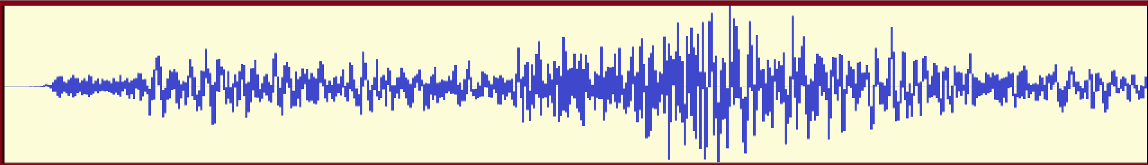
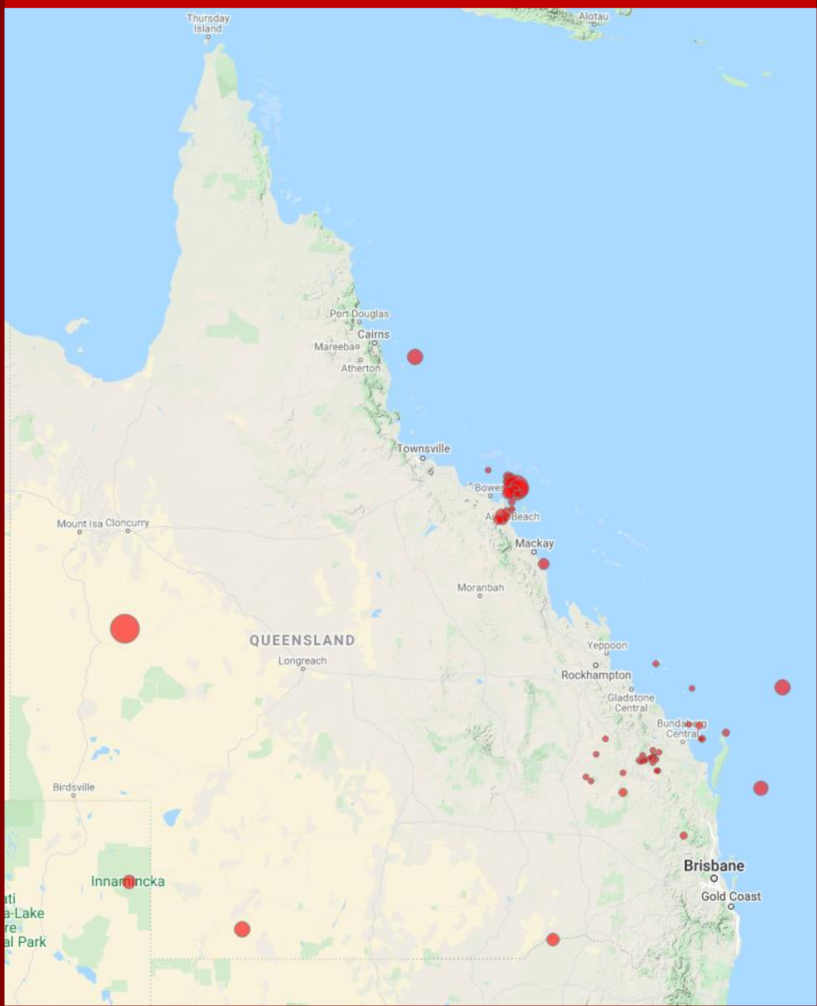
CENTRAL QUEENSLAND SEISMOLOGY RESEARCH GROUP (CQSRG)



CQSRG Seismological Report 2021

Edition 1.00 Version 1

Michael Turnbull **BAppSc(Distinction) MAppSc,**
Lead Seismologist, CQSRG.



RESEARCHING EARTHQUAKES IN CENTRAL QUEENSLAND SINCE 2002.
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Mike Turnbull may be contacted by email at: Mike.Turnbull@cqsrg.org

Introduction

This report details earthquakes detected and located by the Central Queensland Seismology Research Group (CQSRG) during the 2021 calendar year. Technical and statistical summaries of earthquakes that occurred in Queensland are provided. The date and time of earthquakes noted in this report are provided in Universal Coordinated Time (UTC).

Data and information provided in this report may supersede or supplement data and information provided in previous CQSRG Annual Seismological Reports. This is due to ongoing CQSRG research that may add to or revise data and information collected and analysed from previous years.

CQSRG was established in 2002, under the auspices of the Faculty of Informatics and Communication of Central Queensland University (CQU), with Michael Turnbull (Lecturer, and later Adjunct Research Fellow) and Kevin McCue (Visiting Professor, and later Adjunct Professor) as the designated researchers. This affiliation with CQU continued until February 2013, when, due to a divergence in academic focus of CQU and CQSRG, the researchers allowed their Adjunct appointments to lapse. From February 2013 until December 2016, CQSRG operated independently of CQU, with the same two people conducting the research. In mid-2016 Dr Andrew Hammond, Senior Lecturer in Geology at CQUniversity, joined CQSRG as a research collaborator. Mike Turnbull's and Kevin McCue's adjunct academic appointments with CQUniversity were re-established in October 2016.

During the 2021 calendar year CQSRG operated one seismic monitoring station, designated FS03. Details of this station, including location and equipment, are provided in Appendix A. This report contains information relating to earthquakes detected by the FS03 seismic monitoring station, as well as earthquakes of significance located within Queensland, but outside the CQSRG detection area, and reported by Geoscience Australia (GA).

CQSRG locates and quantifies earthquakes using the methods detailed Appendices in B, C, D, E and F.

CQSRG Station Reports

FS03 Uptime 2021

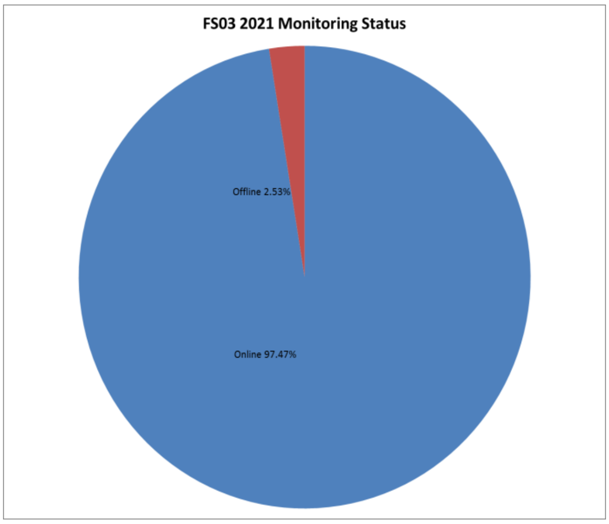

Figure 1: Percentage Uptime/Downtime of FS03 during 2021.

The FS03 station has been in continuous operation since 2003-01-01 00:00:00.00 (UTC). Technical details of the station are found at http://cqsrg.org/network/FS03technical/.

Throughout the 2021 calendar year the FS03 station was actively monitoring for seismic events greater than 97% of the year.

This high proportion of availability was due to automation of the data download process, and the provision of an RS232 serial data radio link to the station in April 2015.

The down time was wholly comprised of data download time.

The Continuing Bowen Earthquake Sequence

On 2016-08-18 at 04:30 UTC an ML 5.8 earthquake[1] occurred 63 km north east of Bowen in the Whitsunday Passage. This was followed over the next three weeks by 77 aftershocks ranging from ML 1.6 to ML 4.2 that were located by CQSRG; however there were many more aftershocks of magnitudes below ML 1.6 that have been identified by CQSRG in the Bowen Urban Monitoring (UM) network site (BW1H) seismic records but have not been located due to insufficient recordings. This sequence of events is known within CQSRG as the **2016 Bowen or Whitsunday Passage Earthquake** and Aftershock Sequence (BW 2016).

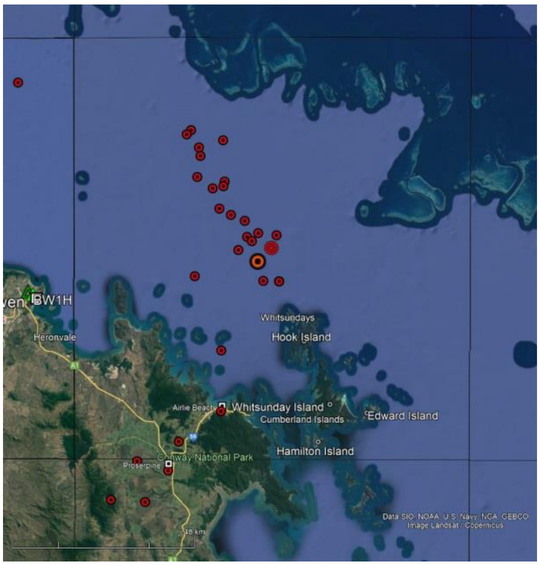

Figure 2: Bowen aftershocks that occurred in 2021, and were located by CQSRG, in relation to the August 2016 ML 5.8 earthquake (shown as red concentric ring marker).

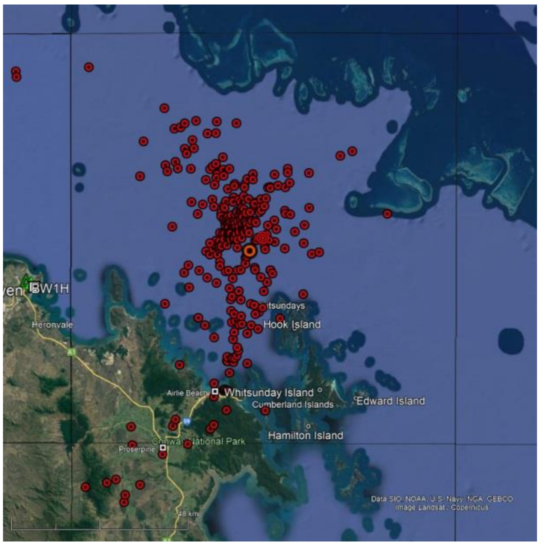

Figure 3: Bowen main shock and all aftershocks located by CQSRG through to the end of the 2021 calendar year.

During the 2021 calendar year 91 aftershocks ranging in magnitude from ML 3.6 down to ML 0.9 were detected by CQSRG; 65 of which were not located due to lack of sufficient instrumental records.

Of those 91 events that were detected, 26 provided sufficient recordings to be reliably located. A map showing locations of aftershocks that were located by CQSRG during 2021 is presented in Figure 2. This figure also shows the location of the main ML 5.8 August 2016 event as a red concentric ringed marker.

A significant ML 5.0 earthquake event occurred on Wednesday 2020-04-15 at 07:11 (UTC) (17:11 Local Time). This event was located only 5 km south-west of the August 2016 main earthquake; however, given the locational error margins, the two events may well have occurred at the same location. Due to the relatively large magnitude of this event it is considered by CQSRG as being a second main earthquake shock, rather than an aftershock.

The second main shock is shown in Figure 2 and Figure 3 as an orange marker.

To provide an overall context for the Bowen Aftershock Sequence from the time of the initial main shock to the end of the 2021 calendar year, all of the events located by CQSRG are shown in Figure 3

The black grid lines shown in Figure 2 and Figure 3 are the ±0.5° WGS-84 World Geodetic System latitude and longitude square with the 2016 main earthquake location at its centre.

[1] The magnitude assigned by CQSRG is that assigned by Geoscience Australia.

The locations of the aftershock/reactivation events depicted in Figure 2 and Figure 3 indicate that the effects of the ongoing sequence are directly impinging on the Airlie Beach and Proserpine urbanised areas and surrounding agricultural areas. Although, to date, the earthquake events in these areas have been small in magnitude (ML 2.9 and less), there is a heightened probability that a larger event (say ML 5.0 or larger) can occur in this southern tail of the sequence. If this were to occur then structural damage in Airlie Beach and Proserpine would be expected to occur, with a coincidental probability of injury to the ambient population. The author's qualitative assessment of the current earthquake hazard in the Whitsunday/Airlie Beach/Proserpine area is that it is possibly the highest hazard than anywhere else in Queensland (at the current time), and that this level of hazard will persist for the foreseeable future.

Figure 4 shows a graphical plot of the 2016 Bowen sequence time line up to the end of 2021.

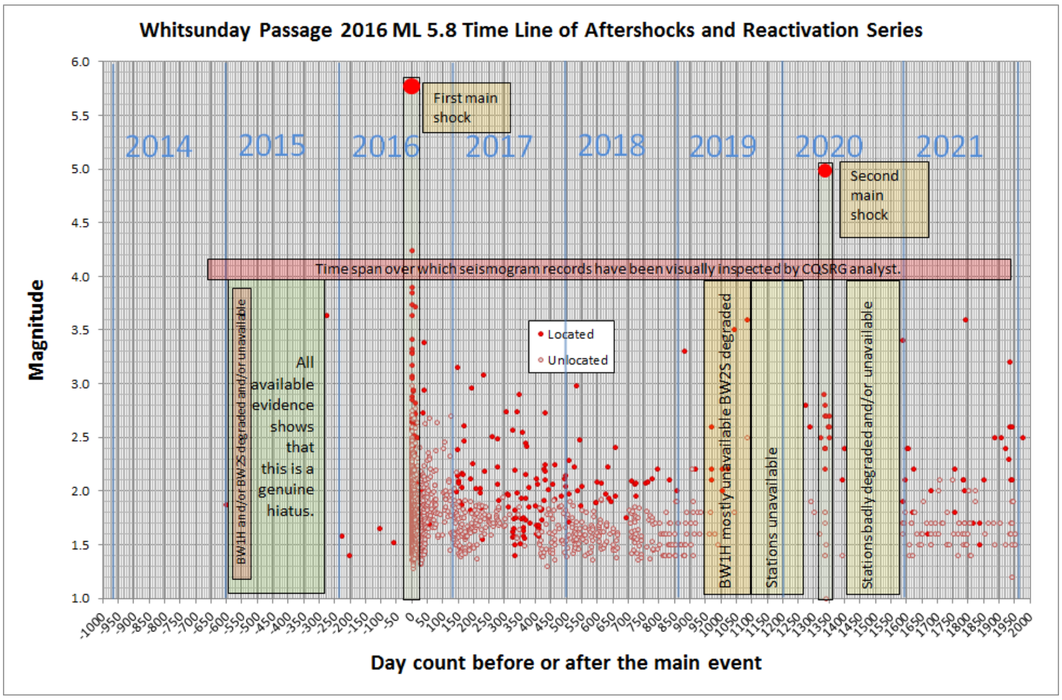

Figure 4: Time line of events associated with the 2016 Bowen ML 5.8 earthquake, as detected and located by CQSRG.

Figure 5: Far North Queensland seismic monitoring stations used by CQSRG to locate Bowen sequence events.

