Continuing seismicity in the Arthur River area, Southwest Western Australia (September 2022 - September 2023)

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Abstract

A seismic sequence near Arthur River, in the southwest of Western Australia, began in January 2022 and has continued into late 2023. Since September 2022 the seismicity has continued to be monitored, but by a reduced network of field stations. Locations of the newer events are presented here, plus relocations of some of the better recorded events of 2022. The results suggest that all the large events (ML 4.0+) may occur within an elongated area about 2 km wide near the centre of the seismicity. A possible north-easterly trend in seismicity is noted, although a small group of events towards the west of the zone show a clear east-west trend. Other events occur over an area approximately 6 km x 6 km, as noted by Murdie et al. (2022), which approximately delineates an area that INSAR observations identified as slightly uplifted. The results suggest most events are 3 km deep or less. Most of the deeper events occur in the northwest but no conclusions about possible fault planes can be made without additional data.

Keywords: southwest Western Australia, seismicity, focal depths

1 Introduction

The Arthur River area of southwest Western Australia (SWWA - Figure 1) has been the source of major seismicity since early January 2022, including a moderately-large shallow earthquake of ML 4.8 which caused some local damage, and was felt in Perth 200 km to the NNW. This earthquake had a large number of aftershocks, unlike a larger event east of Gnowangerup, 18 months later (5 August 2023, ML 5.6, MW 5.0). The Arthur River sequence probably started at least 2 months before the January 2022 activity; two events were located by Geoscience Australia in the area (ML 2.4 & 2.2) in November 2021.

The most significant previous cluster in the region was north of Narrogin in January – February 1966, when ~ 20 events, the largest being ML 4.0, occurred over ~ 4 weeks. A closer, but smaller cluster occurred north of Wagin in December 1989, the largest event being ML 2.6 (Dent & Collins, 2022). Another small cluster, about 17 km northeast of the epicentral area, or 20 km NW of Wagin (5 located events, largest ML 2.7, Dent & Collins, 2022), was contemporaneous with the Arthur River activity. Two temporary seismic recorder deployments were installed after the largest event (24 January 2022, ML 4.8). The Geological Survey of

WA (GSWA) deployed instruments at nine different locations between 11 January and October 2022 (Murdie et al., 2022). Dent & Judge deployed a smaller network of Public Seismic Network (PSN) stations (Dent, 2013) from 26 January 2022 (Dent & Love, 2022). Data from the PSN network was used to deduce an approximate central location for the seismicity (location G11 in Dent & Collins, 2022). This is shown as a grey hexagon in Figure 2. Relocations of the three largest events by Murdie et al., (2022) are also indicated in Figure 2.

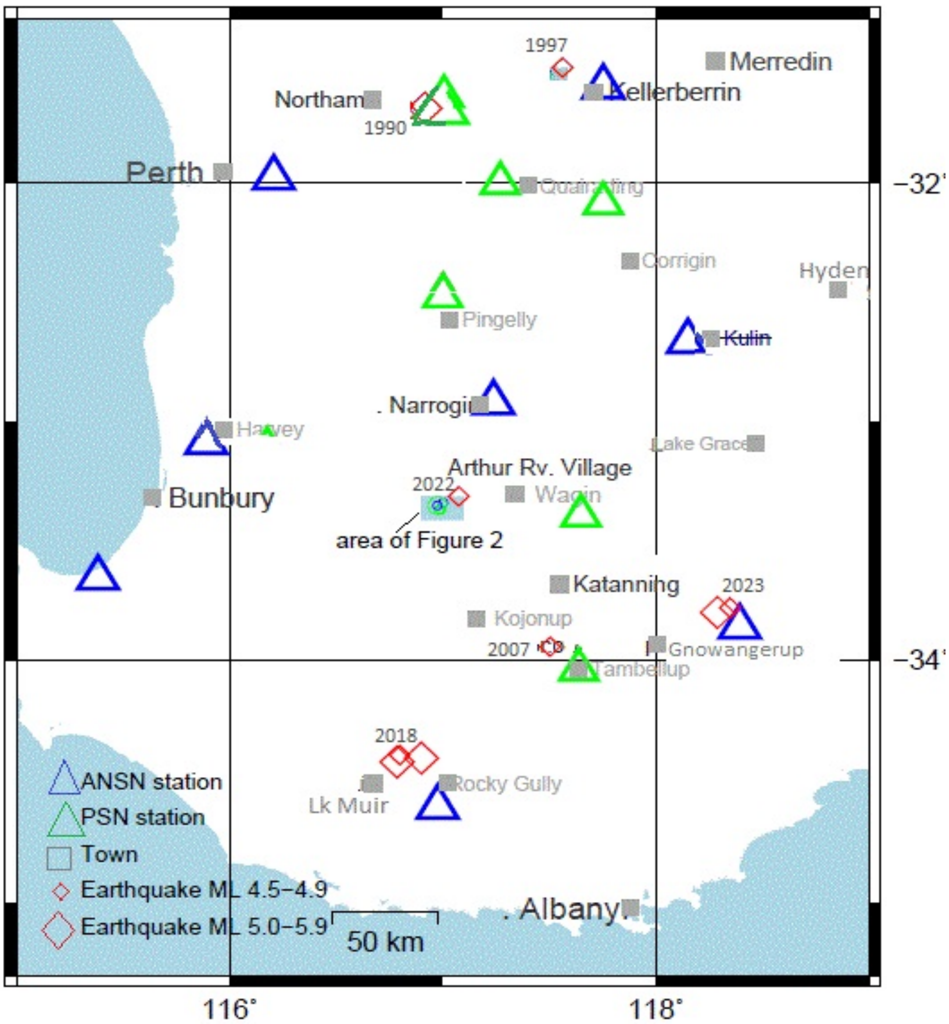

Figure 1. Earthquakes in SWWA ML 4.5+ since 1980

While the GSWA network was closed towards the end of 2022, some PSN stations continue to operate up to the present time (September 2023) and have enabled relocations for the continuing seismicity in the region. In addition, the GSWA is operating a temporary state-wide array (the SWAN network, Murdie et al., 2022), which has 3 stations within approximately 60 km of Arthur River.

