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A Compilation of Ground Truth Events in Australia

Dariush Nadri, Spiro Spiliopoulos, Sharmin Shamsalsadati, Svetlana Nikolova

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INTRODUCTION AND MAIN RESULTS

We have compiled 25 GT seismic events for the period of 2002-2025 occurred in Australia. Events have been assessed on individual criteria including surface rupture, satellite imagery, temporary seismic installations or aftershock kits. GT events range from GT0 to GT10. We also discuss how 3D models can relax the strict GT criteria. The source parameters and more than 4600 carefully picked arrivals for different phases up to 100° will help constraining 3D tomography models.

SnT 2025 CTBT: SCIENCE AND TECHNOLOGY CONFERENCE
8 SEPTEMBER ONLINE DAY
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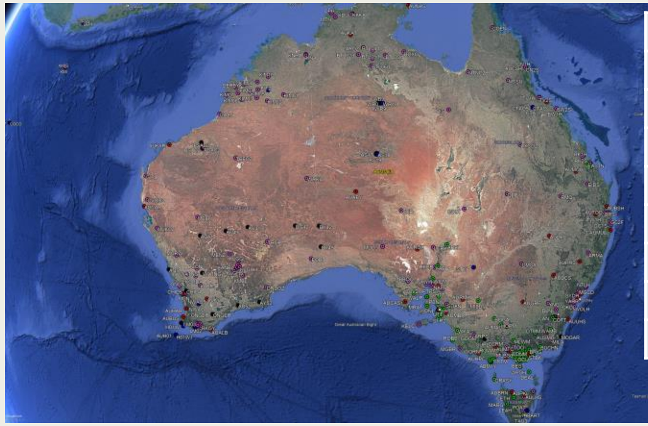
Introduction

Most of the Australia's continent have poor seismic network coverage particularly the inland due to. remoteness and lack of strong seismicity (Figure 1). This leaves the continental crust and upper mantle velocity structures not well resolved. Transportable arrays deployed during recent years driven by mineral resource explorations have contributed to defining the tectonic features. From the CTBT perspective, on site inspection provision limits the inspection area to 1000 Km^2 (Bondár et. al, 2001). To enforce this, epicenters must not only be accurately located but the error ellipse at 90% confidence level should be small enough to achieve this. Global seismic velocity models hardly fulfil this criteria and the detailed velocity models are required. Ground truth (GT) events are important to constrain the traveltime tomography studies.

In this study we present 25 GT events from different sources for the period 2002 to 2025. We use several methods to define the GT events such as Interferometric Synthetic Aperture Radar (InSAR), blast location, seismic networks in mining sites, surface ruptures and cracks, and GT criteria studies. We also discuss how the existing 3D global models can relax the strict GT criteria, where they are not met. We also present location of the events from 1D and 3D velocity models using a neighbourhood algorithm locator (Sambridge et. al, 2001).



IMS	6
AU	135
S1	50
OZ	42
M8	18
VW	11
IU	3
II	2
G	1

Figure 1. Map of the 268 permanent and semi permanent location of the seismic station in Australia from major networks

Methods

Although, Australian continent is classified as a stable continental region both in term of tectonic and seismicity (Clark et. al, 2014), more than 300 earthquakes of magnitude 2.5+ , 13 of magnitude 4+ and 4 events of magnitude 4.5+ on average are recorded every year. These intraplate small and moderate events are due to accumulating the stress fields originate from plate boundaries and sudden release of energy from old faults and fractures. They are often shallow within the top 10 km but can be as deep as 35 Km more in the north of the continent.

In Geoscience Australia we have been collecting the GT events as early as 2013 (De Kool et al., 2013) from a variety of sources. Within the current station coverage hardly any earthquake event qualifies at GT5, though some may qualify at GT10 but these may not be much useful unless location in areas with poor seismicity or azimuth coverage. InSAR analysis of earthquakes in Australia (Figures 2,4,5,6,7) have shown important contribution to the GT events where they are shallow and for moderately size earthquakes (Dawson et al., 2008, Polcari et. al, 2018).

