	Meckering	2.2	-31.655	117.000	1.4	MECK	
41	2021-06-28 2305	N of Cunderdin	2.4	-31.397	117.234	4.4	MEKS	D3*
42	2021-06-10 1822	Meckering	2.6	-31.667	116.993	5.0	MEKS	