The initial, well-studied, period from January to August 2022 is here referred to as Period 1, and the period studied here, from September 2022 to August 2023, as Period 2.

2 Earthquake activity since September 2022 (Period 2)

Geoscience Australia (GA) located 112 events in the region (Figure 2) of ML 2.0 and above.

The events were located using data from the Australian National Seismograph Network (ANSN); the nearest station of this network is Narrogin (NWAO), about 60 km to the NNE of most of the activity.

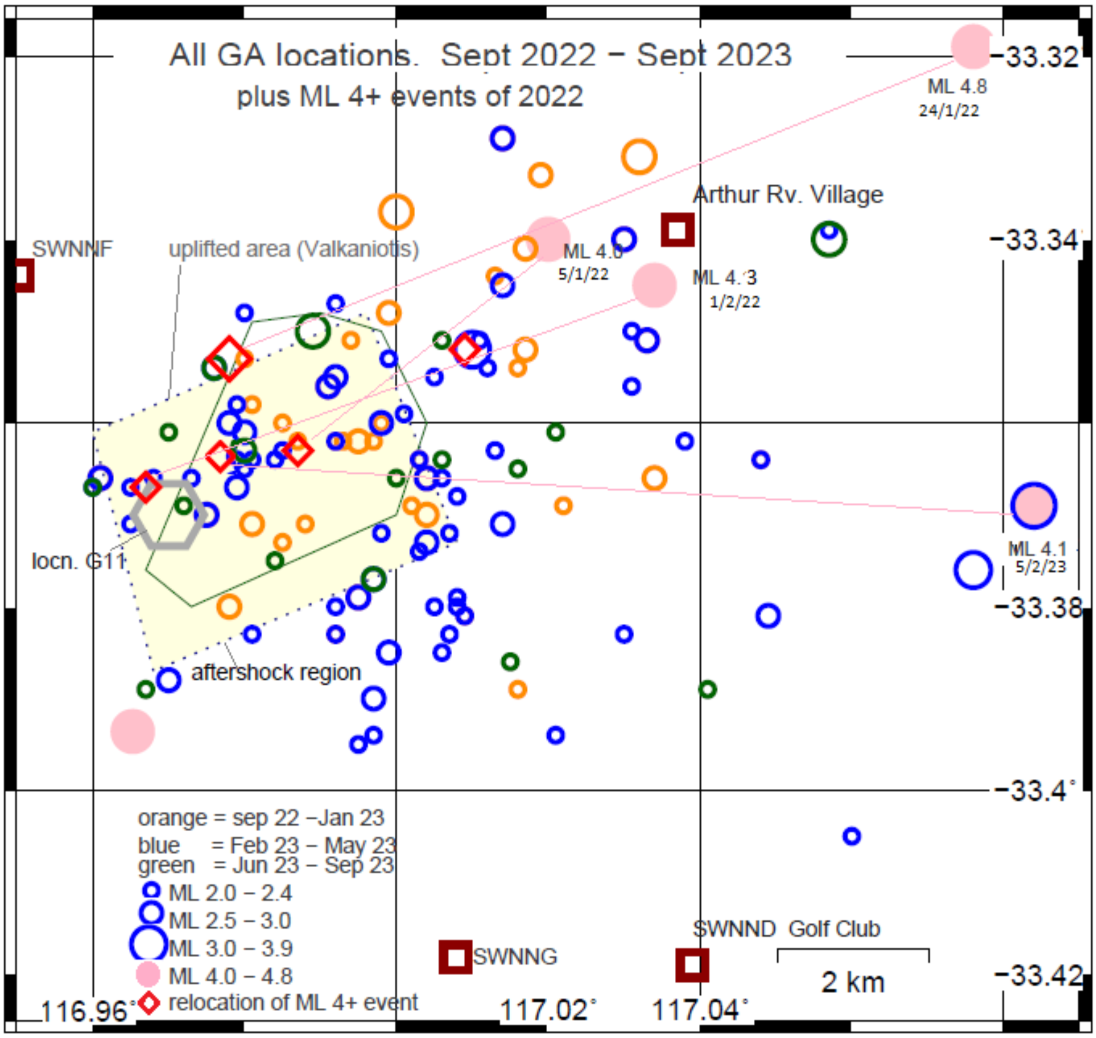

Figure 2. Plot of GA-located events for Period 2 (September 2022-2023)

There were peaks in seismic activity in September 2022, February 2023 and late August-early September 2023. In Figure 2, the seismicity is plotted in three periods to separate these periods of higher seismicity.

While GA located events of ML 2.0 and above, there were many smaller events in this sequence. Many of these could be well located if data were available from closer (temporary) stations. Murdie et al. (2022) located many hundreds of small events using data from the field network in place from January to September 2022. These events lie within the pale-yellow coloured area in Figure 2.

The three initial large events of the cluster (Table 1) were relocated by Murdie et al., (2022) using temporary field station data; these relocations are plotted in Figure 2. These relocations show substantial shifts (~8 km) to the southwest, which is the common pattern for relocations of GA epicentres in this area.

2.2 Focal depths

Focal depths given by GA for the events shown in Figure 2 vary from zero to 8 km. Uncertainties, as indicated in the GA catalogue, are of the order of +/- 5 km. The relocations presented here usually use phase data from at least two close stations (< 6 km), and this reduces focal depth uncertainties significantly. The strong InSAR response suggests all activity is very shallow, and it is therefore necessary to have a station very close to the epicentre to have confidence in the computed depth.

The pale-yellow area in Figure 2 is based on the map presented by Murdie et al. (2022) indicating the area where most of their locations plotted. It correlates well with the green polygonal area in Figure 2, which shows an area of minor uplift (approximately 2 cm) identified from InSAR data by Valkaniotis (2022, unpubl.).