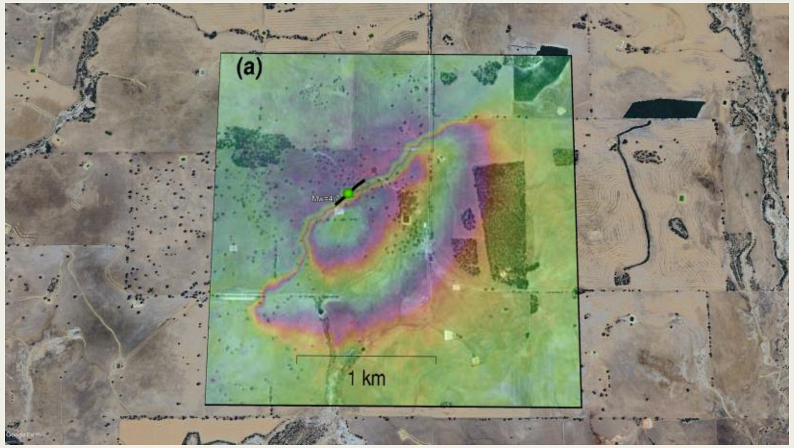


Figure 2. Interferogram image from Katanning earthquake in Western Australia (9th Oct. 2007). Black line is the surface rupture (Dawson, et. al, 2008)

In recent years, transportable arrays have been deployed by several agencies mostly for highlighting the tectonic structures for Ore genesis. These include The Australian Passive Seismic Array Project (AusArray)

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Methods Continued…

operated by Geoscience Australia (2016-2024), WA Array, operated by The Geological Survey of Western Australia (GSWA) (2022 to 2025) (Figure 3). There are several other temporary transportable deployments and data are hosted at the Australian Passive Seismic Server. For more information and to access data, please visit https://auspass.edu.au.

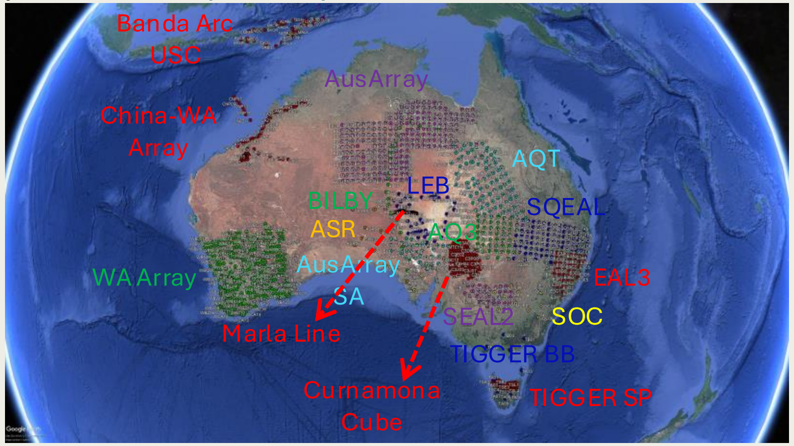

Figure 3: Location of the transportable and temporary arrays used in this study.

For the events in this study we have carefully picked arrivals for Pg, Pn, P, Sg, Sn, and S phases where possible up to 100° from IMS and Non-IMS stations from seismic networks across the world. We located the events using a neighbourhood algorithm and by using global velocity model AK135 (Kennett et. al, 1995) and precomputed traveltimes from the global 3D model by Lawrence Livermore National Lab (Simons, et. al, 2012).

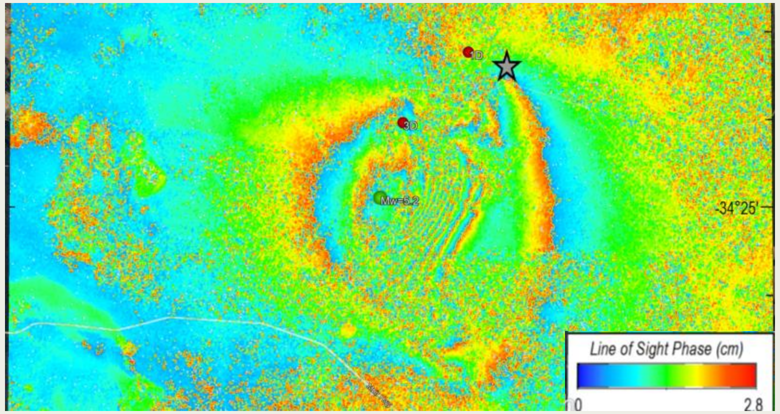

Figure 4. Phase wrapped Interferograms image from the Lake Muir Earthquake in Western Australia (16th Sep. 2018). Image from InSAR team at Geoscience Australia.