Figure 5 shows the location of the ten seismic monitoring stations that are regularly used by CQSRG to locate earthquake events that occur in the Bowen area; although, not all of those ten stations can be relied on to produce seismic records that can be used for locations.

The stations shown in Figure 5 are as follows, listed in order of their radial distance from Bowen.

- BW1H and BW2S, Urban Monitoring Project (UMP) stations in Bowen operated by Geoscience Australia (GA) the principal purpose of which is to monitor for large potentially damaging events to obtain data for structural engineering purposes.
- AUAYR, operated by the Australian National University (ANU) as part of their Australian Seismometers in Schools project. This station is provided principally for educational purposes, and rarely provides seismic records of sufficient quality to be used to locate small events in the Bowen area.
- TV1H and TV2S, UMP stations in Townsville operated by GA the principal purpose of which is to monitor for large potentially damaging events to obtain data for structural engineering purposes.
- CTA, operated by GA in Charters Towers as part of the Australian National Seismograph Network (ANSN). Although this is intended to be a high quality station data from it is often not available from the public distribution system.
- CTAO, operated in Charters Towers by the Albuquerque Seismological Laboratory (ASL) in the U.S.A. as part of the Global Seismograph Network (GSN). This is a high quality station, good quality data from which is regularly available from the public distribution system.
- MTSU, operated by GA in Mount Surprise as part of the ANSN. This station produces reliable data on the public distribution system.
- CN1H and CN2S, UMP stations in Cairns operated by GA the principal purpose of which is to monitor for large potentially damaging events to obtain data for structural engineering purposes.

The errors in locational precision for all of the earthquake events shown in Figure 2 and Figure 3 are of the order of a few kilometres to tens of kilometres (and in some instances over 100 km), and it is not possible to get an accurate estimate of the depths at which these events are occurring. The epicentral locations shown in Figure 2 and Figure 3 are statistically the most likely locations for where the events occurred. The low density of instrumental monitoring stations in the immediate Bowen seismogenic region is the principal reason for this. For more accurate locations, and in order to measure the event depths, a higher density of permanent instrumental monitoring stations would be required in the immediate area of Bowen. Typically this would consist of additional permanent stations to be established along the coast northwest and southeast of Bowen, with an orthogonal arm of stations running to the northeast of Proserpine, extending out to the Whitsunday islands. CQSRG strongly urges Bowen, Whitsunday, and Mackay Regional Councils to actively investigate the feasibility of working with the Queensland State Government to establish such a monitoring network with a rolling ten year tenure, along with the employment of qualified staffing or contracting of suitable commercial companies to install, operate and maintain it, and actively analyse and report on the data collected by the network.

It is clear from Figure 4 that the Bowen 2016 sequence is ongoing and has been strengthened by the April 2020 ML 5.0 event. All indications are that it will continue into the foreseeable future.

CQSRG has also inspected Bowen regional seismic records going back to the beginning of 2015 to detect any earthquake events that occurred in the area prior to the main August 2016 earthquake; and these are also shown in Figure 4. Although there were a few (six) events detected and located (ranging in magnitude from ML 1.4 to ML 3.6) it is not clear whether these were precursor events, or if they are simply representative of the pre-August 2016 background seismicity.

Extending the investigation further back in time will prove difficult due to lack of reliable seismic records.

A full listing of the 91 Bowen earthquake events detected by CQSRG in 2021 is given in Table 1. Due to lack of available data only 27 of the listed events had mathematical locational analysis performed.

The method used by CQSRG to identify Bowen August 2016 ML 5.8 aftershocks is detailed in Appendix F - Method Used to Identify Bowen August 2016 ML 5.8 Aftershocks.

Table 1: Earthquake events in the Bowen/Whitsunday Passage area detected by CQSRG in 2021.

Date (UTC)	Time (UTC)	Latitude	Longitude	Magnitude (ML)
2021-01-01	08:04:09.65	-19.624	148.627	2.1
2021-01-08	09:14:20.34	-19.752	148.693	2.4
2021-01-11	05:05:57.59	-19.725	148.654	2.4
2021-01-15	06:42			1.4
2021-01-15	21:09			1.5
2021-01-20	21:50			1.7
2021-01-22	12:06			1.7
2021-01-23	00:41:37.68	-19.971	148.821	1.8
2021-01-24	14:35			1.4
2021-01-28	10:14:17.20	-19.815	148.739	2.2
2021-02-01	03:24			1.8
2021-02-08	09:27			1.6
2021-02-14	18:21			1.5
2021-02-21	10:21			1.5
2021-02-21	16:48			1.6
2021-02-25	14:00			1.6
2021-03-01	06:45			1.9
2021-03-11	15:48			1.7
2021-03-13	02:20:47.29	-20.280	148.714	1.6
2021-03-25	00:08:27.49	-19.972	148.861	2.0
2021-03-25	09:24			1.5
2021-03-26	04:14			1.6
2021-03-26	13:58			1.5
2021-03-26	15:30			1.7
2021-04-06	04:44			1.6
2021-04-08	10:59			1.7
2021-04-17	23:59			2.0
2021-04-18	11:15			1.6
2021-04-20	00:18			2.1
2021-04-27	08:22			1.7
2021-05-03	09:31			1.7
2021-05-15	13:59			1.5
2021-05-15	14:00			1.5
2021-05-15	16:43			1.8
2021-05-24	15:30			1.5
2021-06-04	20:20			2.1
2021-06-05	14:58			1.6
2021-06-08	11:19:25.06	-19.800	148.710	1.8
2021-06-08	13:21:25.26	-19.655	148.658	2.2
2021-06-19	08:06			1.4
2021-06-19	23:12			1.6
2021-06-22	10:34			1.7
2021-06-23	11:26			1.7
2021-07-04	08:34			1.6
2021-07-06	14:36:56.84	-20.352	148.607	2.1
2021-07-06	15:26:53.93	-20.421	148.580	2.1
2021-07-07	17:12			1.5
2021-07-11	17:37:13.35	-19.747	148.720	2.0

Date (UTC)	Time (UTC)	Latitude	Longitude	Magnitude (ML)
2021-07-11	19:44:02.09	-19.614	148.638	1.7
2021-07-12	08:38			1.7
2021-07-12	11:10			1.6
2021-07-13	01:36:14.61	-19.858	148.808	3.6
2021-07-16	20:15			1.5
2021-07-17	09:34			1.5
2021-07-23	09:56			1.6
2021-07-25	04:39			2.0
2021-07-28	11:11			1.7
2021-07-28	13:45			1.4
2021-07-29	08:29			1.7
2021-07-31	14:47			1.4
2021-08-07	21:44:28.91	-19.638	148.719	1.7
2021-08-14	01:56			1.9
2021-08-14	02:06			2.0
2021-08-27	16:37:32.42	-19.877	148.792	1.5
2021-08-29	19:45:29.76	-20.136	148.715	1.7
2021-09-11	21:35			2.1
2021-09-17	11:59			1.6
2021-09-26	15:11			1.7
2021-10-15	18:04			1.7
2021-10-17	21:38:09.21	-19.675	148.662	2.5
2021-10-18	13:45			1.5
2021-11-05	13:01			1.7
2021-11-06	18:17:14.31	-19.829	148.774	2.5
2021-11-20	09:09			1.5
2021-11-22	15:04:15.67	-19.736	148.723	2.4
2021-11-30	12:34:49.95	-20.496	148.521	2.3
2021-12-03	04:16:39.23	-19.863	148.854	3.2
2021-12-05	02:08:02.46	-19.960	148.648	2.6
2021-12-06	19:37			1.6
2021-12-06	19:43:29.65	-19.867	148.780	2.1
2021-12-10	12:14			1.6
2021-12-10	15:45			1.7
2021-12-13	10:43:56.59	-20.399	148.501	2.6
2021-12-13	10:54:36.81	-19.898	148.758	2.1
2021-12-13	10:56			1.9
2021-12-13	14:25			1.7
2021-12-13	14:42			1.2
2021-12-13	15:05			1.5
2021-12-14	22:30			1.9
2021-12-21	19:18			1.5
2021-12-22	22:05			1.6

The available evidence indicates that the BW 2016 aftershock sequence is continuing, and will continue into the foreseeable future. What is currently being observed may well represent the continuation of a new long-term seismicity regime for the Bowen/Whitsunday Passage area.

Although the 27 unlocated events listed in Table 1 are not included in the Main CQSRG Earthquake Catalogue, CQSRG has the source data used to identify those events on record, and this data can be made available to interested parties on request.

CQSRG Main Earthquake Catalogue 2021

During 2021, 51 earthquake events were detected, located, and catalogued by CQSRG. Details of these events are provided in Table 2. The online full version of the CQSRG catalogue can be accessed at http://cqsrg.org/catalogue/. The 51 events listed in Table 2 include the 26 Bowen aftershock events that were sufficiently well recorded to have been located.

An additional 65 Bowen aftershock events were identified, but insufficient recordings of those events were available to allow for reliable locations. While the methodology used to identify BW 2016 aftershocks is considered reliable, it is possible that a small number of them (less than 3%) have been incorrectly assigned. For this reason, these 65 events have not been included in the main CQSRG Earthquake Catalogue, but are included in a CQSRG Supplementary Catalogue, listed in Table 1.

During 2021 there were two large (ML 5.9 and ML 4.7) earthquakes in Victoria that were recorded by CQSRG on its FS03 station; these are included in Table 2. Also included in Table 2 due to its proximity to the Far Southwest Queensland Seismogenic zone is an earthquake that occurred near Innamincka, South Australia.

It should also be noted that, although the main ML 5.8 Bowen event and some of the listed aftershocks were well recorded on the CQSRG FS03 station, several other aftershocks that are listed in the CQSRG main and supplementary catalogues were not principally detected on the CQSRG network. Most of those aftershock events were identified by manual inspection of the daily records obtained off the BW1H and BW2S Urban Monitoring (UM) stations at Bowen.

It is also noted that, where the EQLOCL algorithm could not calculate a depth due to lack of vertical resolution, the focal depths listed in the CQSRG Earthquake Catalogue have been constrained to the local norm (10 km). This is indicated in Table 2 in the Depth column by ‘10N’.

Table 2: Main CQSRG Earthquake Catalogue of Events Detected, Located, and Catalogued by CQSRG during 2021.

Date (UTC)	Time (UTC)	Latitude	Longitude	Depth (km)	Place	Magnitude (ML)	Comment
2021-01-27	20:20:41.24	-28.624	149.580	17	Boomi	2.6	11 km N Boomi, NSW/Qld border. Reviewed 2021-02-02.
2021-01-31	19:34:05.12	-21.373	149.390	10N	Sarina	2.4	19 km NE Sarina. Reviewed 2021-02-22.
2021-02-03	11:29:16.88	-25.236	151.481	10N	Mt Perry	1.1	18 km SW Mt Perry. Reviewed 2021-02-22.
2021-02-11	15:50:10.21	-23.809	154.498	10N	Bundaberg	2.9	248 km NE Bundaberg. Reviewed 2021-02-22.
2021-02-17	21:24:12.99	-25.218	151.536	10N	Mt Perry	1.0	12 km SW Mt Perry. Reviewed 2021-02-26.
2021-02-25	19:25:28.14	-25.760	154.020	10N	Rainbow Beach	2.8	94 km ENE Rainbow Beach. Reviewed 2021-03-06.
2021-03-05	16:00:25.10	-24.802	152.758	10N	Bundaberg	1.3	42 km ENE Bundaberg. Reviewed 2021-03-08.
2021-03-08	12:53:42.05	-19.499	148.199	10N	Bowen	1.4	57 km N Bowen. Reviewed 2021-03-10.
2021-03-09	12:58:38.17	-20.491	148.434	10N	Proserpine	2.2	18 km SW Proserpine. Reviewed 2021-03-12.
2021-03-14	00:08:27.49	-19.972	148.861	10N	Bowen	2.0	64 km E Bowen. Reviewed 2021-03-27.
2021-03-25	01:03:36.53	-25.215	151.546	10N	Mt Perry	0.9	11 km SW Mt Perry. Reviewed 2021-03-27.
2021-03-25	01:18:49.60	-25.058	151.847	10N	Gin Gin	1.3	14 km SW Gin Gin. Reviewed 2021-04-18.
2021-04-16	08:57:08.77	-25.263	151.723	10N	Mt Perry	0.7	12 km SE Mt Perry. Reviewed 2021-04-18.
2021-04-17	08:30:44.20	-25.544	150.301	10N	Cracow	1.5	27 km S Cracow. Reviewed 2021-04-26.
2021-04-26	17:24:10.28	-24.799	152.768	10N	Bundaberg	1.7	43 km E Bundaberg. Reviewed 2021-05-03.
2021-05-02	05:10:30.93	-25.149	151.741	10N	Mt Perry	0.5	10 km NE Mt Perry. Reviewed 2021-05-16.
2021-05-14	21:16:49.37	-25.154	151.725	10N	Mt Perry	0.9	9 km NE Mt Perry. Reviewed 2021-05-16.
2021-05-14	21:39:43.57	-25.151	151.737	10N	Mt Perry	0.2	10 km NE Mt Perry. Reviewed 2021-05-16.
2021-05-14	01:43:18.01	-25.153	151.729	10N	Mt Perry	0.9	9 km NE Mt Perry. Reviewed 2021-05-16.
2021-05-15	12:50:19.83	-24.797	150.701	10N	Monto	1.1	43 km WNW Monto. Reviewed 2021-05-20.
2021-05-16	16:46:02.23	-24.530	152.482	10N	Bundaberg	1.4	40 km N Bundaberg. Reviewed 2021-05-22.
2021-05-20	05:50:53.05	-25.222	151.432	10N	Mt Perry	1.7	22 km WSW Mt Perry. Reviewed 2021-05-22.
2021-05-21	08:56:35.87	-25.114	150.508	10N	Eidsvold	1.4	68 km NW Eidsvold and SW Monto. Reviewed 2021-06-24.
2021-06-02	00:24:54.42	-25.840	151.079	10N	Monogorilby	2.0	17 km N Monogorilby. Reviewed 2021-06-24.
2021-06-13	11:12:24.32	-17.204	146.637	10N	Innisfail	2.9	74 km NE Innisfail. Reviewed 2021-06-18.