Table 1. Locations and relocations of the largest events

ML	Date & Time	GA Location	Depth Km	Relocation	Nearest station and distance	Author
4.0	05/01/2022 11:37	-33.340 117.020	7	-33.363 116.987	NWAO 54 km	Murdie et al. (2022)
3.8	22/01/2022 07:40:49	-33.313 117.059	8	-33.358 116.974	NWAO 54 km	Dent (this paper)
4.8	24/01/2022 21:24:47	-33.319 117.076	5 G*	-33.353 116.978	SWNNF ~3 km	Murdie et al. (2022)
4.3	01/02/2022 10:41:03	-33.345 117.034	5 G*	-33.367 116.967	SWNNF ~4 km	Murdie et al. (2022)
4.1	05/02/2023 00:39:57	-33.369 117.084	6	-33.364 116.977	ARV4 2 km	Dent (this paper)
	G* - indicates depth constrained to this value in the location process					

2.3 Reducing earthquake location uncertainties; the PSN network

The small PSN network (Dent & Love, 2022) has continued to operate at a reduced scale up to September 2023. Two stations (AJ02 and ARV4, Figure 4) operated with only minor breaks through January 2022 to September 2023. The network was expanded to three stations when sites at AJ03 (February and June 2023), and AJ01 (September 2023) operated for brief periods. Though the amount of data retrieved from 3 stations is limited, it has allowed some relatively accurate locations to be made.

While the locations published by GA have uncertainties of the order of approximately +/- 10 km, when new data from field networks is added, these uncertainties can be reduced to approximately +/- 3 km. A proposed accuracy scale is shown in Table 2. On this scale, original GA locations are assigned Accuracy D, and relocations using field data are assigned accuracies of A, B or C depending on how much field data is available.

Table 2. Criteria determining uncertainty classification

category	Number of close stations	Comment
A +	3 close stations	3 stns with P and S times
A-	3 close stations	2 stns plus S-P time for 3rd
B+	2 close stations	Relocation of GA event, 2 close stn
B-	2 close stations	As above but GPS lock lost on 1 or S is poor
C	nil	Relocation of GA event, 1 close stn
D+	nil	GA location where RMS is < 0.50
D-	nil	GA location where RMS is > 0.50

The GA locations were computed using the IASPEI91 earth model (Kennett & Engdahl, 1991). The relocations were computed using a new earth model, WA5. This new model has seismic velocities within the top 2 km which are lower than the WA2 model (Dent, 1989), used by Dent & Love, (2022), and the IASPEI91 model. The velocities between 2 and 7 km depth are intermediate between WA2 and IASPEI91. These models are illustrated in Figure 3.

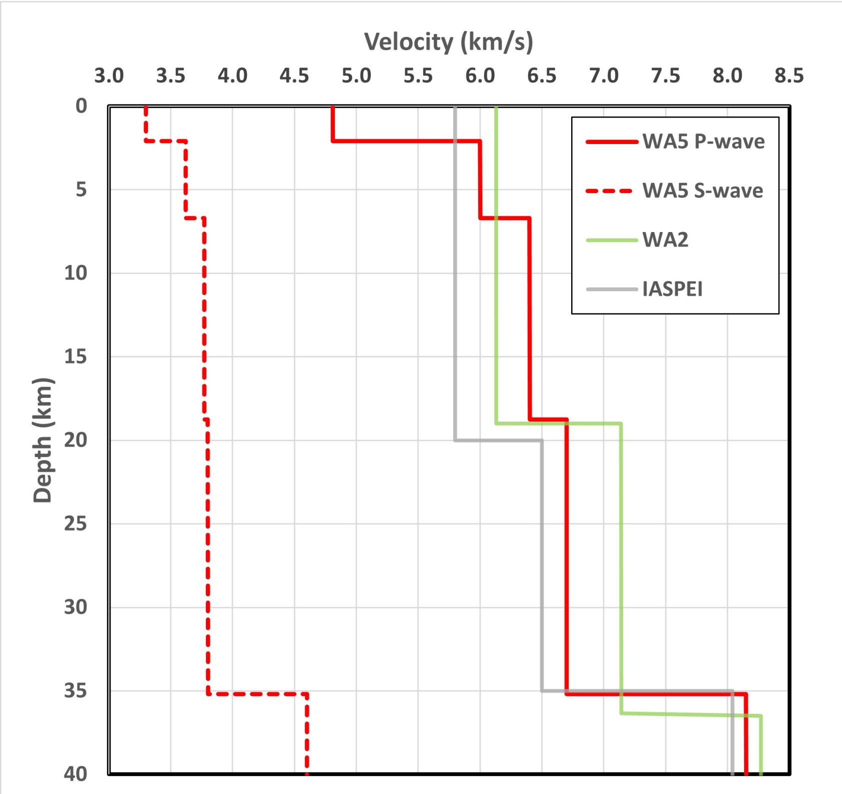

Figure 3. Velocity-Depth models

2.4 Factors affecting location accuracy

To obtain well-constrained locations, a minimum of three close stations is needed. This has been the case for relatively few of the earthquake locations presented here. The earthquake also needs to be located within the area enclosed by the station network. The phase arrivals recorded at the stations should ideally be impulsive and clear to read. This is only occasionally the case for Arthur River events and is a significant limiting factor for accurate locations. The typically emergent arrivals observed in Arthur River data may be problematic for automatic phase-picking routines.

2.5 Relocation of GA-located events, Period 2 (Sept 2022 - Sept 2023)

Fifty of the 113 GA-located events of Period 2 have been relocated here (Appendix 1 and Figure 4). The relocations incorporate data from at least one, and usually two close PSN stations (AJ02 and ARV4). In cases where only one temporary station is available, the event is assigned an accuracy of C; where 2 stations are used it is assigned an accuracy of B.

In the relocation process, the data have been weighted to ensure that the two close stations have very low residuals. Data from at least one regional station (ie, one of the other seismographs plotted in Figure 1) have also been used in the solution. Being more distant, the regional stations often have poorer quality phase-arrivals and it is noted that using regional station data can increase the residuals for the (higher quality) close station data (ie, increase location errors). This is probably due to poor phase onsets at the more distant stations and the cumulative effects of minor inaccuracies in the velocity model. Hence the regional data are used with caution. The root-mean-square (RMS) error achieved in the relocations is always quite low (< 0.1 secs), although the number of phases used is also small (usually about 5 phases). Note that the larger events can be the hardest to locate well, because the seismic signal often saturates the closer recorders.