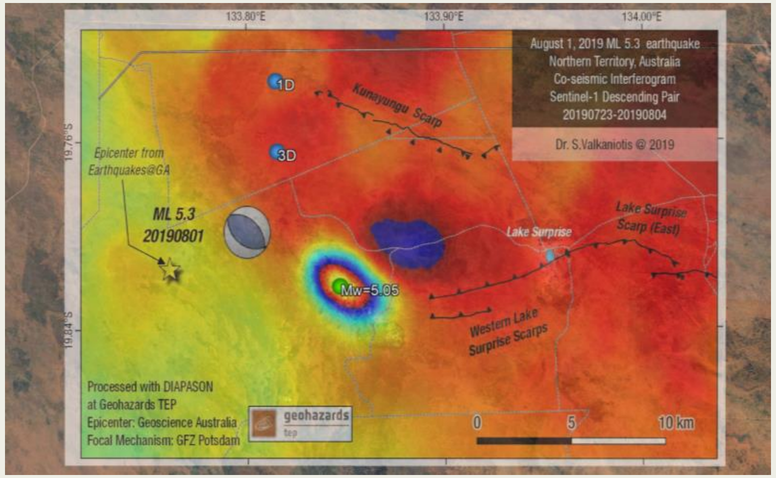

Figure 5. Co-seismic Interferograms image from the Tennant Creek Earthquake in Northern Territory. (1th Aug. 2019). Image from Sotiris Valkaniotis (2019)

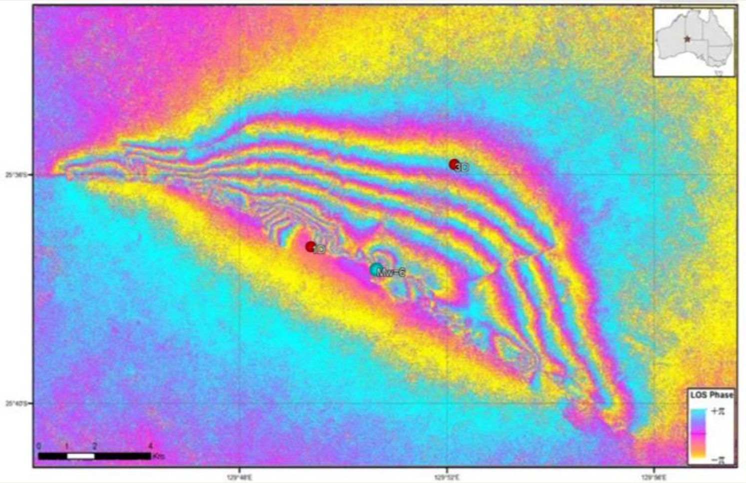

Figure 6. Phase wrapped Interferograms image from the Peterman ranges Earthquake in NT (16th Sep. 2018). Image from InSAR team at Geoscience Australia)

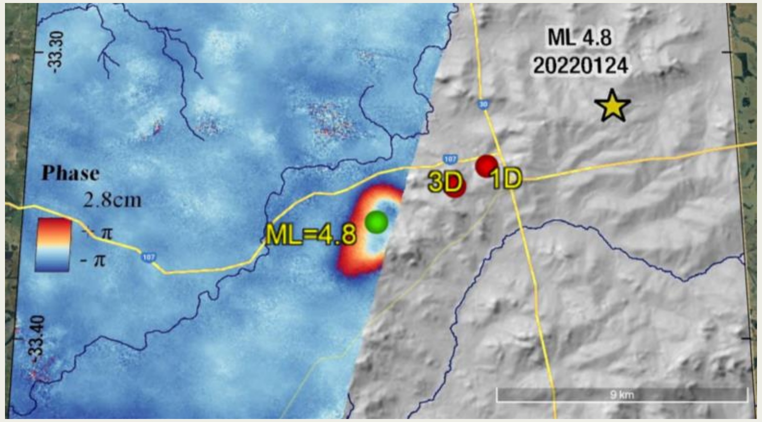

Figure 7. Co-seismic Interferograms image from the Arthur River Earthquake (24th Jan. 2022). Image from Sotiris Valkaniotis (2022)