Date (UTC)	Time (UTC)	Latitude	Longitude	Depth (km)	Place	Magnitude (ML)	Comment
2021-06-17	10:11:59.73	-25.017	151.730	10N	Gin Gin	0.5	23 km W Gin Gin. Reviewed 2021-06-24.
2021-06-20	21:04:23.49	-25.621	150.394	10N	Eidsvold	1.4	78 km SW Eidsvold. Reviewed 2021-06-24.
2021-06-22	08:53:34.55	-25.415	151.804	10N	Biggenden	1.1	26 km NW Biggenden. Reviewed 2021-08-03.
2021-07-19	17:00:11.00			10N	Four Seasons	0.4	13 km SW Four Seasons station. Reviewed 2021-08-03.
2021-07-25	15:44:04.28	-22.664	140.458	10N	Boulia	3.8	63 km NE Boulia. Reviewed 2021-08-13.
2021-08-12	19:12:05.79	-25.160	151.709	10N	Mt Perry	0.5	Foreshock. 7 km NE Mt Perry. Reviewed 2021-09-01.
2021-08-24	19:36:16.86	-25.167	151.689	10N	Mt Perry	0.7	6 km NE Mt Perry. Reviewed 2021-09-01.
2021-08-24	05:15:46.35	-27.543	140.532	10N	Innamincka, South Australia	2.7	30 km NW Innamincka. Reviewed 2021-09-04.
2021-09-04	12:07:30.81	-28.433	142.946	10N	Bulloo Downs	2.9	11 km N Bulloo Downs homestead. Reviewed 2021-09-06.
2021-09-12	23:15:49.90	-37.509	146.226	8	Woods Point, Victoria	5.9	7 km N Woods Point, Victoria. Reviewed 2021-10-14.
2021-09-21	16:47:24.92	-35.362	141.097	10N	Murrayville, Victoria	4.7	14 km SW Murrayville, Victoria. Reviewed 2021-10-13.
2021-10-08	22:26:02.90	-25.214	151.548	10N	Mt Perry	0.7	10 km SW Mt Perry. Reviewed 2021-10-29.
2021-10-12	10:10:12.80	-25.177	151.659	10N	Mt Perry	0.5	1 km E Mt Perry. Reviewed 2021-11-01.
2021-10-27	06:27:57.47	-26.659	152.376	10N	Nanango	1.8	37 km E Nanango in Jimna State Forest. Reviewed 2021-11-01.
2021-10-30	16:05:46.68	-24.679	153.274	10N	Bundaberg	1.8	96 km E Bundaberg. Reviewed 2021-11-05.
2021-11-21	05:12:06.34	-24.551	152.719	10N	Bundaberg	1.8	51 km NE Bundaberg. Reviewed 2021-11-25.
2021-11-22	15:04:15.67	-19.736	148.723	11	Bowen	2.4	59 km NE Bowen. Reviewed 2021-12-01.
2021-11-30	12:34:49.95	-20.496	148.521	19	Proserpine	2.3	12 km SW Proserpine. Reviewed 2021-12-01.
2021-12-03	04:16:39.23	-19.863	148.854	16	Bowen	3.2	66 km NE Bowen. Reviewed 2021-12-03.
2021-12-05	02:08:02.46	-19.960	148.648	21	Bowen	2.6	43 km NE Bowen. Reviewed 2021-12-05.
2021-12-09	05:34	-25.429	151.831	10N	Biggenden	1.2	25 km NW Biggenden. Reviewed 2021-12-10.
2021-12-10	15:53:58.45	-23.828	152.550	10N	Lady Musgrave Island	1.4	18 km NE Lady Musgrave Island. Reviewed 2021-12-14.
2021-12-13	10:43:56.59	-20.399	148.501	14	Proserpine	2.6	8 km W Proserpine. Reviewed 2021-12-14.
2021-12-13	10:54:36.81	-19.898	148.758	7	Bowen	2.1	55 km NE Bowen. Reviewed 2021-12-14.
2021-12-13	17:26:52.16	-23.339	151.791	10N	North West Island	1.8	10 km SE North West Island. Reviewed 2021-12-14.
2021-12-19	00:35:03	-25.460	151.081	10N	Eidsvold	0.4	10 km SW Eidsvold. Reviewed 2021-12-21.

2021 Statistical Summary

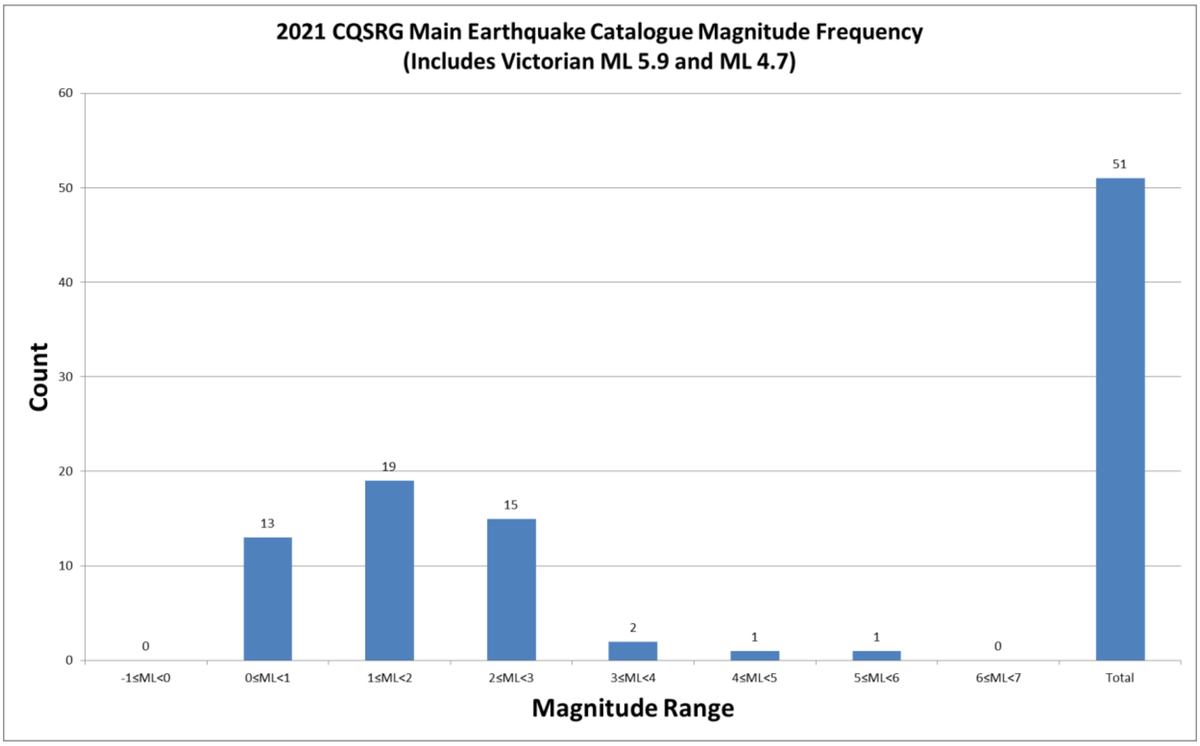

Figure 6: Magnitude frequency count for earthquakes in the main CQSRG 2021 Catalogue.

Figure 6 provides a graphical representation of the frequency of magnitude spread for earthquake events listed in the main 2021 CQSRG Catalogue (Table 2).

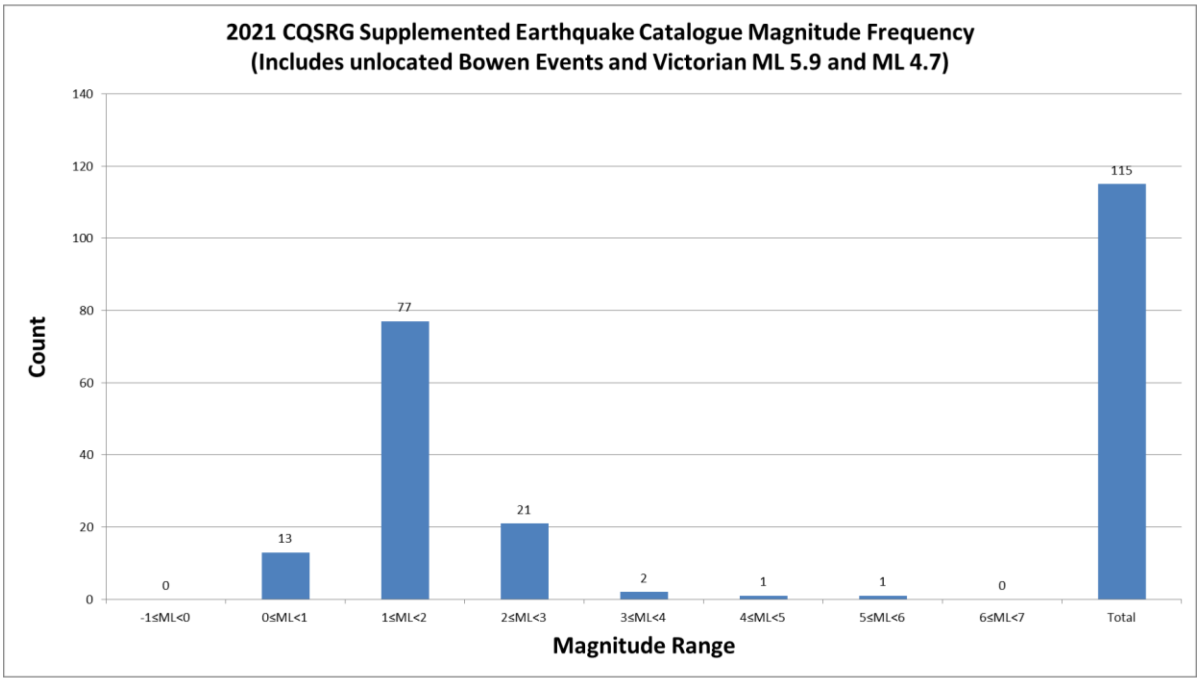

Figure 7: Magnitude frequency count for earthquakes in the augmented CQSRG 2021 Catalogue, which includes the 65 unlocated Bowen earthquakes.

Figure 7 provides a graphical representation of the frequency of magnitude spread for earthquake events listed in both the main CQSRG Catalogue (Table 2) and the supplementary Catalogue (Table 1). This includes the additional 65 unlocated earthquake events that were detected in the Whitsunday Passage, but omitted from the main CQSRG Earthquake Catalogue.

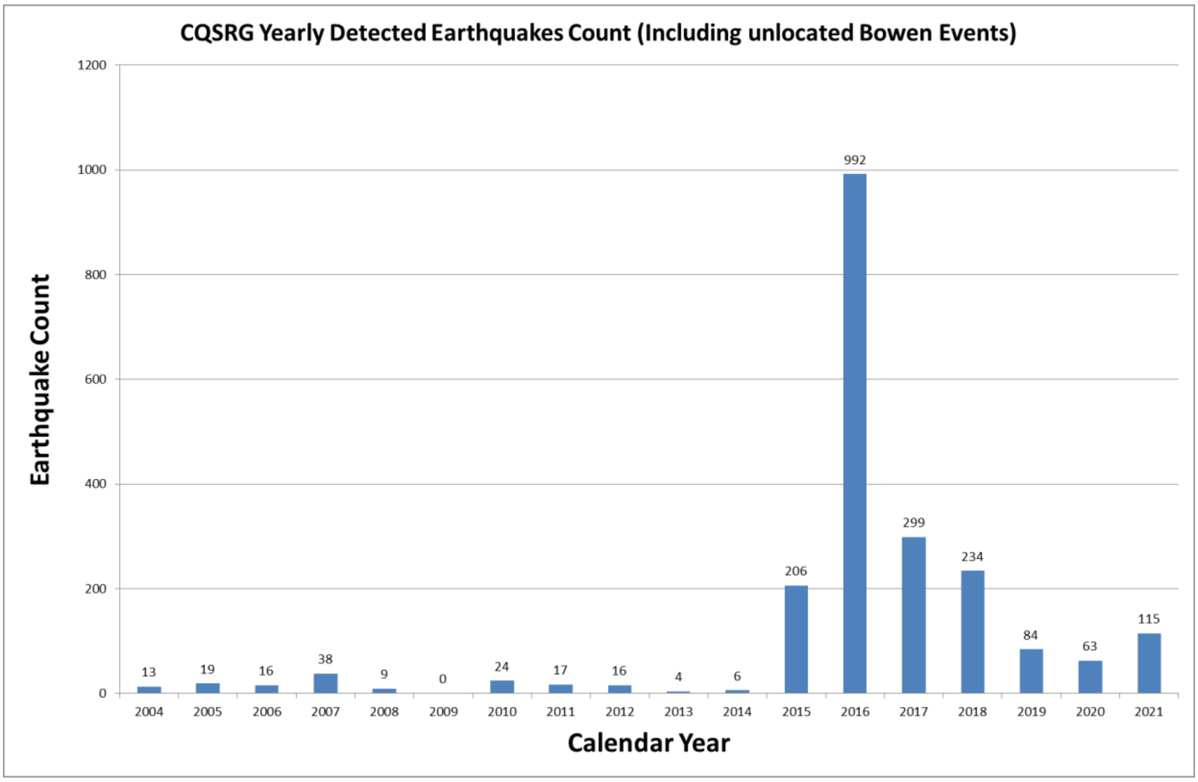

Figure 8: The number of earthquake events detected and catalogued by CQSRG since 2004 (including unlocated Bowen events).

Figure 8 shows the number of earthquake events detected and catalogued by CQSRG since 2004. It puts into context the extraordinary number of earthquakes detected during the years 2015 to 2021 when compared to the numbers detected in previous years. This increase in seismic activity is entirely due to the large magnitude events and their dependent aftershocks that occurred in the Mt Perry, Rainbow Beach, and Bowen areas during 2015, 2016, and 2020.

The seven past years have each exhibited a significantly greater number of earthquake events than all previous years – certainly since 2004, when CQSRG began monitoring. The 2016 ML 5.8 Bowen event was previously arguably the second largest earthquake to have been recorded on the East coast of Mainland Australia in modern times. This has now been eclipsed by the ML 5.9 that occurred in Victoria on 12 September 2021 (this year).