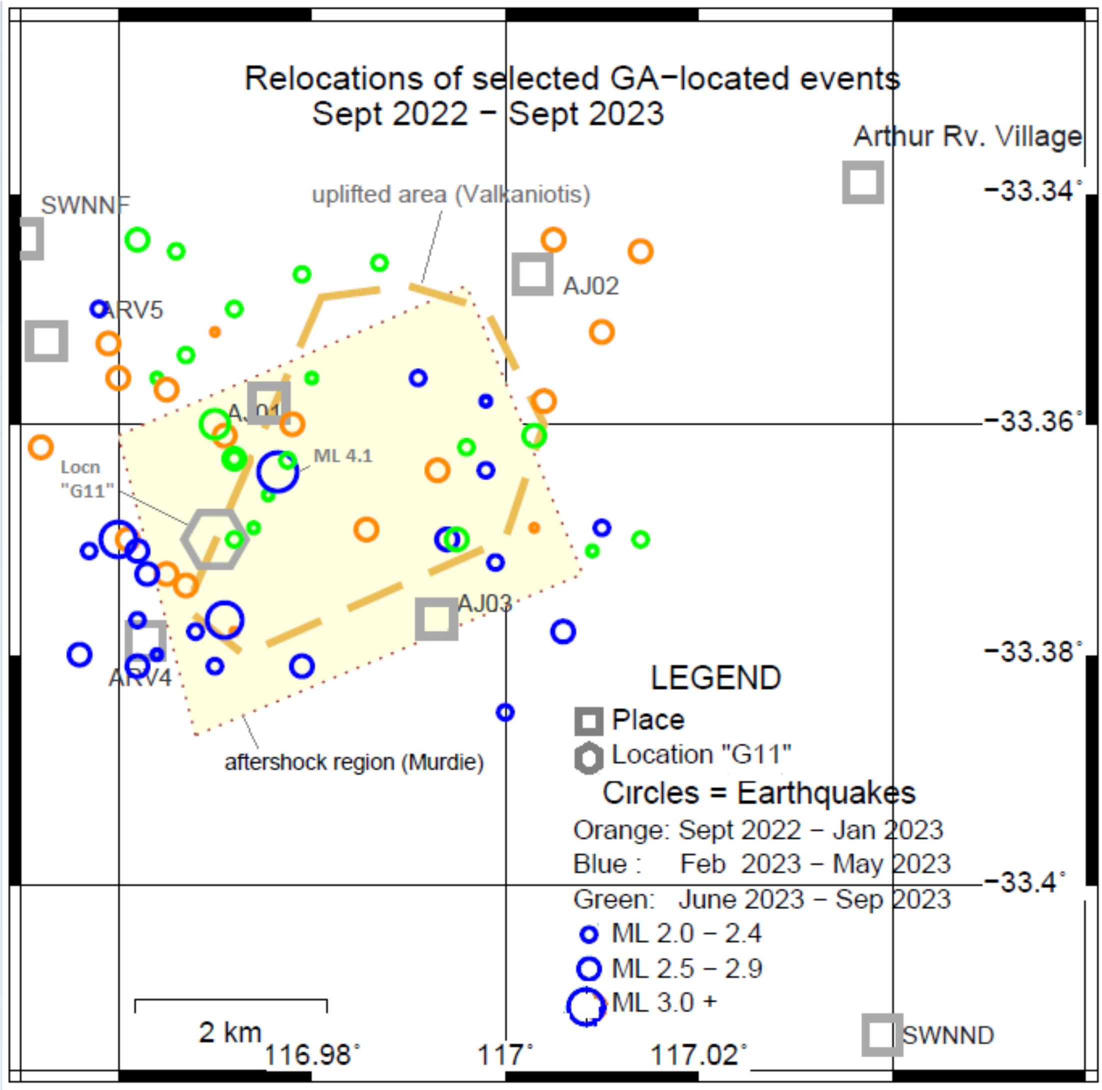

Figure 4. Relocations of selected GA-located events of Period 2, plus well-located minor events.

In Figure 4, most GA locations have been moved westwards, and suggests a concentration of events in the vicinity of the cluster location (G11) noted by Dent & Collins (2022).

2.6 Higher quality locations for Period 2 (September 2022 – September 2023)

Locations which use 3 close stations are considered the most accurate, and are assigned an accuracy A. In 2023, such conditions existed only briefly (ie, when stations AJ02, AJ03 and ARV4 were all operating). These periods are shown diagrammatically in Appendix 3. The well-located events are listed in Table 3 and plotted on Figure 5. The number of well-located events is small, so the sample has been increased by adding the well-recorded events of the previous period (Appendix 2). Whereas in Dent & Love (2022) the events were located using the WA2 model, the locations in Appendix 2 used the WA5 model.

The combined plot of these "good locations" is shown in Figure 5. This plot shows an interesting E-W line of epicentres. It seems significant that the largest event of Period 2 (ie, ML 4.1 on 5 February 2023) is relocated close to the "central location" shown on Figure 2, and reinforces the view that most of the large events are close to this location.