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Results and Discussion

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Event	Event Type	Magnitude	GT	GT Source	Lat	Lon	Depth	Origin Time	#Stations			#Pg|Pn|P	#Sg|Sn|S	CPQ	Azimut Gap		#Def Sta	#Def Phase	#Total Picks
							Preferred		< 10 Km	< 30 Km	< 250 Km				Primary	Secondary			
Katanning, WA	Earthquake	Mw=4.7	2	InSAR	-33.9475	117.5307	5.0	2007-10-09 23:58:39.9 +/- 0.59	0	0	3	2|16|52	2|6|0	0.898	78	115	69	72	78
Arthur River, WA	Earthquake	ML=4.8	2	InSAR	-33.3624	116.9844	5.0	2022-01-24 21:24:47.5 +/- 0.47	0	0	10	6|52|14	6|23|0	0.933	66	69	72	78	101
Lake Muir, WA	Earthquake	Mw=5.2	2	InSAR	-34.4165	116.7736	7.0	2018-09-16 04:56:23.2 +/- 0.43	0	1	7	5|121|71	5|88|0	0.984	34	62	197	202	290
Tennant Creek, NT	Earthquake	Mw=5.05	2	InSAR	-19.8259	133.8627	5.0	2019-08-01 01:22:16.7 +/- 0.63	0	0	58	34|187|82	34|104|0	0.995	28	58	301	338	442
Peterman Ranges, NT	Earthquake	Mw=6.0	10	InSAR	-25.6279	129.8437	6.0	2016-05-20 18:14:05 +/- 0.6	0	0	1	1|74|285	1|26|186	0.996	20	25	360	361	573
Gnowangerup, WA	Earthquake	Mw=5.0	5	Cracks/Transportable Array	-33.8616	118.2333	5.0	2023-08-05 21:34:42.2 +/- 0.27	0	1	52	30|104|82	30|77|0	0.988	45	46	216	246	323
Tanami, NT	Earthquake	Mw=4.9	5	Transportable Array	-21.2958	132.0453	10.0	2019-05-30 02:26:52.4 +/- 0.41	0	1	47	25|110|42	17|22|0	0.998	12	32	178	195	217
Pilbara, WA	Earthquake	Mw=5.3	5	Transportable Array	-21.1070	119.8314	35.0	2021-11-13 13:05:57.3 +/- 0.24	3	15	41	0|147|65	0|106|0	0.995	25	31	212	212	318
Blinman, SA	Earthquake	ML=3.4	5	Transportable Array	-31.0220	139.1148	9.0	2022-07-03 15:47:28.3 +/- 0.18	0	2	110	64|101|0	60|2|0	0.99	25	34	165	225	227
Cadia Mine, NSW	Earthquake	ML=4.3	1	Seismometers in Mine	-33.4586	149.0173	5.0	2017-04-13 16:31:05.5 +/- 0.37	0	0	12	4|37|3	4|3|0	0.938	48	68.5	44	48	114
Innamincka, SA	Earthquake	ML=4.1	1	Seismometers in Site	-27.8052	140.7534	4.3	2012-11-29 19:21:20.8 +/- 0.40	0	0	0	0|85|8	0|14|0	0.967	35	43	93	93	107
Fosterville, NSW	Mining collapse	ML=2.9	0	Seismometers in Mine	-36.7297	144.5044	1.3	2023-11-05 07:51:54.62 +/- 0.00	0	0	18	8|45|0	6|0|0	0.962	59.6	61.2	53	59	59
Leisner, WA	Mining collapse	ML=4.3	0	Seismometers in Mine	-27.8215	120.7056	1.1	2013-10-30 22:25:37.4 +/- 0.64	0	0	1	0|25|4	0|12|0	0.928	50.3	58.5	29	29	41
Maules Creek, NSW	Mine Blast	ML=3.8	0	Blast Location	-30.5775	150.1401	0.0	2020-08-20 00:22:50.4 +/- 0.39	0	0	5	2|35|5	2|2|0	0.92	73	100	42	44	46
Muswellbrook Mine, NSW	Earthquake	Mw=4.2	5	Aftershock Deployment	-32.3720	150.8740	5.0	2024-11-12 01:12:56.7 +/- 0.31	4	10	19	14|28|3	14|2|0	0.96	58	70	45	59	61
Kalgoorlie Mine, WA	Earthquake	ML=5.0	2	Seismometers in Mine	-30.7867	121.4877	5.0	2010-04-20 00:17:08.6 +/- 0.59	0	0	1	1|33|47	1|30|0	0.986	27.7	28.2	81	82	110
Woods Point, VIC	Earthquake	Mw=5.9	5	Aftershock Deployment	-37.5060	146.4020	12.0	2021-09-21 23:15:52.8 +/- 0.52	0	0	18	11|91|125	9|9|2	0.99	35.5	39.5	227	236	247
Ernabella, SA	Earthquake	Mw=5.4	5	Available Networks	-26.1228	132.1256	5.0	2012-03-23 09:25:17.5 +/- 0.55	0	0	0	0|81|136	0|28|0	0.994	27.2	28.6	217	217	245
Burra, SA	Earthquake	ML=4.3	5	Available Networks	-33.7472	138.7474	10.0	2020-05-14 05:53:34.6 +/- 0.46	0	1	23	17|41|5	16|0|0	0.99	23.3	25	63	79	79
Townsville, QLD	Earthquake	ML=4.5	10	Available Networks	-19.4335	146.7988	10.0	2025-03-01 11:31:32.8 +/- 0.71	0	1	4	4|24|4	4|2|0	0.866	101	110	31	35	37
Wyalkatchem, WA	Earthquake	ML=4.5	5*	Available Networks	-31.2880	117.5823	5.0	2024-08-18 18:05:38.8 +/- 0.6	0	0	10	7|39|29	7|17|0	0.967	52.6	55.6	75	82	99
Goomeri, QLD	Earthquake	ML=5.6	10	Available Networks	-26.2985	152.1736	12.0	2025-08-15 23:46:26.3 +/- 0.60	0	0	7	6|67|82	6|0|0	0.909	50	52.5	155	161	161
Eidsvold, QLD	Earthquake	ML=5.2	10	Available Networks	-25.1259	151.4720	10.0	2015-02-15 15:57:08.8 +/- 0.70	0	0	4	2|90|17	2|0|0	0.97	42.4	54.8	109	111	111
Lake Sorell, TAS	Earthquake	ML=4.3	10	Temporary Array	-42.1540	147.3203	10.0	2002-06-15 21:18:43.5 +/- 0.26	0	1	55	38|17|3	5|0|0	0.537	147	147	58	64	64
Otway, VIC	Earthquake	Mw=4.7	5	Available Networks	-38.7110	143.5285	9.0	2023-10-21 15:11:07.5 +/- 0.64	0	1	14	6|88|77	5|0|0	0.95	68.2	69.5	171	176	176