Examination of Figure 8 suggests that the current Queensland seismicity is gradually decaying to a background level typical of the pre-2015 period, but that <u>a heightened seismicity level may be expected to continue for the next decade – particularly in the Bowen/Whitsunday Passage area.</u>

2021 Earthquake Maps

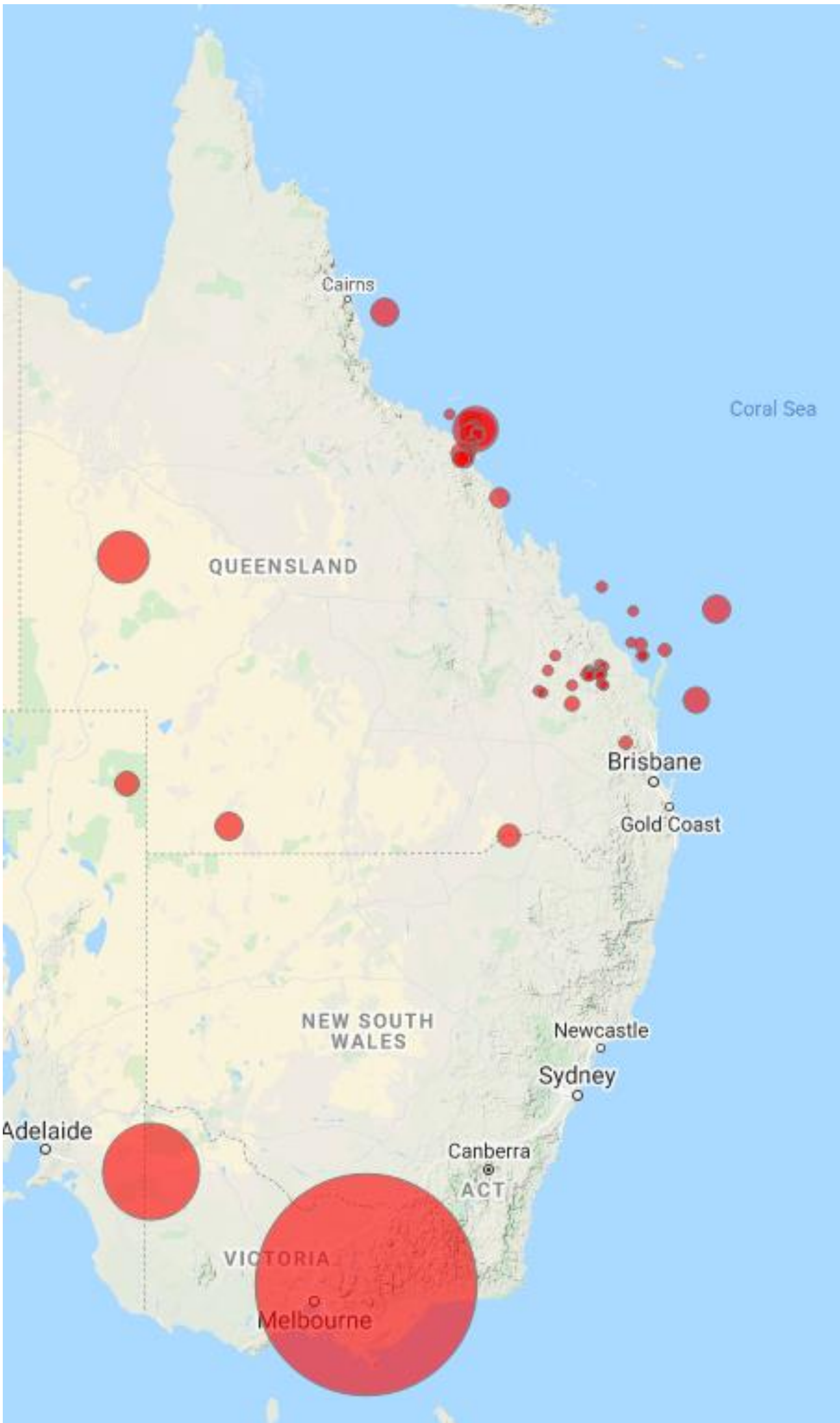

Figure 9: Broad view of earthquakes located in 2021 by CQSRG.

Figure 9 is a broad-view map of the 51 earthquakes located and entered into its Main Earthquake catalogue by CQSRG in 2021. An additional 65 unlocated events were entered into the CQSRG Supplementary Catalogue, and these are not shown in Figure 9.

It should be noted that the earthquakes located in Far Southwest Queensland, Southern Queensland, and Far North Queensland were not directly detected by CQSRG monitoring stations, but were either notified by Geoscience Australia, or detected by manual inspection of seismograms obtained from non-CQSRG stations. These events were, however, independently confirmed and located by CQSRG.

The events in the North-East (in the Bowen area) were detected and located as part of the ongoing CQSRG study of the Bowen 2016 aftershock and reactivation sequence; using the Geoscience Australia stations BW1H and BW2S.

It should not be inferred from the clustering and distributed nature of the earthquake events shown in Figure 9 that small earthquake events did not occur in other parts of Queensland. However, no other Queensland earthquake events other than those shown in Figure 9 were reported by Geoscience Australia during the 2021 calendar year.

Geoscience Australia usually only reports on earthquakes of ML 3.5 or greater or on lesser magnitude events that have generated public interest.

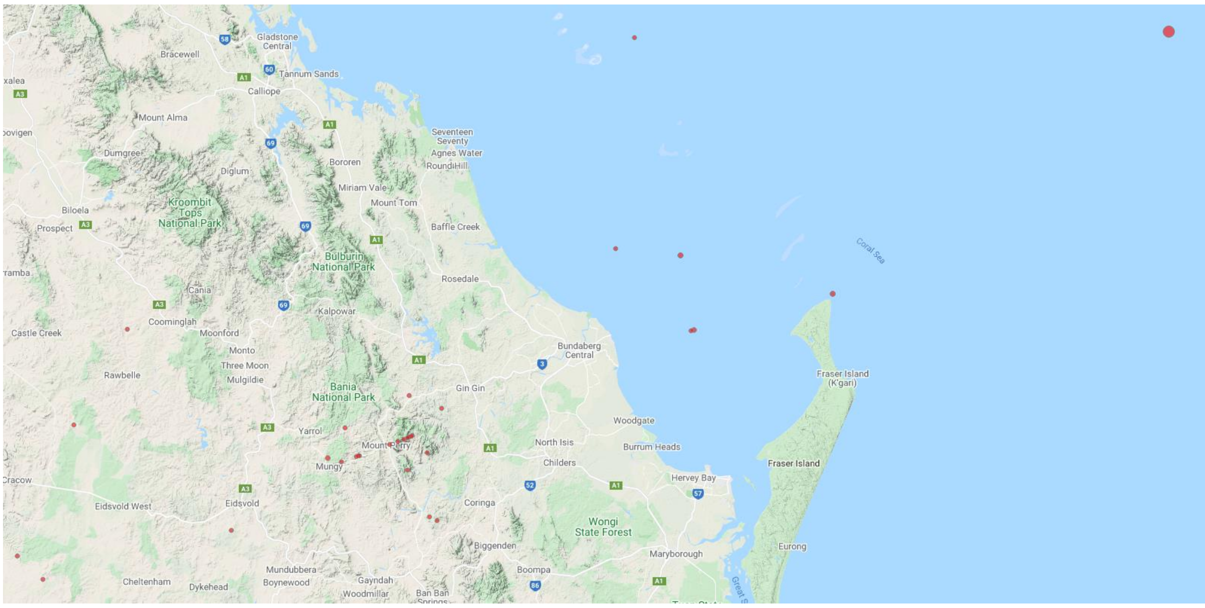

Figure 10: Earthquakes located by CQSRG during 2021 in the Central Queensland Coastal Area.

Figure 10 provides a focused view of earthquakes located by CQSRG in 2021 in the Central Queensland Coastal region.

The author regards the apparent lineation of earthquake events in the confined region between Eidsvold and Gin Gin as being an artefact caused by the earthquake detection efforts of the Central Queensland Seismology Research Group (CQSRG) only incorporating data from the Eidsvold (EIDS) GA station, and the CQSRG FS03 station (a two station location). These very small events have been detected and located only due to the presence of the CQSRG monitoring station FS03. If this monitoring station was not present the earthquake events shown in Figure 10 would undoubtedly not have been detected and located.

The number and distal spread of the monitoring stations operated in Queensland by Geoscience Australia (GA) are only capable of ensuring that any ML 3.5 or greater event that occurs in Queensland is detected; indeed, as openly acknowledged by GA, they only have an obligation to report on earthquakes of magnitude ML 3.5 or greater.

There is no known geological evidence that would indicate that similar small events, such as those indicated in Figure 10, are not occurring throughout Queensland; or, at least, may be occurring in discrete clusters throughout Queensland.

Public Seismic Network (PSN)

Since 2011-08-05 CQSRG has hosted a PSN seismograph station, known to the Australian PSN community as the Gin Gin or the Horse Camp station. Vic Dent and Mike Turnbull originally installed the station with a rudimentary setup consisting of a 3D geophone attached to a PSN A/D board, in a vacant brick shed on Mike Turnbull's property at Horse Camp, 16 km SW of Gin Gin. Mike provided a desktop computer onto which the PSN software was installed. The station regularly uploading GIF pictures of the daily seismogram traces to the Regional Seismic Users web site operated by Dale Hardy; until Dale's untimely death. That web site has now been decommissioned.

Since 2017 CQSRG has hosted a web site for the Australian Public Seismic Network at http://cqsrg.org/psn/stations/.

The Horse Camp station also uploads continuous data to the Regional Seismic Network (RSN), operated by the Australian Centre for Geomechanics (AGC). (Information at https://acg.uwa.edu.au/)

In 2013 the geophone was replaced with a Sprengnether S6000 seismometer, and the PSN A/D board was housed in a respectable electronics housing, along with custom made adaptor electronics to accommodate the sensor and GPS interface.

Since the PSN station is located only 300 m from FS03, data from the PSN station is not used in locating events detected by CQSRG, but is used to identify seismic events of interest to CQSRG.

Appendix A – Details of FS03

Station FS03 is registered with the International Registry of Seismograph Stations maintained jointly by International Seismological Centre & World Data Centre for Seismology.

LOCATION

Latitude -25.1068, Longitude 151.8667, Height above sea level 180 m. Approximately 16 km SW Gin Gin, Queensland, Australia.

SITE AND SAMPLING

Sampling of ground velocity at 100 sample/sec, full scale 4194304 counts.

Ch	Type	Serial	Name	Direction	Gain	Filters	
1	L43D	#1482	East	90 deg true	0.00	DC	50.0
2	L43D	#1482	North	0 deg true	0.00	DC	50.0
3	L43D	#1482	Up	Positive up	0.00	DC	50.0

DATA LOGGER

Kelunji Classic #153, GURIA V4.16A Operating System.

TIME SYNC

Sync every day at 1400 UCT, using GPS. Wait for up to 80 seconds
Wait up to 120 seconds for a position
Auto-correct clock after sync

TRIGGER SETTINGS

STA/LTA Channel 3, filter 1.00 to 7.50 Hz
Time const 0.20, 2.0, 20.0, 200.0 seconds
Ratios Fast 3.50, slow 1.75, squelch 5, 15 days
Length 100 to 200 secs, 80.00 sec pre-trigger, 1.10 cutoff.

Appendix B – CQSRG Method of Earthquake Location

In general, CQSRG only catalogues earthquake events that are detected by its seismic monitoring station(s). However, in the event of significant local events that, for reasons of station downtime, are not recorded by CQSRG stations, locations are conducted by obtaining data from other agencies.

The general process for earthquake event location at CQSRG is as follows.

1. Identify local earthquake events from visual inspection of CQSRG network seismograms.

2. Download extra seismograms from other agencies; typically, University of Queensland, Geoscience Australia, and the Australian National University (ANU) Australian Seismometers in Schools (AuSIS) project.

3. Send email requests to other agencies; typically, the Seismology Research Centre (SRC), and the South East Queensland Water Company (SeqWater).

4. Collect all available seismogram records and pick P and S phase arrival times using EqWave (SRC sourced software).

5. Enter the picked P and S times into EQLOCL (SRC sourced software).

6. Use the location calculated by EQLOCL.

In the not so rare cases where the only record available is that from FS03, an attempt is made to locate the event using first motion polarity and near field trigonometry. This can only be done when the first motions are sufficiently impulsive to give an unambiguous indication of the arrival azimuth. In cases where only two records are available (invariably FS03 and EIDS), and the S-P derived radial distance circles meet, but do not over extend, the touch point is used as a seed to the EQLOCL algorithm.

In cases where only two records are available (invariably FS03 and EIDS), and the S-P derived radial distance circles over extend, but the first motions are sufficiently impulsive to derive an unambiguous azimuth, the radial touch point indicated by the azimuth direction is used as a seed to the EQLOCL algorithm.

In cases where only two records are available (invariably FS03 and EIDS), and the S-P derived radial distance circles over extend, but the first motions are insufficiently impulsive to derive an unambiguous azimuth, the locations of both the radial touch points are used as seeds to the EQLOCL algorithm, and the resulting ambiguous locations are noted in the catalogue entry comments.

In cases where the only information that can be gleaned is the radial distance from FS03, that distance may be noted in the catalogue listing comments.

Appendix C – CQSRG Method of Magnitude Quantification from FS03 Records

Calibration of FS03 Seismometer for Earthquake Magnitude Determination.

Mike Turnbull, 7 November, 2012.

Introduction

FS03 is the designation of a seismic monitoring station operated by the Central Queensland Seismology Research Group (CQSRG). It is located about 16 km south-west of Gin Gin.

When the FS03 station was first installed it had a Sprengnether S6000 seismometer attached to a data logger manufactured by the Seismology Research Centre (SRC). The characteristics of this sensor and the amplification factors of the data logger section of the seismograph were used as input to the SRC software used to locate and quantify earthquakes recorded on the seismograph. When the S6000 sensor failed it was replaced with a Mark Products L43D seismometer sensor. By comparison of the calibration waveform amplitudes of the S6000 against the L43D, a correction factor of 1.7 was calculated and used to adjust the amplitude value input to the SRC software to determine earthquake magnitudes using the new sensor – and this provided a temporary solution.

In order for the SRC software to be able to calculate an earthquake magnitude, it first must be able to calculate the earthquake's epicentral location. This can only be done if seismographic records from at least three different stations are available. In situations where only one or two records are available the software cannot locate the epicentre. Consequently, in cases where an earthquake cannot be located, determination of its magnitude using EQLOCL has always been problematic.

This appendix describes a method of extracting parametric information from past earthquake magnitudes, located with the SRC software using FS03 seismograms, that can be used in a suitable mathematical formula to determine the magnitude of other earthquakes recorded on the FS03 seismograph, using information from the single station data. This allows the magnitude determination to be done independent of the SRC software.

Background Information

The Richter local earthquake magnitude (M) is calculated using the formula given in Eq. 1.

$$M = log_{10}A - log_{10}A_0 \text{ (Eq. 1)}$$

Where:

A is the maximum amplitude of the seismic record of the earthquake, and

$\mathrm{A_0}$ is the maximum amplitude that would be produced on the same sensor by an earthquake of magnitude zero, occurring at the same location as the earthquake under consideration.