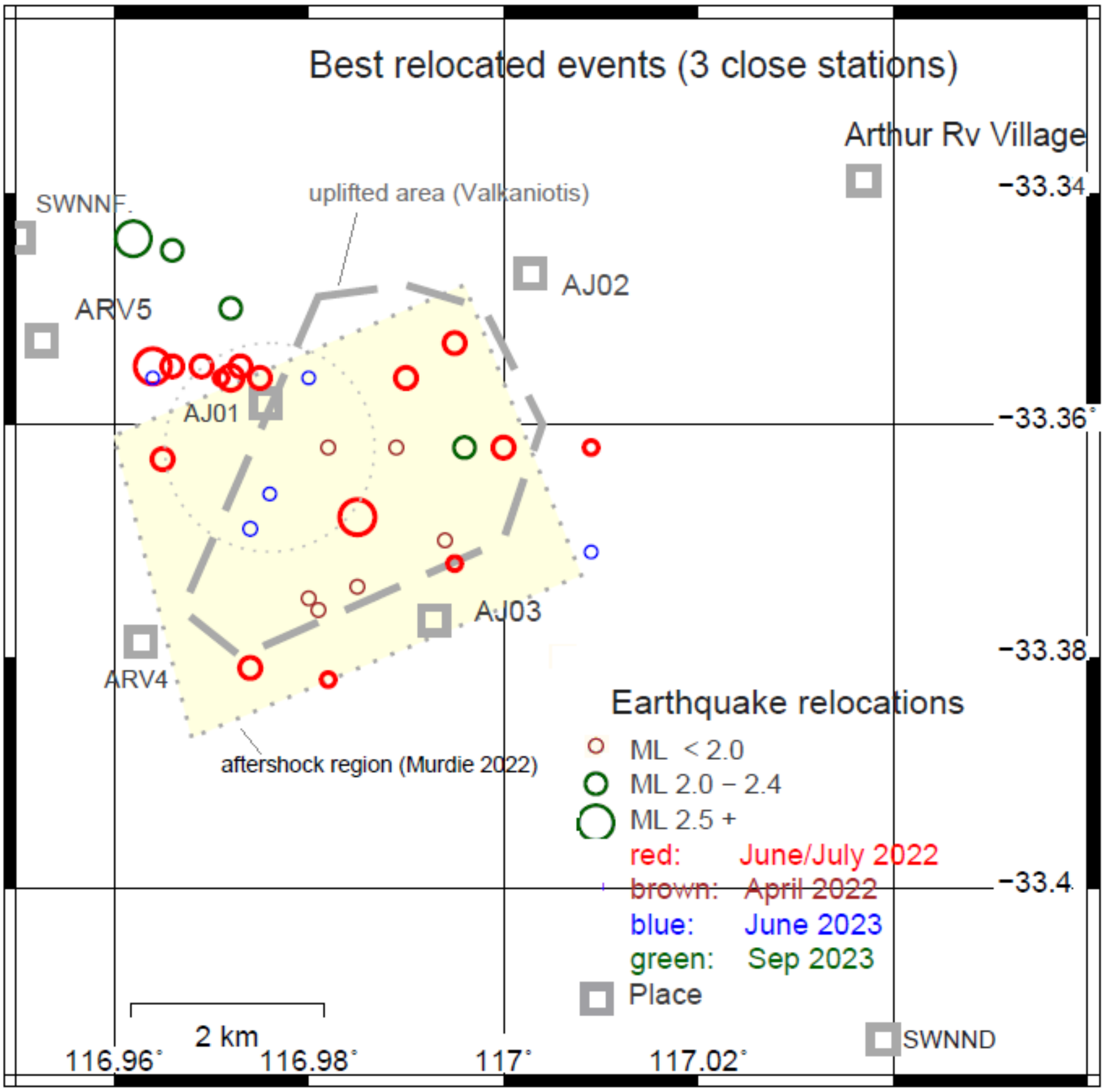

Figure 5. The best constrained locations of Periods 1 and 2 (January 2022 – September 2023)

3. Epicentral plot by Focal Depths

The computed focal depths are partially dependent on the velocity model used. Focal depths presented in Dent & Love (2022), using the WA2 model, were commonly 0 – 1 km, whereas the focal depths in Appendix 2 are 0 – 2.2 km. Relocations of some of the better located events of Period 1 using the WA5 model, have focal depths commonly 1.5 – 2.8 km. In Table 3, solutions of better observed events (Periods 1 and 2) using both the WA5 and WA2 models are shown, and the small increase in focal depth, for a similar RMS of residuals, can be observed.

Table 3. Comparison of solutions for events located with three close stations, Periods 1 & 2

Date & time	ML	WA5 solution		Dep (km)	RMS WA5	WA2 solution		Dep (km)	RMS WA2	stns/ phas
22 Feb 23 1305	2.4	116.971	-33.366	1.9	.022	116.972	-33.367	0.7	.024	4/7
22 Feb 26 2104	2.3	116.969	-33.354	2.2	.021	116.969	-33.354	1.5	.008	3/6
22 Mar 07 2159	2.2	116.978	-33.374	1.8	.030	116.977	-33.374	0.7	.016	3/6
22 Mar 09 1155	2.1	116.977	-33.377	2.5	.020	116.977	-33.377	1.4	.008	3/5
23 Feb 08 1053	< 2.0	116.993	-33.366	2.2	.007	116.993	-33.365	1.6	.009	3/6
23 Jun 19 0242	< 2.0	117.009	-33.371	2.1	.015	117.012	-33.372	0.6	.002	3/6
23 Jun 24 0401	< 2.0	116.976	-33.366	2.5	.004	116.976	-33.367	2.1	.003	3/5
23 Jun 29 2220	< 2.0	116.964	-33.356	2.8	.017	116.964	-33.356	1.9	.012	3/5
23 Sep 15 2031	2.9	116.962	-33.344	0.9	.026	116.966	-33.347	0.0	.019	
23 Sep 15 2047	2.4	116.966	-33.345	1.4	.013	116.967	-33.346	0.0	.005	