Table 1: Location of the GT events and their parameters. There were 7 stations within 3° for the Eidsvold event.

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Results and Discussion Continued…

Event	Model	Lat	Lon	Depth	Depth error	Origin Time	Error Ellipse (%90 confidence level)				RMS error	Distance from GT
							Smaj	Smin	Azimuth	Area		
Katanning, WA	3D	-33.9143	117.5532	0.0	3.7	2007-10-09 23:58:39.9 +/- 0.48	4.4	3.9	20.9	54	1.26	3.9
	1D	-33.9048	117.5735	0.0	5.2	2007-10-09 23:58:39.7 +/- 0.79	7.2	6.4	20.8	145	1.86	5.7
Arthur River, WA	3D	-33.3500	117.0156	0.0	3.3	2022-01-24 21:24:47.5 +/- 0.47	4.3	4.0	153.6	53	1.63	3.3
	1D	-33.3430	117.0286	0.0	6.1	2022-01-24 21:24:47.0 +/- 0.88	8.0	7.4	153.6	187	2.32	4.7
Lake Muir, WA	3D	-34.4022	116.7788	0.0	2.9	2018-09-16 04:56:23.2 +/- 0.43	3.5	2.9	34.1	31	1.30	1.7
	1D	-34.3887	116.7939	0.0	5.9	2018-09-16 04:56:23.0 +/- 0.87	7.0	5.8	34.7	128	1.95	3.7
Tennant Creek, NT	3D	-19.7780	133.8332	2.0	3.1	2019-08-01 01:22:16.5 +/- 0.38	2.8	2.0	14.0	17	1.57	6.7
	1D	-19.7243	133.8314	3.4	4.3	2019-08-01 01:22:15.6 +/- 0.54	3.9	2.8	14.9	34	2.24	12.5
Peterman Ranges, NT	3D	-25.5974	129.8456	6.0	3.9	2016-05-20 18:14:05.0 +/- 0.60	2.8	2.1	39.6	18	2.74	3.5
	1D	-25.6103	129.8688	0.0	5.4	2016-05-20 18:14:04.0 +/- 0.83	4.1	3.0	39.7	38	2.74	3.2
Gnowangerup, WA	3D	-33.8418	118.2003	0.0	2.1	2023-08-05 21:34:42.2 +/- 0.27	1.8	1.8	34.4	10	1.15	3.8
	1D	-33.8423	118.2159	0.0	3.7	2023-08-05 21:34:42.0 +/- 0.48	3.2	3.1	32.5	31	1.68	2.7
Tanami, NT	3D	-21.2958	132.0453	0.0	3.4	2019-05-30 02:26:52.4 +/- 0.41	2.7	2.1	41.2	18	1.69	0.0
	1D	-21.2991	132.0482	0.0	6.0	2019-05-30 02:26:52.0 +/- 0.73	4.7	3.8	41.2	56	2.45	0.5
Pilbara, WA	3D	-21.1292	119.8277	35.0	3.2	2021-11-13 13:05:57.2 +/- 0.26	4.4	3.2	111.4	45	1.43	2.5
	1D	-21.1098	119.8417	35.0	3.4	2021-11-13 13:05:57.0 +/- 0.41	6.8	4.9	112.0	104	2.34	1.1
Blinman, SA	3D	-31.0220	139.1148	9.0	Fixed	2022-07-03 15:47:28.3 +/- 0.18	1.7	1.3	88.5	6	1.52	0.0
	1D	-31.0261	139.0727	8.8	1.5	2022-07-03 15:47:27.7 +/- 0.21	1.9	1.4	88.4	8	1.41	4.0
Cadia Mine, NSW	3D	-33.4800	149.0357	0.0	3.9	2017-04-13 16:31:05.3 +/- 0.51	4.5	3.2	73.0	45	1.41	2.9
	1D	-33.4717	148.9775	0.0	3.4	2017-04-13 16:31:05.1 +/- 0.44	3.9	2.7	72.4	33	1.25	3.9
Innamincka, SA	3D	-27.8102	140.7305	0.0	2.6	2012-11-29 19:21:20.8 +/- 0.40	4.0	3.0	45.8	38	0.76	2.3
	1D	-27.7850	140.7113	0.0	5.3	2012-11-29 19:21:19.3 +/- 0.80	8.1	6.1	45.8	153	1.59	4.8
Fosterville, NSW	3D	-36.7454	144.5109	0.0	Fixed	2023-11-05 07:51:54.9 +/- 0.45	4.1	3.3	50.9	40	1.32	1.8
	1D	-36.7184	144.4789	0.0	Fixed	2023-11-05 07:51:54.5 +/- 0.48	4.4	3.3	50.8	46	1.17	2.6