The value of $\log_{10}\mathrm{A_0}$ is dependent only on the epicentral distance of the earthquake from the sensor, and the response characteristics of the sensor itself. It is assumed that the relationship is as given in Eq. 2 **(NOTE: This assumed relationship has yet to be confirmed as being valid)**.

$$log_{10}A_0 = a\delta + b \qquad \text{(Eq. 2)}$$

Where:

δ is the epicentral distance, and

a and b are parameters yet to be determined, characteristic of the sensor.

Method

It is clear that Eq.2 is linear. Therefore the sensor parameters a and b can be determined from the slope and intercept, respectively, of the graph of $\log_{10}A_0$ plotted against δ, providing that sufficient data is available

The epicentral distance δ can be expressed in any value that provides a valid determination of the distance from the sensor to the epicentre. This could be (for example):

- the difference in arrival times of the P and S waves (in seconds for example); or,
- the surface distance from sensor to epicentre (in km for example); or,
- the Earth centric angle of arc from sensor to epicentre (in degrees for example).

The values for $\log_{10}A_0$ can be calculated from past earthquake events, the magnitudes of which have been determined with the SRC software using FS03 seismograms.

Transformation of Eq.1 gives Eq. 3.

$$log_{10}A_0 = log_{10}A - M \text{ (Eq.3)}$$

Table 3 presents the calculations of $\log_{10}A_0$ based on nine past events that were quantified with the SRC software, showing the S-P time differences used to measure epicentral distances.

Table 3: Determination of $\log_{10}A_0$ from past events recorded on the FS03 seismograph.

Earthquake Date	Measured P arrival in relative seconds	Measured S arrival in relative seconds	S-P time (s)	Measured Amplitude A	Magnitude estimated using ES&S algorithm M	Calculated $\log_{10}(A_0)$
2012-09-19 06:14	11.54	14.97	3.43	1900	1.6	1.6787536
2012-05-20 17:58	42.23	45.79	3.56	1103	1.5	1.5425755
2012-09-22 23:59	38.31	41.91	3.6	243	1.0	1.3856063
2012-04-10 01:51	37.54	42.57	5.03	473.2	1.4	1.2750447
2012-09-25 03:06	10.56	22.7	12.14	456	1.9	0.7589648
2012-08-19 22:37	29.38	41.82	12.44	215	1.5	0.8324385
2012-09-03 15:04	10.86	26.84	15.98	1828	2.8	0.4619762
2012-09-23 16:29	36.21	53.77	17.56	3620	3.2	0.3587086
2012-01-05 14:05	9.96	56.18	46.22	1352	4.3	-1.1690233

Figure 11 shows the graph of $\log_{10}A_0$ plotted against the associated S-P time difference (extracted from Table 3).

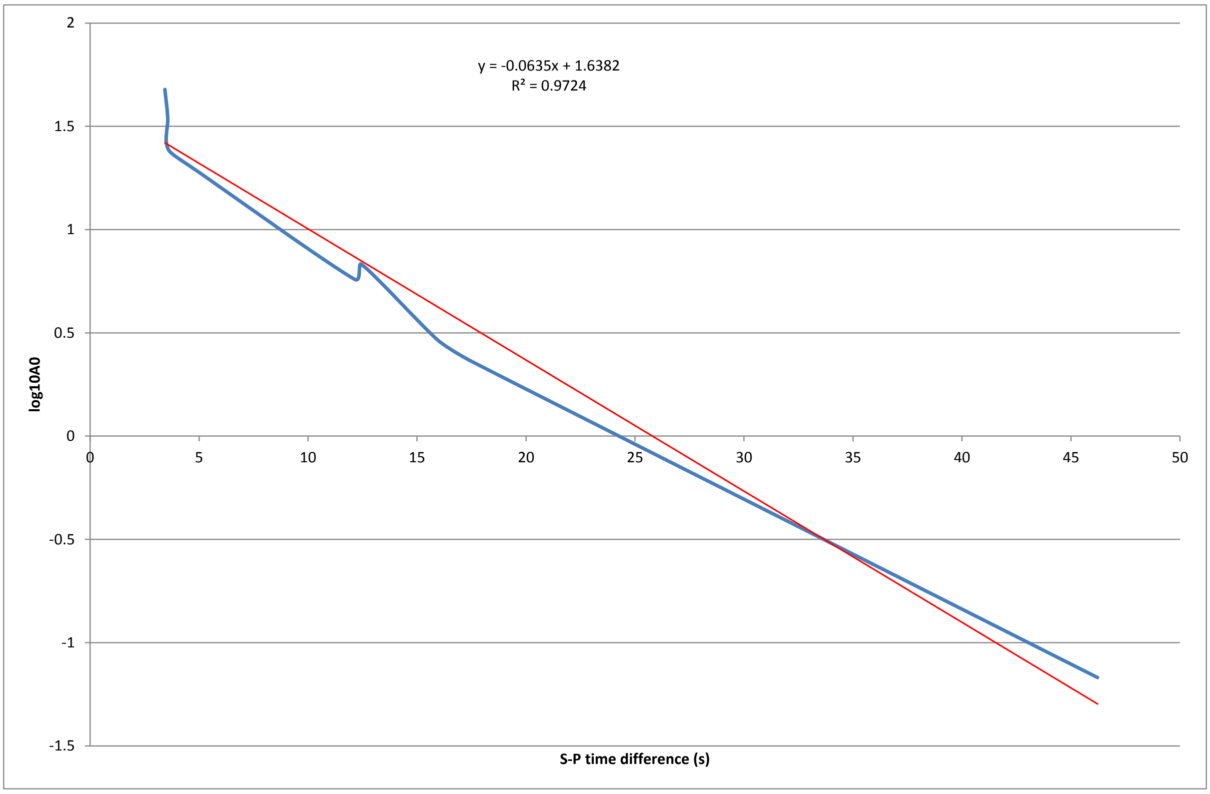

Figure 11: log10A0 Vs S-P.

Figure 11 also displays the line of best fit, calculated using linear regression of the plotting data, along with the slope, intercept, and correlation coefficient (R^2). **The R^2 value of 0.97 confirms that the assumed linear relationship is valid.**

By substituting the slope and intercept values into Eq.1 and Eq.2 we arrive at the formula for FS03 magnitudes given in Eq.4.

$$M_{FS03} = log_{10}A - (-0.064(S - P) + 1.64) \qquad \text{(Eq.4)}$$

Where:

M_{FS03} is the Richter magnitude determined from an FS03 seismogram record;

A is the maximum amplitude of the unfiltered FS03 seismogram record;

S is the arrival time of the S wave in seconds, and;

P is the arrival time of the P wave in seconds.

Important Note Concerning Accuracy and Precision

Table 3, Figure 11, and Equation 4, show a shortened calculation using only 9 historical events, to demonstrate the method. A consequence of using so few input values is that the resulting error ranges will suffer. Consequently, in order to reduce the standard errors in magnitude calculations based on this method, and extend the accuracy to at least one decimal point, many more input data are required.

The calculations used to determine the actual $\log_{10}A_0$ values for FS03, used in quantifying earthquake magnitudes, used 34 historical events. This resulted in parameter **a** and **b** values for Equation 2, as shown in Table 4.

Table 4: Equation 2, a and b Parameter values and Standard Errors.

	a	b
Estimation	-0.088	1.81
Standard Error	±0.004	±0.05
Correlation	0.94	

This implies that magnitudes determined using this method will be accurate to at least one decimal place. The a and b values shown in Table 4 are those used at CQSRG to calculate local magnitudes of events recorded by station FS03.

Example Usage

Figure 12 shows the seismogram of an earthquake that was recorded on station FS03 on 26 October 2012.

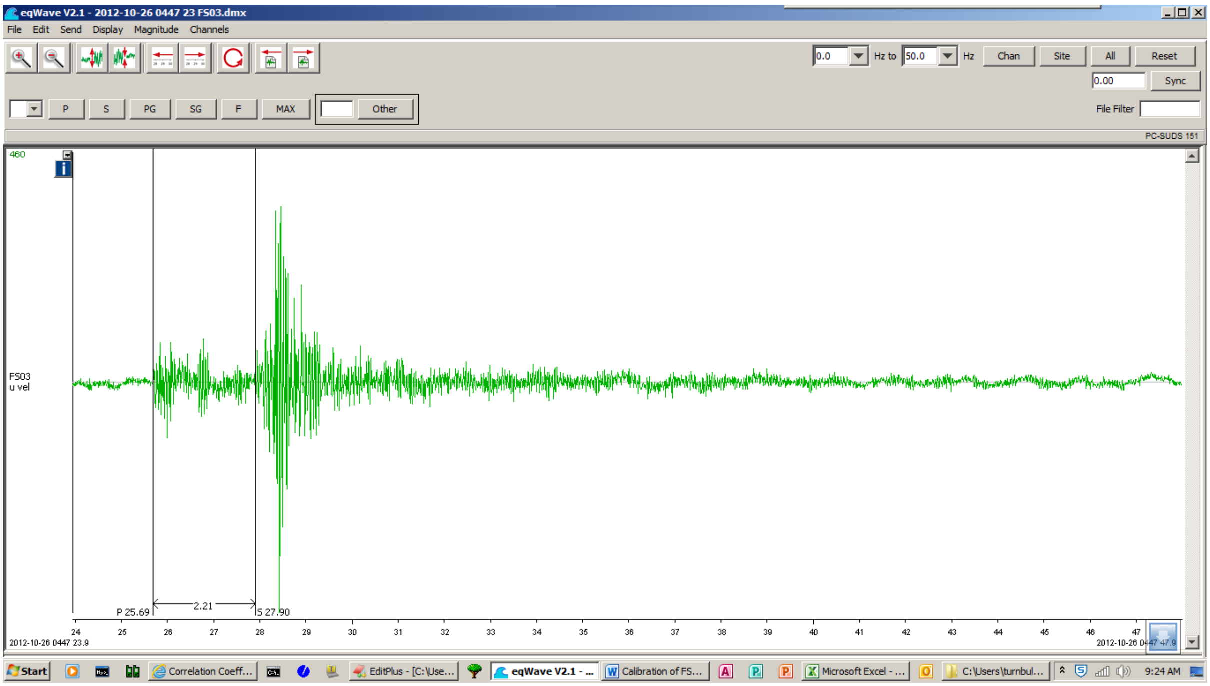

Figure 12: FS03 record of an earthquake.

From Figure 12 we can obtain the maximum amplitude (A = 460), the P wave arrival time (P = 25.69 s) and the S wave arrival time (S = 27.90 s); from which the time difference (S – P = 2.21 s) can be determined.

Inserting these values into Eq.4 we calculate a Richter magnitude of 1.2 (rounded to one decimal place).

Table 5 shows the results of some other similar calculations, for different earthquakes.

Table 5: Calculations of FS03 Richter magnitudes for some earthquakes.

Earthquake Date	Measured P arrival in relative seconds	Measured S arrival in relative seconds	S-P time (s)	Measured Amplitude A	Calculated M_{FS03} Magnitude
2012-09-28 16:38	10.56	22.7	12.14	304	1.6
2012-10-03 17:29	25.09	27.69	2.6	259	0.9
2012-10-18 14:48	23.43	25.91	2.48	911	1.5
2012-10-26 04:47	25.69	27.9	2.21	460	1.2

Student Resources

Figure 13, Figure 14, Figure 15, and Figure 16 are images of earthquake seismograms recorded by FS03. They are included here for the reader to use as practice on the CQSRG magnitude determination method. They can also be used as a resource for High School science teachers who may want to use the formulae presented here as real-world examples of applied mathematics.

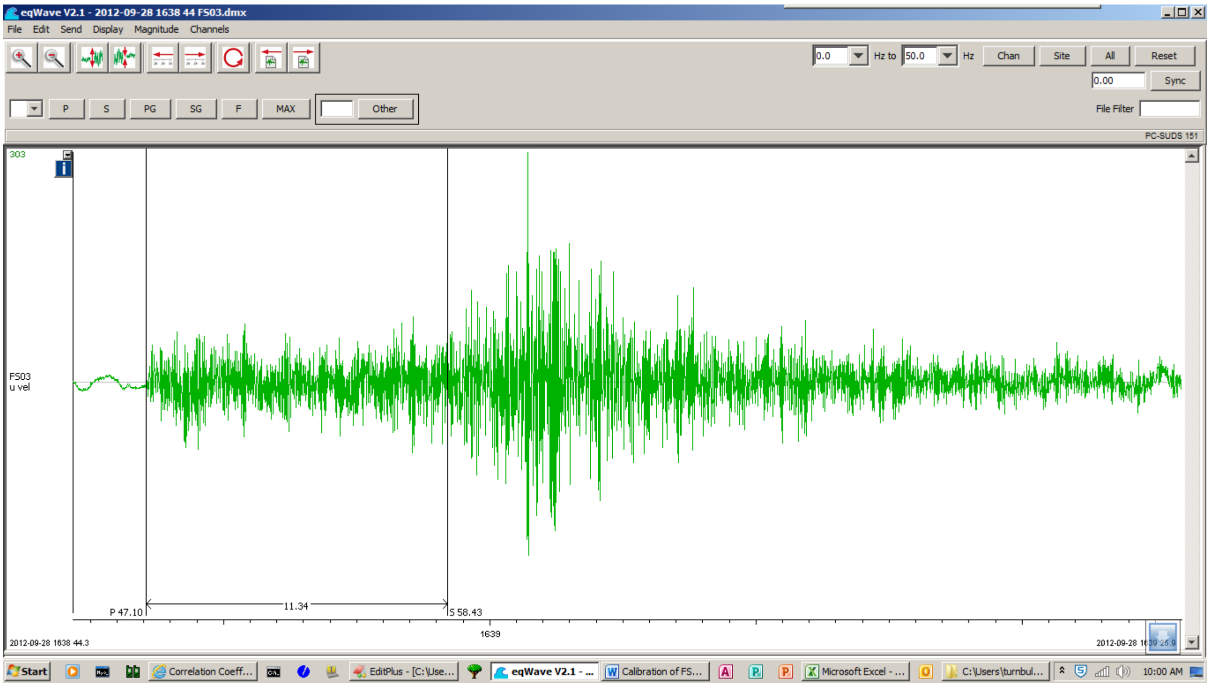

Figure 13: Earthquake recorded on FS03 on 28 September 2012.