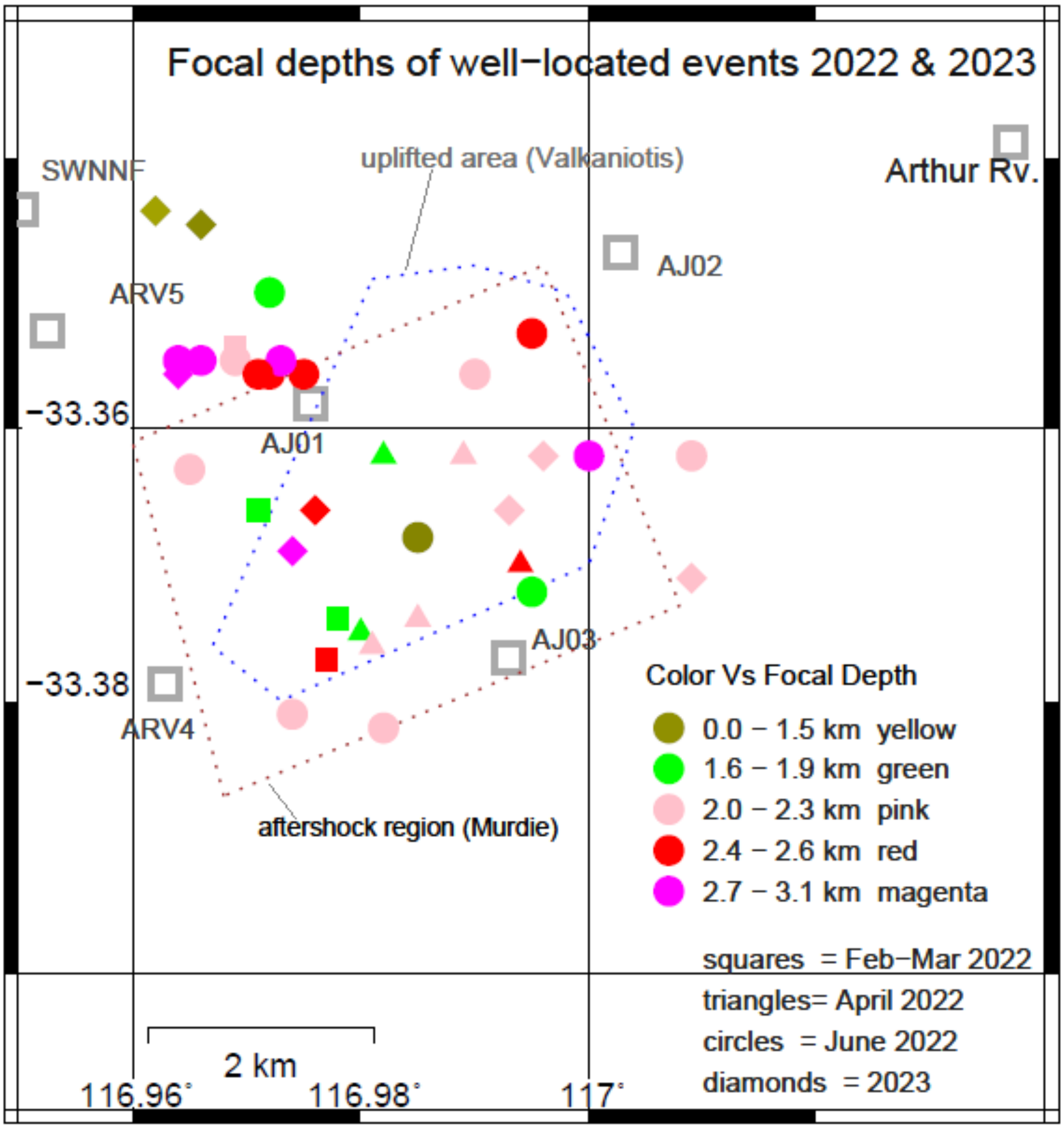

Figure 6. Best located events January 2022 – September 2023 plotted by focal depth

Figure 6 shows the epicentres coloured by focal depth. Possibly the most interesting feature of the plot is the east-west line of events near AJ01 mentioned earlier, and which, if the depths are reliable, would indicate a near-vertical plane. However, another possible trend is of shallower events to the SE and deeper events to the northwest, which could suggest a NE striking fault plane which dips to the NW. More and better focal depth determinations are needed to help lend substance to either of these suggestions.

4. Previously unreported macro-seismic effects

As noted by Murdie et al. (2022) a “wet” area developed near the Pascoe farmhouse (site AJ02) after the ML 4+ earthquakes of January/February 2022 (Figures 7 & 8a). In late 2022 the farmer noticed that there was a small area (diameter approximately 150 m) about 1.2 km west of the wet area, (and close to temporary station AJ01), in which the outcropping granite seemed to have very recently shed weathered surfaces, and portions of outcrops had opened up or broken off (Figure 8b-f). He also noted objects in his kitchen pantry were strewn about after the seismic activity.