Table 2: Event related parameters. Mining collapse and blast are displayed in red colour. Depth for the shallow events have been fixed to either 0 or 5Km. The later is due to presence of Rg phases. Zero distance in the last column shows the estimated location was used as the GT. This was decided either by small rms or error ellipse where there was no independent source of GT location. 3D corrections were not available for temporary array stations and were only applied to permanent and semi permanent stations.

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Results and Discussion Continued…

Event	Model	Lat	Lon	Depth	Depth error	Origin Time	Error Ellipse (%90 confidence level)				RMS error	Distance from GT
							Smaj	Smin	Azimuth	Area		
Leisner, WA	3D	-27.7873	120.6521	0.0	Fixed	2013-10-30 22:25:37.4 +/- 0.64	6.3	5.3	132.4	106	1.14	6.5
	1D	-27.7541	120.7562	0.0	Fixed	2013-10-30 22:25:35.0 +/- 0.90	9.0	7.0	133.5	213	1.66	9.0
Maules Creek, NSW	3D	-30.5878	150.1445	0.0	Fixed	2020-08-20 00:22:50.4 +/- 0.39	4.3	3.0	57.4	41	0.90	1.2
	1D	-30.5791	150.1283	0.0	Fixed	2020-08-20 00:22:50.1 +/- 0.72	7.9	5.6	57.3	139	1.52	1.2
Muswellbrook Mine, NSW	3D	-32.3720	150.8740	5.2	3.0	2024-11-12 01:12:56.7 +/- 0.31	4.3	2.8	76.9	48	1.24	0.0
	1D	-32.3624	150.8651	5.7	3.9	2024-11-12 01:12:56.6 +/- 0.40	5.6	3.6	78.4	63	1.41	1.3
Kalgoorlie Mine	3D	-30.7974	121.4224	0.0	3.6	2010-04-20 00:17:08.6 +/- 0.59	5.3	4.9	4.3	80	1.15	6.3
	1D	-30.7618	121.4277	0.0	7.4	2010-04-20 00:17:08.0 +/- 1.22	10.9	10.0	3.7	343	2.35	6.4
Woods Point, VIC	3D	-37.5167	146.3939	6.6	3.9	2021-09-21 23:15:52.8 +/- 0.52	2.9	2.6	177.8	23	1.71	1.3
	1D	-37.4964	146.3721	2.6	4.9	2021-09-21 23:15:52.4 +/- 0.65	3.4	3.1	178.3	33	1.89	2.9
Ernabella, SA	3D	-26.1188	132.0822	8.8	3.6	2012-03-23 09:25:17.5 +/- 0.55	3.5	2.8	38.8	31	1.11	4.4