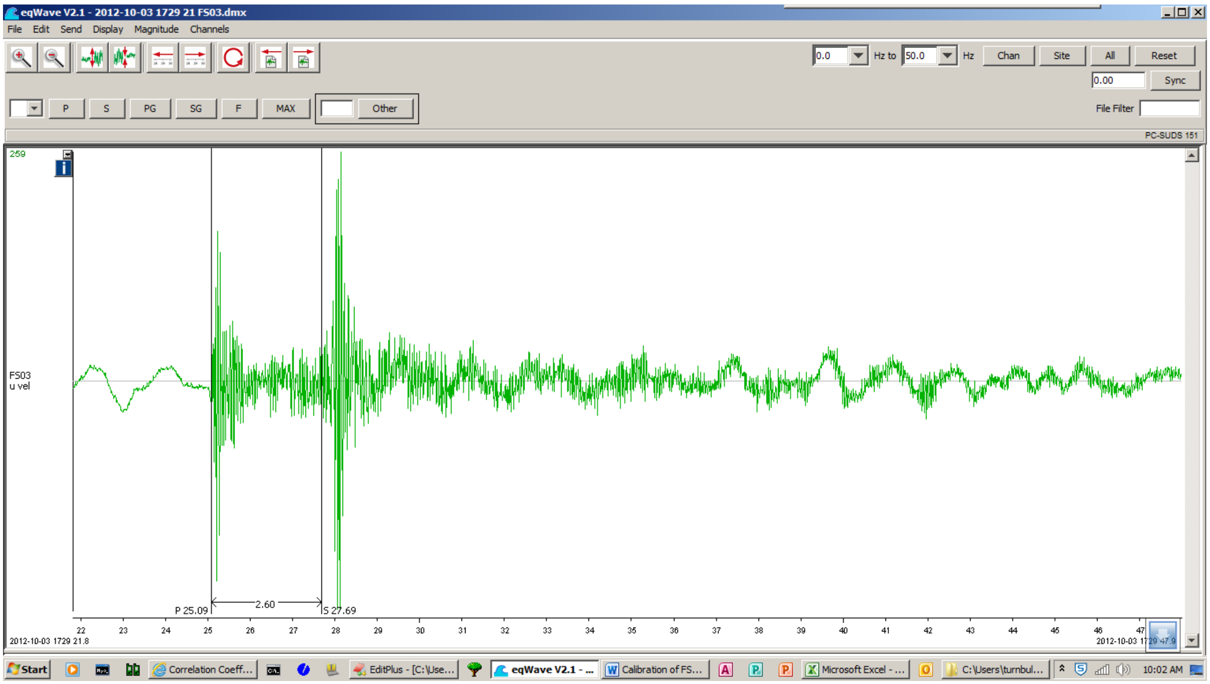

Figure 14: Earthquake recorded on FS03 on 3 October 2012.

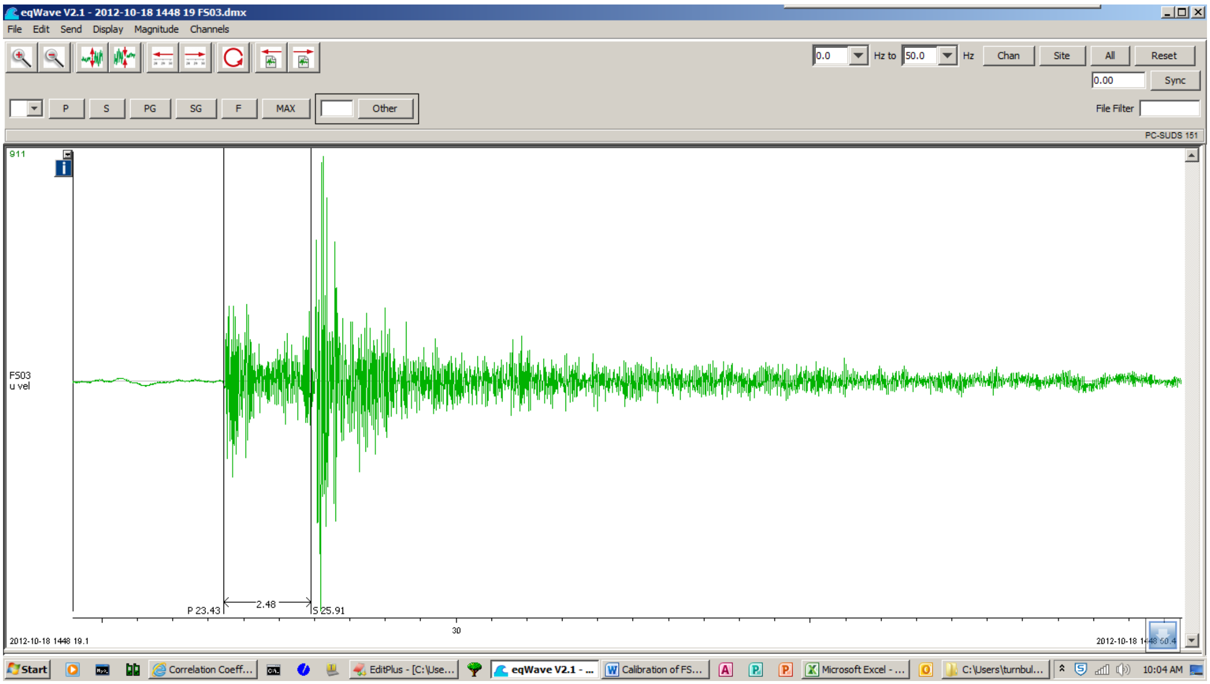

Figure 15: Earthquake recorded on FS03 on 18 October 2012.

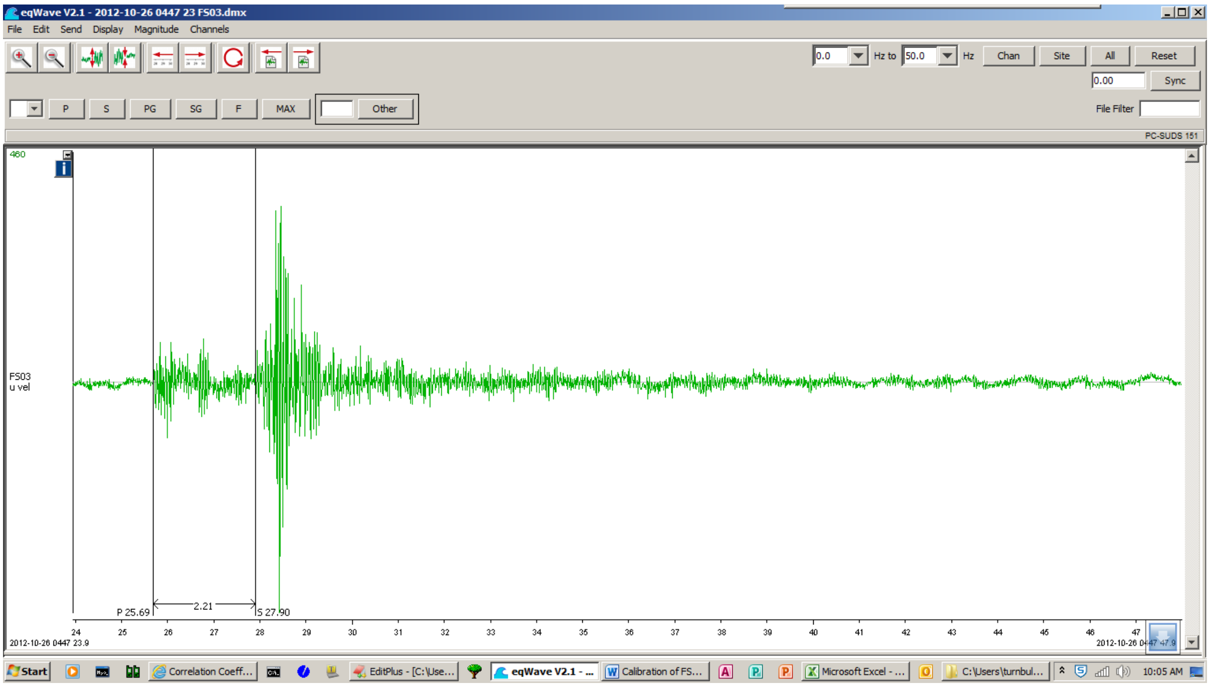

Figure 16: Earthquake recorded on FS03 on 26 October 2012.

Appendix D - CQSRG Method of Magnitude Quantification from EIDS Records

Relative Calibration of EIDS Seismometer for Earthquake Magnitude Determination Based on FS03 Past events.

Mike Turnbull, 17 Feb, 2015.

Introduction

FS03 is the designation of a seismic monitoring station operated by the Central Queensland Seismology Research Group (CQSRG). It is located about 24 km south-west of Gin Gin.
EIDS is the Geoscience Australia station located near Eidsvold. The characteristics of the EIDS sensor and associated equipment are unknown (to the author); however, it would be useful to be able to estimate event magnitudes using records from EIDS.

This paper describes a method of extracting parametric information from past earthquakes recorded by both FS03 and EIDS, and quantified using the FS03 seismograms or some other reliable method, that can be used in a suitable mathematical formula to determine the magnitude of earthquakes recorded on the EIDS seismograph.

Background Information

The Richter local earthquake magnitude (M) is calculated using the formula given in Eq. 1.

$$M = log_{10}A - log_{10}A_0 \text{ (Eq. 1)}$$

Where:

A is the maximum amplitude of the seismic record of the earthquake on a given sensor, and
$\mathrm{A_0}$ is the maximum amplitude that would be produced on the same sensor by an earthquake of magnitude zero, occurring at the same location as the earthquake under consideration.

The value of $\log_{10}\mathrm{A_0}$ is dependent only on the epicentral distance of the earthquake from the sensor, and the response characteristics of the sensor itself. It is assumed that the relationship is linear as given in Eq. 2 **(NOTE: This assumed relationship has yet to be confirmed as being reasonable)**.

$$log_{10}A_0 = a\delta + b \qquad \text{(Eq. 2)}$$

Where:

δ is the epicentral distance from the sensor under consideration, and
a and b are parameters yet to be determined, characteristic of the sensor under consideration.

Method

Eq.2 is linear, therefore the sensor parameters a and b can be determined from the slope and intercept, respectively, of the graph of $\log_{10}\mathrm{A_0}$ plotted against δ, using linear regression, providing that sufficient data is available for the sensor being considered.

The epicentral distance δ can be expressed in any value that provides a valid determination of the distance from the sensor to the epicentre. This could be (for example):

- the difference in arrival times of the P and S waves (in seconds for example); or,
- the surface distance from sensor to epicentre (in km for example); or,
- the Earth centric angle of arc from sensor to epicentre (in degrees for example).

The values for $\log_{10}A_0$, for the sensor under consideration, can be calculated from the amplitudes and S-P times of records of past earthquake events, the magnitudes of which events have been determined by some other reliable method – in this case, from magnitudes determined from FS03 records, or as published by Geoscience Australia.

Transformation of Eq.1 gives Eq. 3.

$$log_{10}A_0 = log_{10}A - M \text{ (Eq.3)}$$

Table 6 presents the calculations of $\log_{10}A_0$ values for EIDS based on past events that were quantified with FS03 seismograms, showing the S-P time differences used to measure epicentral distances from the EIDS sensor. The EIDS seismograms were all similarly conditioned using a 2 Hz to 10 Hz band-pass filter.

Table 6: Determination of $\log_{10}A_0$ from past events recorded on the EIDS seismograph.

Earthquake Date	Measured EIDS P arrival	Measured EIDS S arrival	EIDS S-P	Measured EIDS Amplitude A	Magnitude Estimated using FS03 M	Calculated EIDS $\log_{10}(A_0)$
14/06/2014 14:19	17.82	25.48	7.66	99198	3	1.996503
26/06/2014 11:02	17.63	45.34	27.71	678	2.4	0.43123
22/08/2014 08:34	37.56	43.62	6.06	6649	1.9	1.922756
22/08/2014 08:35	27.14	33.69	6.55	92100	2.7	2.26426
22/08/2014 08:38	21.63	28.42	6.79	137217	2.8	2.337408
03/01/2013 19:11	55.16	65.87	10.71	1422	1.6	1.5529
07/01/2013 18:41	60.16	71.28	11.12	822	1.3	1.614872
14/02/2013 23:03	15.7	34.76	19.06	3992	2.1	1.501191
05/01/2012 14:05	75.3	128.37	53.07	4691	4.3	-0.62873
10/04/2012 01:51	43.44	52.12	8.68	2440	1.4	1.98739
20/05/2012 17:58	50.12	59.56	9.44	3879	1.5	2.08872
19/08/2012 22:37	16.48	19.93	3.45	14340	1.5	2.656549
03/09/2012 15:03	15.13	34.44	19.31	14467	2.8	1.360378
19/09/2012 06:14	17.89	25.65	7.76	5905	1.6	2.17122
22/09/2012 23:59	40.45	46.17	5.72	1761	1	2.245759
23/09/2012 16:29	32.05	46.23	14.18	65547	3.2	1.616553
25/09/2012 03:05	22.88	44.51	21.63	2944	1.9	1.568938
03/12/2012 07:41	44.89	51.7	2447	9544	1.4	2.57973
04/12/2012 20:17	55.01	61.41	6.4	570212	3.2	2.556036
12/12/2012 10:36	53.69	60.33	6.64	20513	2.2	2.112029

Figure 17 shows the graph of $\log_{10}A_0$ plotted against the associated S-P time difference (extracted from Table 6: Determination of $\log_{10}A_0$ from past events recorded on the EIDS seismograph. Figure 17 also displays the line of best fit, calculated using linear regression of the plotting data, along with the slope, intercept, and correlation coefficient (R^2). **The R^2 value of 0.91 confirms that the assumed linear relationship is reasonably valid.**

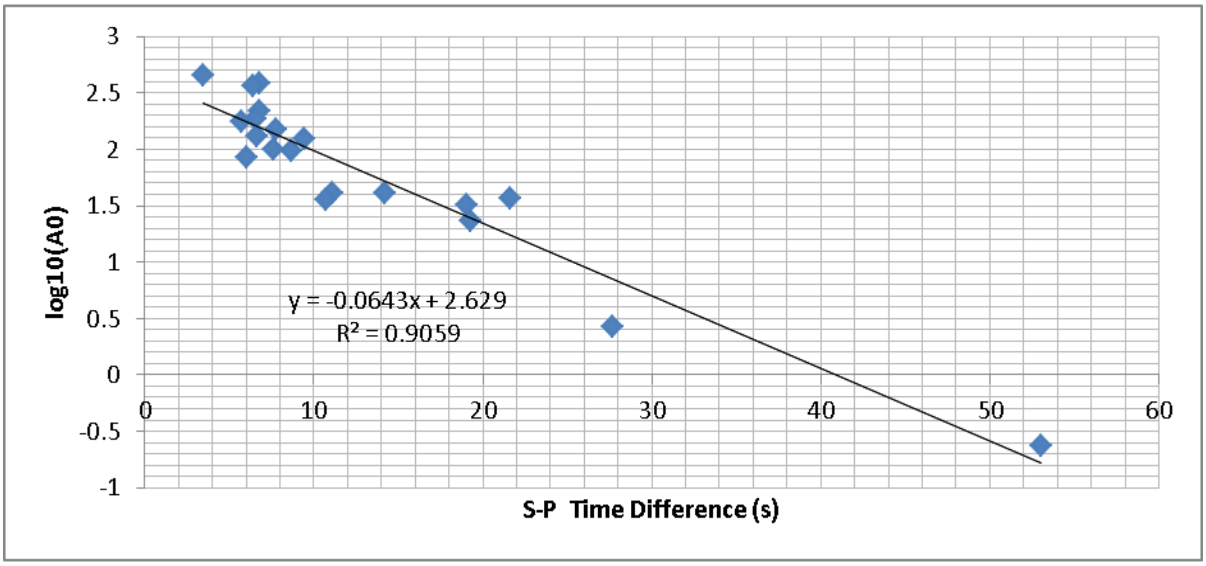

Figure 17: 23: $\log_{10}A_0$ Vs S-P

By substituting the slope and intercept values into Eq.1 and Eq.2 we arrive at the formula for EIDS magnitudes given in Eq.4.

$$M_{EIDS} = log_{10}A - (-0.064(S - P) + 2.63) \qquad \text{(Eq.4)}$$

Where:

M_{EIDS} is the Richter magnitude determined from an EIDS seismogram record;

A is the maximum amplitude of the EIDS seismogram record;

S is the arrival time of the S wave in seconds, and;

P is the arrival time of the P wave in seconds.