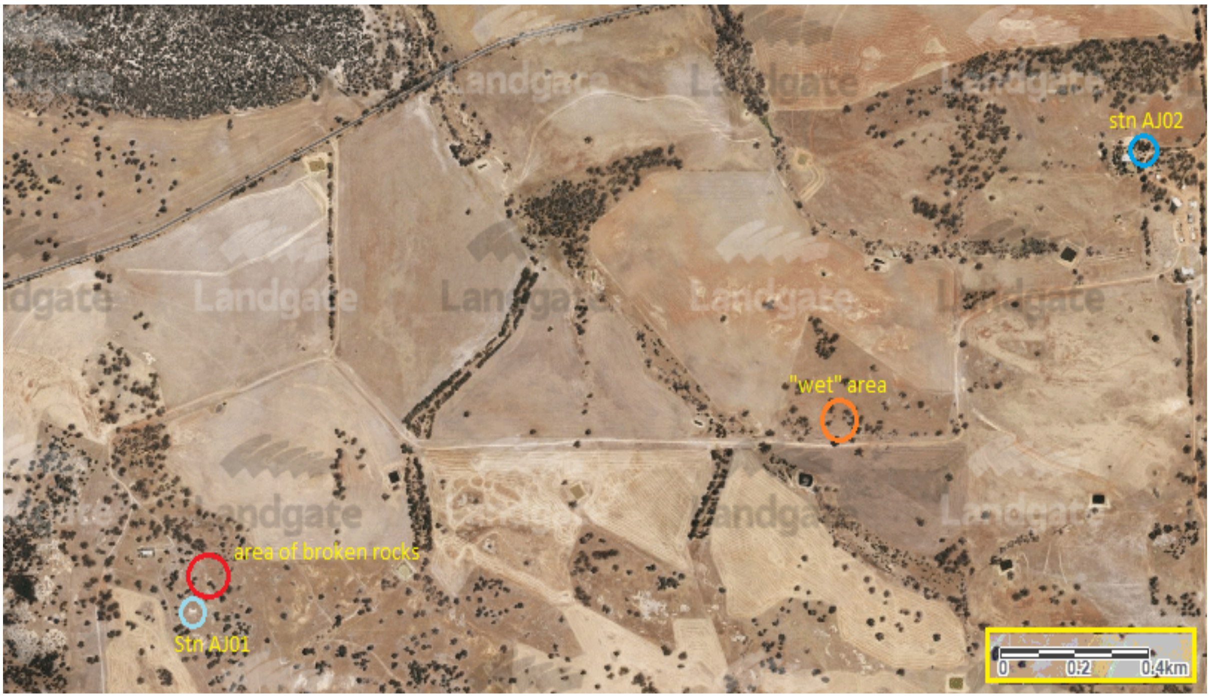

Figure 7. Macro-seismic effects – “wet” area and area of broken rocks

It is also noteworthy that all events apparently had audio effects, ie, “booms” were frequently heard, while no shaking was noticed at all. The booms could be heard for quite small events (magnitude ~ ML 1.0?). These audible effects accompanying earthquakes are relatively common in southwest WA, and have also been experienced by the author from locations near York (1988) and northwest of Beacon (2012).

Figure 8. Macro-seismic effects. (a) Long-lasting wet patch first noted after Ml 4.8 event of January 2022. (b, d, e, f) Onion-skin weathered section apparently displaced by seismic vibration. (c) End of granite boulder possibly sheared off by seismic vibration.

5. Discussion

The epicentres presented here are consistent with the conclusions of Murdie et al. (2022) of a broad epicentral area for events in the 2022-2023 Arthur River seismic sequence. However, there is a possible east-west trend observed in a group of events trending westwards from the largest event of January 2022 (ML 4.8). Seven of these events occurred in June & July 2022, and a further three between September 2022 and July 2023. The relocations of the largest events of the Arthur River sequence (ie, ML 4.0 and above) show they all occur within a zone about 2 km wide, the centre of which is about 1 km northeast of cluster location G11 (Figure 2). There may be a congregation of events along the north-westerly boundary of the uplifted area identified by Valcaniotis (pers. comm., 2022). The focal depths computed for the best located events are less than 3 km, although the uncertainties are relatively high.

The focal depths of the best located earthquakes could be interpreted as occurring on a northwesterly dipping plane. However, this does not appear to be consistent with the general trend of recent faults in southwestern WA, which generally show a northerly or NNE strike (Clark et al., 2010). The distribution of earthquakes is yet to show clear evidence for the orientation of a fault plane, but this may be in part due to the relatively large uncertainties in earthquake locations. Careful reanalysis of earthquake solutions, possibly using a better earth model, may yet allow fault lines to be more positively identified.

It is noted that the majority of epicentres seem to occur in a locally elevated area, up to 40-50 m above the immediate countryside, and this raises the question as to whether the small uplift seen here is a repeat of earlier, and possibly larger episodes which have resulted in an overall uplift of this small area.

There was some minor seismicity in the region, which appears to be unrelated to the major activity southwest of Arthur River. An ML 2.1 event on 14th March 2023 seems to belong to a cluster location about 25 km NW of Wagin (location G12) identified in Dent & Collins (2022). The largest event from that cluster (of 6 located events) was ML 2.7 in April 2022. In addition, a small isolated event (ML 2.2), about 20 km ESE of Arthur River, was recorded on 9th May, 2023.

6. Acknowledgements

The authors would like to thank Ruth Murdie and David Love and an anonymous reviewer for their inputs to this report, and also the invaluable assistance of the local farmers, John and Martina Pascoe, Sam Burgess and John Bird. The temporary seismograph network is operated only via the generous assistance of Paul Harris and others at the Australian Centre for Geomechanics, Perth.

7. References

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Appendix 1. Relocated events, Period 2