	1D	-26.1522	132.1198	0.0	6.0	2012-03-23 09:25:15.7 +/- 0.91	5.8	4.6	38.7	83	1.86	3.2
Burra, SA	3D	-33.7472	138.7474	2.0	3.0	2020-05-14 05:53:34.7 +/- 0.33	3.3	2.4	65.7	24	1.14	0.0
	1D	-33.7401	138.7440	11.5	4.4	2020-05-14 05:53:34.6 +/- 0.46	4.9	3.4	64.8	53	1.47	0.9
Townsville, QLD	3D	-19.4335	146.7988	6.3	5.6	2025-03-01 11:31:33.1 +/- 0.8	9.1	7.3	58.2	209	1.67	1.3
	1D	-19.4327	146.7869	10.0	5.1	2025-03-01 11:31:32.8 +/- 0.71	8.3	6.7	57.9	172	1.65	0.0
Wyalkatchem, WA	3D	-31.2878	117.5823	5.0	Fixed	2024-08-18 18:05:38.8 +/- 0.6	5.4	4.3	124.8	72	1.66	0.0
	1D	-31.2452	117.6584	5.0	Fixed	2024-08-18 18:05:38.2 +/- 0.98	8.7	6.7	128.9	183	3.12	1.3
Goomeri, QLD	3D	-26.2985	152.1736	12.0	Fixed	2025-08-15 23:46:26.3 +/- 0.6	4.4	3.4	65.9	47	1.37	0.0
	1D	-26.3119	152.1006	12.0	Fixed	2025-08-15 23:46:26.3 +/- 0.8	5.3	4.0	65.9	67	1.80	7.2
Eidsvold, QLD	3D	-25.1259	151.4720	10.0	Fixed	2015-02-15 15:57:08.8 +/- 0.7	5.1	4.4	95.7	70	2.38	0.0
	1D	-25.1380	151.4342	10.0	Fixed	2015-02-15 15:57:08.6 +/- 0.6	4.5	3.8	96.4	54	2.48	4.1
Lake Sorell, TAS	3D	-42.1540	147.3203	10	Fixed	2002-06-15 21:18:43.5 +/- 0.26	2.5	2	134	15.9	0.94	0
	1D	-42.1436	147.3204	10	Fixed	2002-06-15 21:18:43.6 +/- 0.31	2.9	2	151.4	17.9	1.05	1
Otway	3D	-38.7216	143.5398	9.0	Fixed	2023-10-21 15:11:07.9 +/- 0.65	4.7	3.1	22.0	46	1.90	1.5
	1D	-38.7112	143.5285	9.0	Fixed	2023-10-21 15:11:07.5 +/- 0.64	4.6	3.0	21.8	44	1.86	0.0

Table 2: Continued.

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A Compilation of Ground Truth Events in Australia

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Results and Discussion Continued…

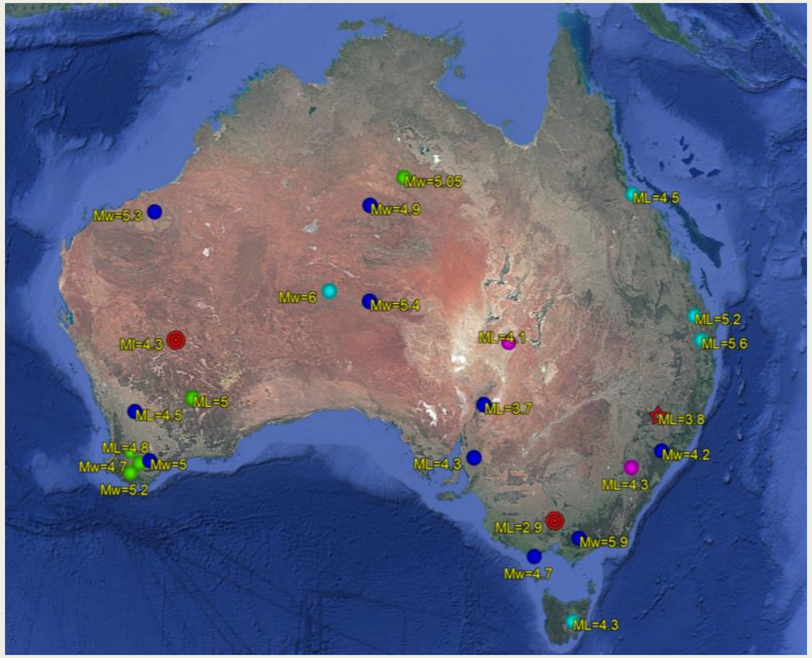

Figure 8. Location of 25 GT events. Earthquakes are shown in sphere, mining collapse in multi rings and mining blast in star.