Example Usage

Figure 18 shows the seismogram of an earthquake that was recorded on station EIDS on 15 February 2015.

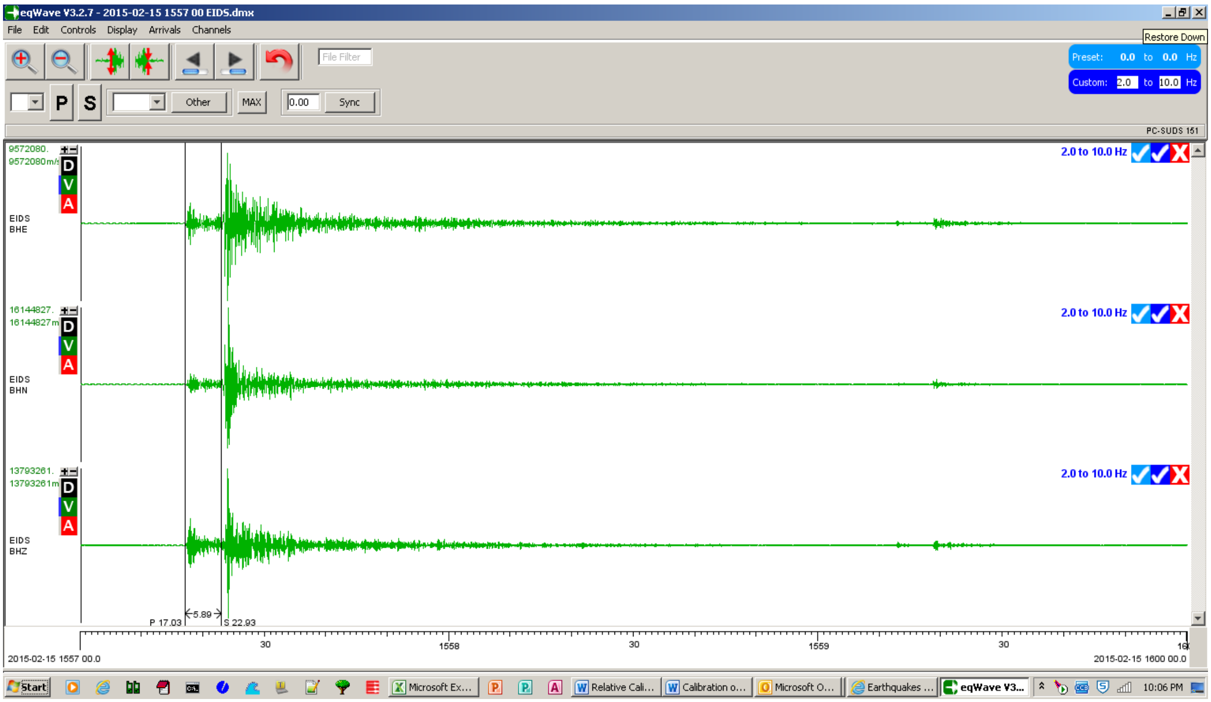

Figure 18: EIDS record of an earthquake.

From Figure 18 we can obtain the maximum amplitude (A = 13793261), the P wave arrival time (P = 17.03 s) and the S wave arrival time (S = 22.93 s); from which the time difference (S – P = 22.93 s) can be determined.

Inserting these values into Eq.4 we calculate a Richter magnitude of 4.9 (rounded to one decimal place).

Table 7 shows the results of some other similar calculations, for different earthquakes, along with the GA published magnitudes for the same events.

Table 7: Calculations of EIDS Richter magnitudes for some earthquakes.

Earthquake Date	Measured P arrival	Measured S arrival	S-P	EIDS Amplitude A	Calculated M_{EIDS} Magnitude	GA Published Magnitude
15/02/2015 15:57	17.03	22.93	5.9	13793261	4.9	5.1
15/02/2015 15:58	12.58	18.56	5.98	869195	3.7	
15/02/2015 16:40	43.7	49.25	5.55	278525	3.2	3.2
15/02/2015 17:37	13.18	19.15	5.97	907859	3.7	3.4
15/02/2015 18:06	14.56	20.54	5.98	125151	2.9	2.5
16/02/2015 05:56	58.18	64.14	5.96	1703875	4.0	4.0

Appendix E - Magnitude Calibration of BW1H for the Bowen 2016 Earthquake Sequence.

Introduction

In August 2016 a magnitude 5.8 earthquake occurred in the Whitsunday Passage east of Bowen and North of Airlie Beach. This was followed by many aftershocks over the next few months. The nearest seismic monitoring stations were the Urban Monitoring (UM) network stations in Bowen. There are two stations: one on soft basement (BW2S); and one on hard basement (BW1H).

The BW1H station provided relatively clean records of the main and aftershocks.

The locations of the earthquakes in the sequence formed a relatively tight group around the main event. Figure 19 shows the grouping pattern.

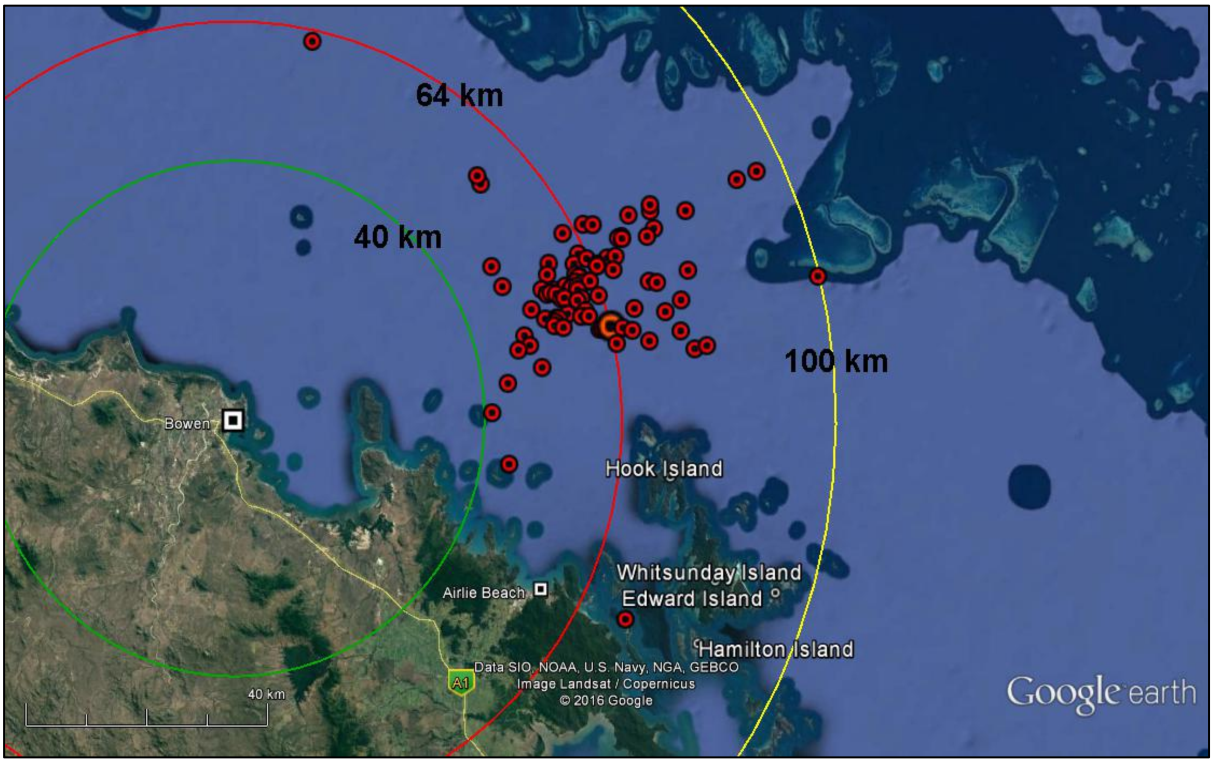

Figure 19: The grouping of the 2016 Bowen earthquake sequence.

The main event was located 64 km NNE of Bowen, with the other earthquakes ranging from 40 km to 100 km radial distance from Bowen.

The relative proximity of all earthquakes to Bowen meant that the radial attenuation of the seismic energy over that distance would vary only slightly; and it was assumed that any such slight attenuation would not adversely affect any logarithmic magnitude values determined within the 40 to 100 km range. It was therefore decided to calibrate the BW1H records against the Geoscience Australia (GA) published magnitudes, so that those records could be used to determine the magnitudes of those smaller events not analysed by GA.

The method of calibration was as follows.

Method of Calibration

Thirty three earthquakes with published GA magnitudes in the range from ML 2.1 to ML 5.8 were selected (See Table 8).

Table 8: List of earthquake magnitudes published by GA.

Date	Time	P	S	S-P	Amplitude 2-10 Hz	Published GA Mag	Calculated BW1H ML
2016-08-20	01:17	4654.46	4662.07	7.61	669	2.2	2.2
2016-08-19	17:03	61422.39	61430.16	7.77	697	2.1	2.2
2016-08-18	15:47	56863.64	56871.33	7.69	753	2.3	2.2
2016-08-19	22:41	81707.73	81715.41	7.68	1205	2.5	2.4
2016-08-18	17:17	62271.91	62279.60	7.69	1324	2.4	2.4
2016-08-19	11:15	40552.57	40560.20	7.63	1574	2.2	2.4
2016-08-20	20:11	72668.06	72675.76	7.70	1794	2.3	2.5
2016-08-18	15:05	54340.74	54348.38	7.64	1810	2.6	2.5
2016-08-20	00:53	3224.43	3232.12	7.69	1857	2.1	2.5
2016-08-18	13:57	50252.43	50260.39	7.96	2159	2.3	2.5
2016-08-19	23:56	86213.38	86220.91	7.53	2349	2.4	2.6
2016-08-18	16:23	58987.97	58995.55	7.58	2387	2.8	2.6
2016-08-18	05:54	21249.73	21257.29	7.56	2430	2.7	2.6
2016-08-18	10:06	36414.70	36422.36	7.66	2653	2.7	2.6
2016-08-19	20:40	74439.78	74447.37	7.59	2715	2.4	2.6
2016-08-18	15:52	57131.48	57138.86	7.38	2928	2.5	2.7
2016-08-18	07:35	27311.40	27319.08	7.68	2940	2.6	2.7
2016-08-18	09:23	33823.41	33830.84	7.43	2965	2.8	2.7
2016-08-18	05:57	21467.21	21474.69	7.48	3240	2.6	2.7
2016-08-18	05:36	20196.43	20203.14	6.71	3561	3.3	2.7
2016-08-20	07:10	25849.39	25857.21	7.82	3832	2.8	2.8
2016-08-18	21:38	77887.80	77895.31	7.51	4140	3.1	2.8
2016-08-20	16:46	60410.48	60418.09	7.61	9503	3.2	3.1
2016-08-18	05:09	18579.10	18586.66	7.56	9553	2.9	3.1
2016-08-18	14:03	50598.61	50606.19	7.58	9780	3.4	3.1
2016-08-18	04:36:53.28	16622.15	16629.53	7.38	10228	3.9	3.1
2016-08-18	05:23	19445.18	19452.59	7.41	22102	3.6	3.5
2016-08-18	09:30	34261.85	34269.63	7.78	22753	3.5	3.5
2016-08-18	08:56	32219.57	32227.10	7.53	40768	3.4	3.8
2016-08-18	04:39:52.05	16740.36	16747.92	7.56	42854	3.8	3.8
2016-08-18	05:30	19847.18	19854.69	7.51	52254	4.0	3.9
2016-08-18	18:27	66467.63	66474.96	7.33	128115	4.1	4.4
2016-08-18	04:30:08.43	16219.32	16227.00	7.68	973331	5.8	5.8

The amplitudes stated in Table 8 are those of the associated earthquake's S phase maximum, with a bandpass filter of 2 Hz to 10 Hz applied to the time series data.

The filtered amplitudes were then plotted against the published GA magnitudes as shown in Figure 20.

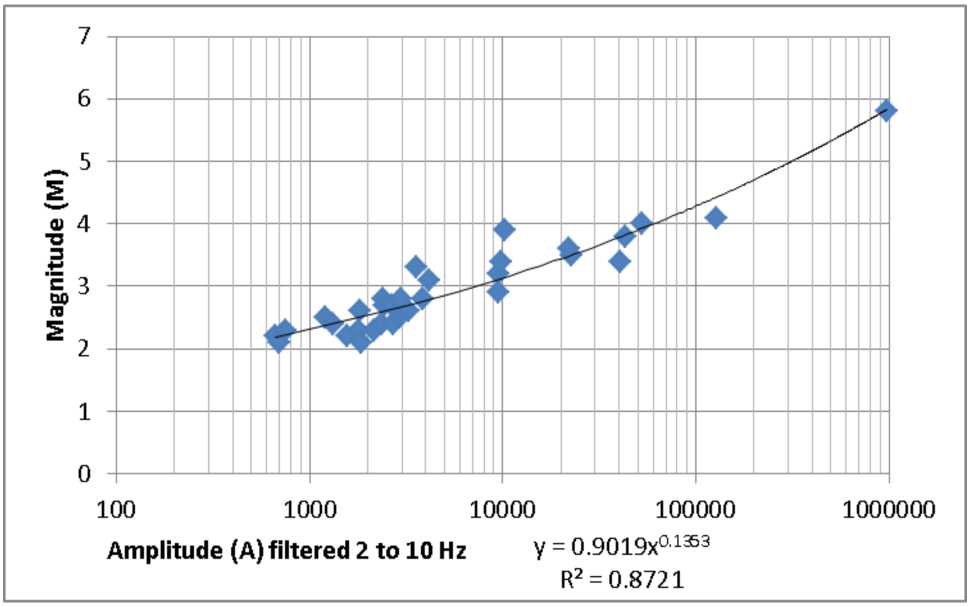

Figure 20: Filtered Amplitudes Vs Published Magnitudes.