Date/ Time (UTC)	Acc	Lon	Lat	ML	Depth	Stn/pha
		(WA5 earth model)		(GA)	Km	RMS
2022-09-02 2103 44	B	116.990	-33.387	2.8	2.1	5/7/.024
2022-09-02 2200 07.7	B	116.971	-33.361	2.3	2.0	3/5/.028
2022-09-03 0056 39	B	116.967	-33.374	2.6	2.1	4/3/.067
2022-09-04 1637 02	c	116.971	-33.347	2.8	2.8	5/7/.110
2022-09-11 0852 31.8	C	116.955	-33.367	2.4	2.6	5/6/.007
2022-09-11 1041 52	C	116.952	-33.362	2.6	2.1	3/4/.061
2022-09-15 0757 48.3	B	117.014	-33.345	2.7	1.9	5/5/.009
2022-09-15 0809 42.5	B	116.998	-33.343	2.5	1.1	3/5/.017
2022-09-15 1446 42.4	B	117.005	-33.344	2.5	2.1	5/5/.046
2022-09-15 1745 44.9	B	117.01	-33.352	2.6	2.1	5/6/.049
2022-09-15 2000 29.7	B	116.971	-33.358	3.0	2.4	5/6/.010
2022-09-15 2013 33.6	B	116.965	-33.357	2.7	3.2	5/7/.083
2022-09-15 2140 05.4	B	116.978	-33.36	2.6	3.0	5/6/.030
2022-10-28 2203 36		116.965	-33.375	2.6	2.4	
2023-01-06 1710:33	B	116.994	-33.37	2.5	2.8	3/5/.001
2023-02-03 0516:22.82	B	116.96	-33.372	3.2	3.3	4/6/.053
2023-02-03 2216:25.37	B	116.963	-33.373	2.6	1.4	5/7/.039
2023-02-05 0039:58.24	C	116.977	-33.364	4.1	1.7	3/5/.038
2023-02-05 0123:35.91	B	116.958	-33.35	2.1	2.9	4/6/.017
2023-02-05 0249:41.05	B	116.999	-33.372	2.4	3.1	5/8/.018
2023-02-05 0340:25.90	C	116.956	-33.38	2.5	2.1	3/5/.037
2023-02-05 0504:27.96	B	117.004	-33.375	2.7	1.9	5/7/.043
2023-02-05 0520:54.52	B	116.998	-33.364	2.3	1.9	7/9/.031
2023-02-05 0759 19.1		117.001	-33.367	2.1	1.4	5/7/.027
2023-02-05 1825:23.18	C	116.963	-33.39	2.8	2.8	4/5/.011
2023-02-05 1844:45.13	B	116.968	-33.378	2.3	1.9	3/7/.024
2023-02-06 0201:12	B	116.962	-33.371	2.7	3.6	4/6/.048
2023-02-06 0605:54.85	B	116.989	-33.356	2.7	2.0	4/5/.004
2023-02-06 1044:18.73	B	116.971	-33.377	3.0	3.7	4/6/.021
2023-02-08 0957:02.99	C	116.964	-33.38	< 2.0	2.2	3/6/.022
2023-02-21 2104:51.63	C	116.998	-33.358	< 2.0	2.7	4/6/.023
2023-02-21 2303:53.45	B	117.01	-33.369	2.3	1.6	5/7/.030
2023-03-10 1855:09.52	B	116.97	-33.381	2.1	2.1	5/7/.019
2023-03-12 0749:10.75	B	116.957	-33.371	2.1	2.1	4/6/.027
2023-03-20 1109:07.75	B	117.000	-33.385	2.1	2.1	3/5/.019
2023-04-05 1126 49.4		116.962	-33.377	2.3	2.1	3/5/.063
2023-05-09 1211:13.70	B	117.15	-33.367	2.2	4.0	4/5/.049
2023-06-09 0125:18.24	B	117.014	-33.37	2.6	0.0	4/6/.064
2023-07-04 0357 39.5	B	116.972	-33.37	2.4	2.4	4/5/.008
2023 07 -05 0051: 32.6	B	117.003	-33.361	2.6	3.6	3/5/.114
2023 07-23 1109:56.1	B	116.967	-33.354	2.3	3.3	4/6/.019
2023-08-25 1901:10	B	116.979	-33.347	2.2	3.1	7/8/.038
2023-08-31 1551:47	B	116.972	-33.363	2.2	1.7	5/7/.166
2023-09-01 0607:36	B	116.970	-33.36	3.1	3.4	6/8/.045
2023-09-01 0742:31	B	116.972	-33.363	2.9	3.5	6/8/.036
2023-09-02 0849:10	B	116.995	-33.370	3.6	2.1	8/10/.062
2023-09-02 1916:05	B	116.978	-33.363	2.4	3.4	6/8/.029

Appendix 1 (continued). Relocated events, Period 2

Date/ Time (UTC)	Acc	Lon	Lat	ML	Depth	Stn/pha
		(WA5 earth model)		(GA)	Km	RMS
2023-09-07 2116:37	B	116.987	-33.346	2.1	2.3	3/5/.025
2023-09-15 2047 30	A	116.966	-33.345	2.4	1.4	3/6/.013
2023-09-15 2031 08	A	116.962	-33.344	2.9	0.9	3/6/.026
2023-09-15 2053 56	A	116.972	-33.350	2.4	1.9	4/7/.026
2023-09-22 2029 08	A	116.966	-33.362	2.2	2.2	3/5/.018

Appendix 2. Relocation of best-recorded events of Period 1 using WA5 model

Date & time 2022	ML (GA)	WA2		Dep km	WA5		Dep km	GA		Dep Km*
		Lon	Lat		Lon	Lat		Lon	Lat	
04 Apr 1154	--	116.996	-33.370	2.5	116.994	-33.370	3.1			
07 Apr 1124	--				116.982	-33.362	1.9			
08 Apr 0954	--	116.984	-33.374	1.1	116.985	-33.374	2.3			
08 Apr 2102	--	116.982	-33.373	0.8	116.980	-33.375	1.7			
09 Apr 0851	--	116.981	-33.375	0.8	116.981	-33.376	2.1			
10 Apr 0437	--	116.989	-33.361	0.01	116.989	-33.362	2.0			
10 June 2333	–	116.975	-33.36	1.8	116.972	-33.356	2.5			
11 June 1129	2.4	116.977	-33.361	1.7	116.975	-33.356	2.4	116.958	-33.363	5
11 June 1225	–	116.974	-33.358	2.2	116.973	-33.355	2.8			
13 June 0006	2.6	116.988	-33.39	-0.3	116.985	-33.368	1.5	116.980	-33.344	4
13June 0416	--	116.974	-33.350	1.6	116.974	-33.350	2.7			
14 June 0959	2.3	116.993	-33.374	2.2	116.974	-33.381	2.1	116.952	-33.378	2
14 June 1031	2.5	116.964	-33.355	2.1	116.964	-33.355	2.7	117.021	-33.350	5G
23 June 1004	2.21	116.965	-33.363	1.6	116.965	-33.363	2.3	116.981	-33.333	5G
24 June 0614	2.2	116.966	-33.355	1.9	116.966	-33.355	2.7	116.975	-33.356	2
26 June 0000	2.5	116.991	-33.357	1.1	116.99	-33.356	2.1	117.013	-33.330	5
26 June 0357	2.1	116.993	-33.367	2.1	116.995	-33.353	2.6	117.035	-33.331	7
27 June 1155	2.2	116.967	-33.355	1.7	116.969	-33.355	2.0	116.967	-33.359	5G
27 June 1223	2.7	117.001	-33.374	2.1	117.000	-33.362	2.7	116.983	-33.357	2
27 June 1540	2.2	116.996	-33.387	1.8	116.995	-33.372	1.8	116.991	-33.378	5G
02 July 2002	–	116.982	-33.384	0.1	116.982	-33.382	2.1			
04 July 0402	–	116.971	-33.356	2.1	116.971	-33.356	2.6			
05 July 0924	–	117.008	-33.371	1.2	117.009	-33.362	2.1			

"*" G indicates focal depth has been constrained to 5 km in the location procedure

Appendix 3. Field station Operating Periods