The results are shown in Table 1 and 2. We have also computed cyclic polygon quotient (CPQ) that better describes the azimuthal station coverage for an event (Gallacher et. al, 2025). See Atkinson (2018) for the Cadia Mine, Hopkins et. al, (2018) for Leisner Mine , Bathgate et. al, (2010) for Kalgoorlie, and Clark et. al, (2012) for Ernabella event. Some of the events were recorded by transportable and temporary arrays in Australia. For example, we used EAL3 array for Ernabella event, TIGGER SP and TIGGER BP arrays

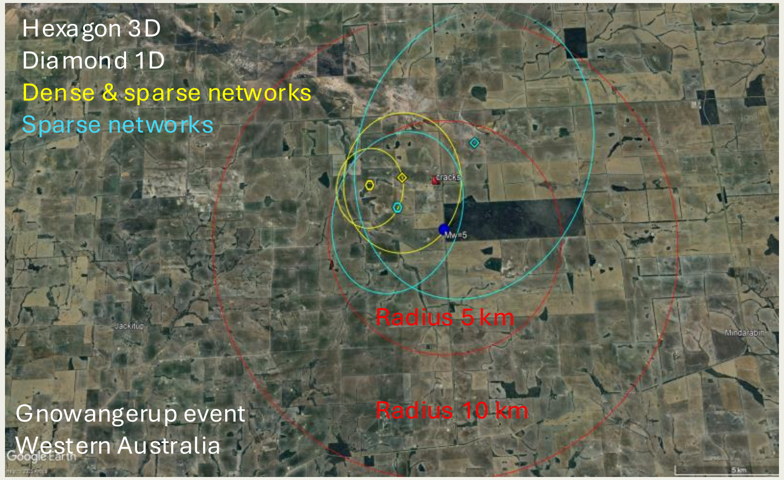

Figure 9. The impact of 3D model on relaxing the GT criteria in Western Australia.

for Lake Sorell event, and Curnamona Cube for Blinman event. We also used Aus-Array for Tanami and Tennant Creek events, China-WA Array, Lake Eyre Basin (LEB), and Aus-Array SA for Pilbara event, WA-Array for Gnowangerup and Otway events, AQ3 for Eidsvold event, SQEAL for Innamincka event, SEAL2 & SOC for Katanning event, AQT for Cadia mine, ASR, China-WA Array , Marla Line, and Banda Arc for Lake Muir event, LEB, and Aus-Array SA for Arthur River event , and BILBY Array for Kalgoorlie event.

For each GT event, we have presented their associated parameters derived from source location in Table 1. In Table 2 we have presented more detailed location parameters including error ellipse and their distance from GT locations. We have provided in total 4610 picks and they can be used for velocity model calibration and tomography studies. Figure 8 shows the location of GT events. For the Maules Creek blast in New South Wales, 896256 Kg explosion (ANFO) was used. This was one of the biggest mining blasts in Australia. (https://nwprotectionadvocacy.com/maules-creek-mine-guilty/).

We now show how 3D model shrinks the error ellipse and locates closely to GT for Gnowangerup event in Western Australia. We have seen this in most of the events in Table 1 and Figure 4 and 7 for this region. Figure 9 shows the locations and error ellipses for this event using local sparse network and combining with dense WA Array. For the sparse network there were no stations within 30km and 4 stations within 250km whereas adding the WA array, there were 1 station within 30Km and 65 within the 250Km. The Wyalkatchem event in Western Australia does not qualify the strict GT5 criteria since the minimum distance is 37 km, despite having 10 stations within 250 km. Having shown the impact of 3D models on relaxing the GT event for this region, we can assign it a GT5 event. Although the primary azimuth gap for Lake Sorell earthquake is more than 110°, the minimum distance is less than 14 km and 38 Pg and 5 Sg phases contribute to the location. Given the small ellipse error, we might be able to assign it a GT5 event.

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