A power curve was then fitted to the plotted data to determine the following relation.

$$M_{BW1H} = 0.9019 A_{BW1H}{}^{0.1353}$$

This relation has a correlation coefficient of 87%.

Although the use of the power relation parameters to four decimal places is not warranted (two decimal places would probably suffice), the full precision was maintained when determining the magnitudes of 2016 Bowen aftershocks not published by GA.

Verification of Calibration

The right hand column of Table 8 lists the M_{BW1H} values calculated using the power relation. This shows that the calculated magnitudes are typically accurate to one decimal place ±0.1, in the range from ML 2.0 up to ML 5.8, with occasional inaccuracies up to ±0.8.

Calibration Saturation

Inspection of Figure 20 indicates that the power relation is flattening out at the bottom end to become asymptotic between ML 2.0 and ML 1.5.

Therefore M_{BW1H} values in the range ML 1.5 to ML 2.0 will be overestimated, and values below that range should be ignored.

Appendix F - Method Used to Identify Bowen August 2016 ML 5.8 Aftershocks

As state in the CQSRG web page at http://cqsrg.org/, CQSRG's primary research aim is to monitor for, and catalogue, earthquakes in Eastern Central Queensland; in the region bounded (approximately) north to Mackay, South to the Sunshine Coast, west to Roma, and out to sea some hundreds of kilometres. The main reason for generally restricting research to that broad region is that it encompasses the earthquake detection capability of the main recording station operated by CQSRG – that is, the FS03 seismic monitoring station just west of Gin Gin, in the Bundaberg Regional area. When the Bowen August 2016 ML 5.8 event occurred it triggered the FS03 recorder, as did several of the aftershocks that occurred in the following weeks.

As the aftershock sequence progressed, the average magnitude of the events reduced. Consequently, after a short time, the aftershocks were no longer triggering on the CQSRG network. However, experience gained during analysis of the earlier, larger magnitude aftershocks indicated that the lesser magnitude aftershocks, of about ML 1.3 and above, could be unambiguously identified by visual inspection of the BW1H and BW2s station seismograms with a very high degree of reliability.

The key diagnostic features used to visually identify the aftershock recordings were:

- The consistent S-P times being confined to a precise spread within three standard deviations of the sequence average.
- The characteristic shape of the wave form (the wave form *signature*).
- Suitable and consistent choice of amplitude and time-scale gain settings on the seismogram viewer being used to visually inspect the seismogram records.

Analysis of S-P Times

In the first two days following the main earthquake Geoscience Australia published location solutions for 34 events (including the main event and aftershocks). The closest station to the events was BW1H, the Bowen hard site Queensland UMP station. Using the S and P arrival times picked from the BW1H records of the 34 published events the S-P times were obtained, averaged, and the sample standard deviation was derived. The results of this analysis are provided in Table 9.

Table 9: Statistical Analysis of Main event and aftershock S-P Times.

S-P Time	Statistic Description
7.6	Average S-P time for 34 events recorded on BW1H and verified by Geoscience Australia.
0.2	Sample standard deviation of the aftershock S-P times.
8.2	Upper S-P time expected for valid aftershocks.
6.9	Lower S-P time expected for valid aftershocks.

Based on the statistics listed in Table 9, individual events with S-P times greater than 8.2 s were treated with suspicion as being non-aftershock events. Extra analysis and inspection of the vast majority of these suspect events proved them to be exclusively extraction blasts from the Collinsville and Sonoma Coal Mines, 70 km south west of Bowen.

Many of the prospective "events" with S-P times less than 6.9 s, especially those with dramatically short S-P times, turned out on further inspection and analysis to be local social noise – as shown by not being present on the BW2S records. However, valid aftershock events were recorded with S-P times as low as 5.59 s.

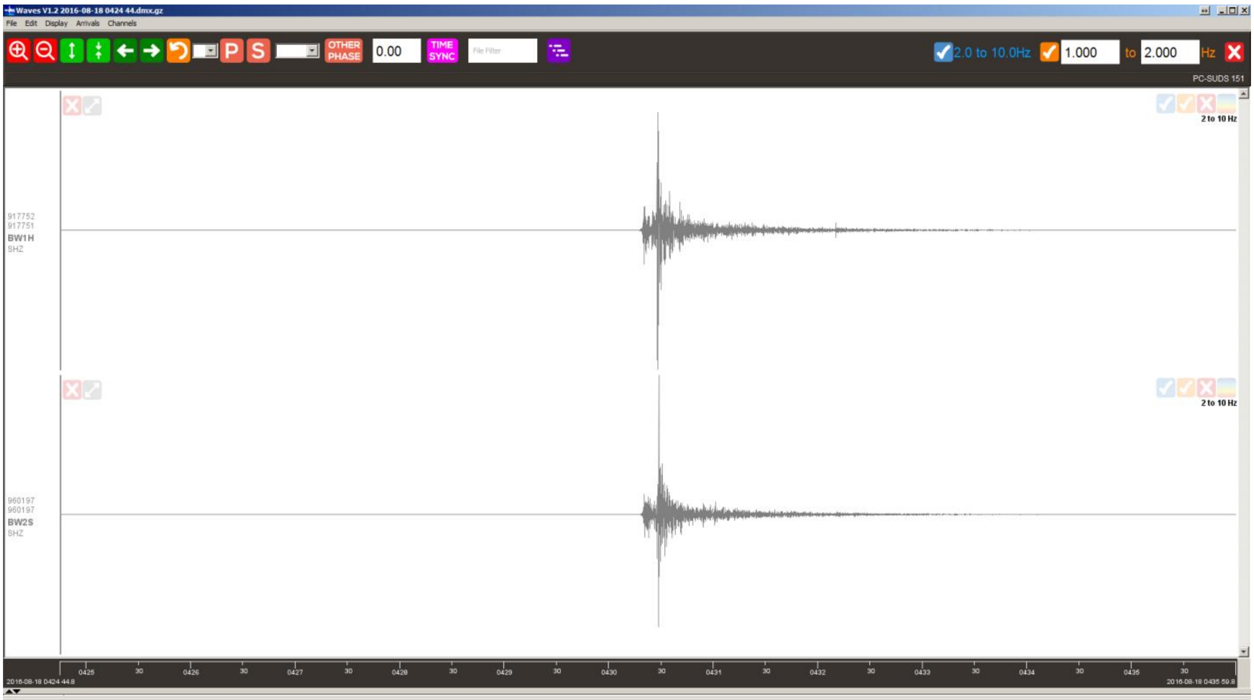

Figure 21: BW1H and BW2S Recordings of the Main ML 5.8 event.

The characteristic shape of the wave form

Figure 21 is the seismographic record of the main ML 5.8 earthquake event, as recorded on the BW1H and BW2S stations' vertical sensors, and as viewed on the Seismology Research Centre's (SRC) Waves V1.2 Seismic Waveform Analysis Software. The visual characteristics to note are:

- The S-P time, as previously mentioned.
- The impulsive nature of both the S and P arrivals.
- The rapid decay of the P train resulting in a single maximum amplitude P peak, and clean distinction of the subsequent S arrival.
- The rapid decay of the S train resulting in a single vertical line maximum S amplitude feature.

Observation of numerous verified aftershock records showed that these visual characteristics were invariably present in all valid aftershock records – even those of magnitudes less than ML 1.5; as can be seen in Figure 22, a BW1H/BW2S recording of an ML 1.3 aftershock.

Figure 22: Record of an ML 1.3 Aftershock on BW1H and BW2S.

Despite the signature of the P and S arrivals on both BW1H and BW2S stations being only just proud of the ambient noise, they can be readily distinguished on both stations (indicating that it is not a local noise event), and the S-P times for both stations are consistent with the expectation statistics. The magnitude of ML 1.3 was observed to be the lowest magnitude aftershock recording that could be reliably discriminated from the ambient background noise. However, it is considered that even the ML 1.3 events would only have been detected under ideal conditions, and that many valid aftershock events of this magnitude would have not been detected by this observational method. While Figure 21 and Figure 22 represent the two extremes of the magnitude range, the following Figure 23 and Figure 24 provide examples of mid-range aftershocks of ML 1.8, ML 2.2 and ML 2.6.

All three of the events in Figure 23 and Figure 24 have been located using data from multiple stations and verified as being valid aftershocks.

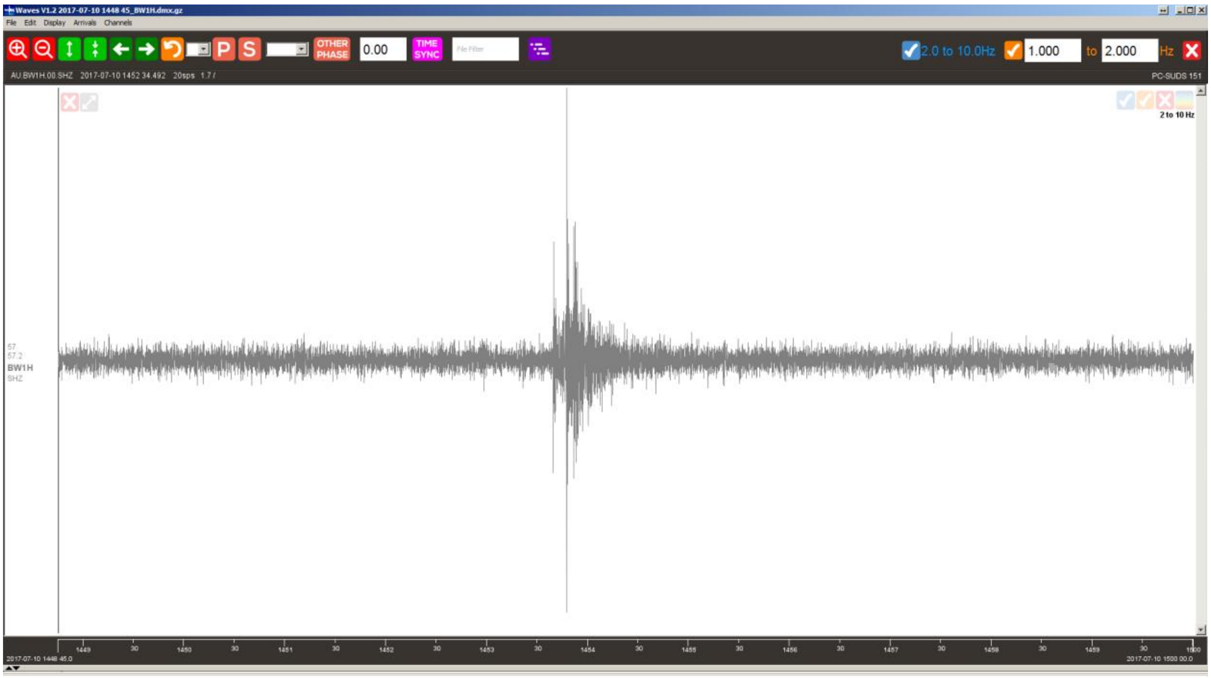

Figure 23: Example of an ML 1.8 aftershock

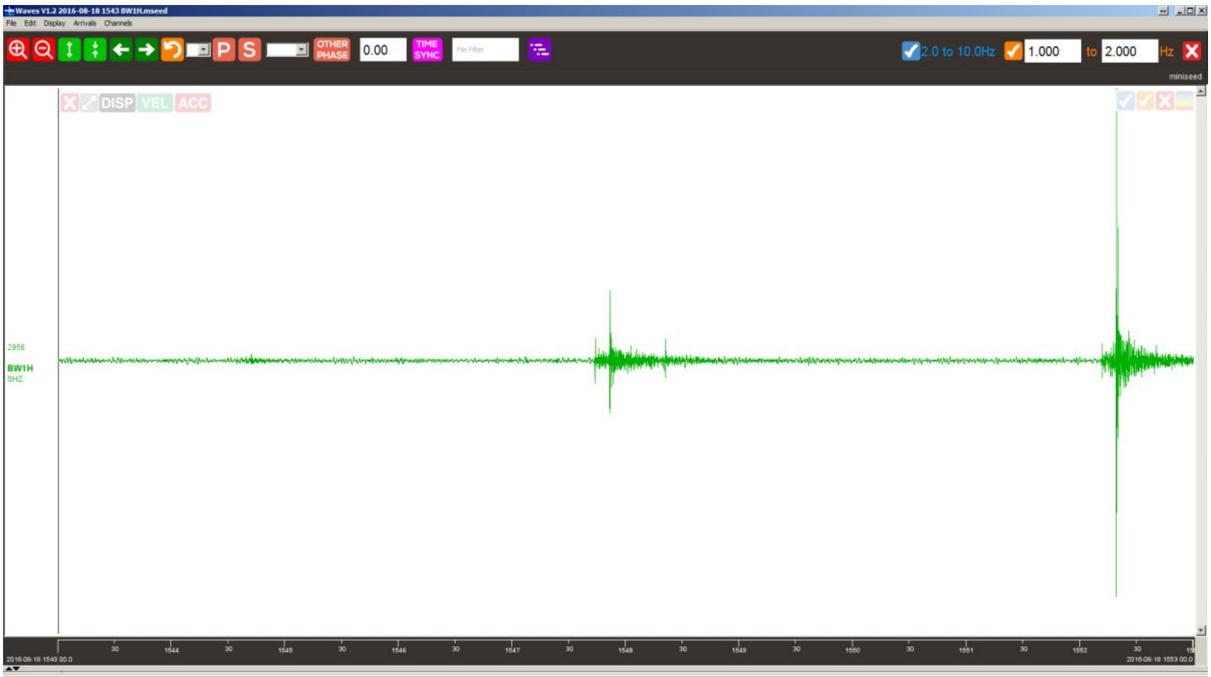

Figure 24: Example of ML 2.2 and ML 2.6 aftershocks.