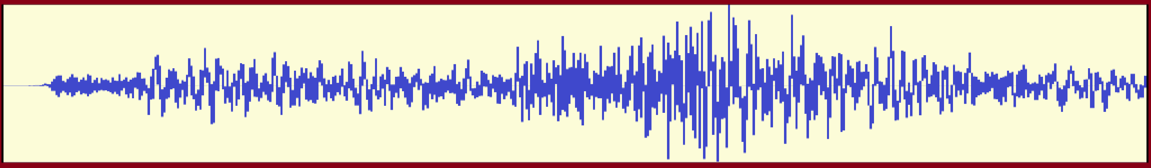
CENTRAL QUEENSLAND SEISMOLOGY RESEARCH GROUP (CQSRG)



CQSRG Seismological Report 2019

Edition 1.00

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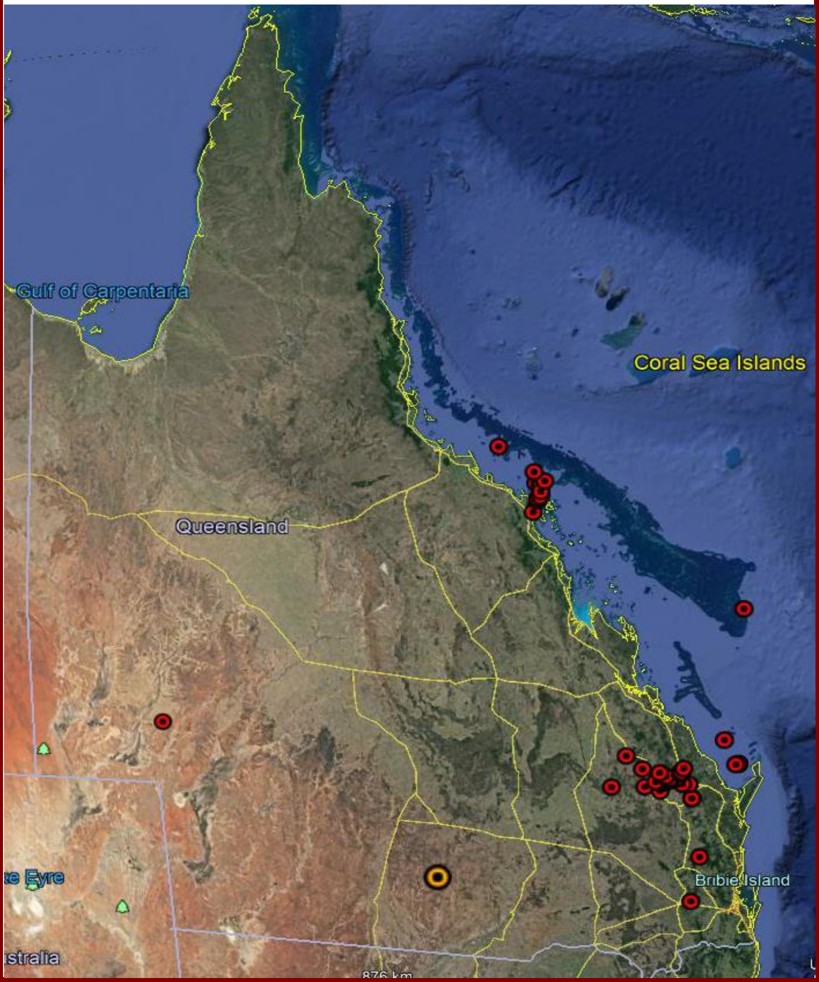
***Lead Seismologist, CQSRG*.**

Version 1.0



RESEARCHING EARTHQUAKES IN CENTRAL QUEENSLAND SINCE 2002.
Web site: http://cqsrg.org

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Edition control

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Versions 1.00

The original version.

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Introduction

This report details earthquakes detected and located by the Central Queensland Seismology Research Group (CQSRG) during the 2019 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 2019 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 2019

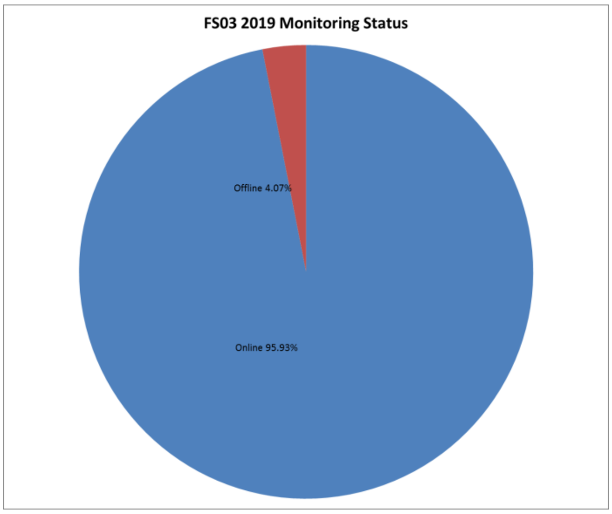

Figure 1: Percentage Uptime/Downtime of FS03 during 2019.

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 2019 calendar year the FS03 station was actively monitoring for seismic events greater than 95% 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 mainly comprised of data download time; except for a one day outage on 14 August.

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).

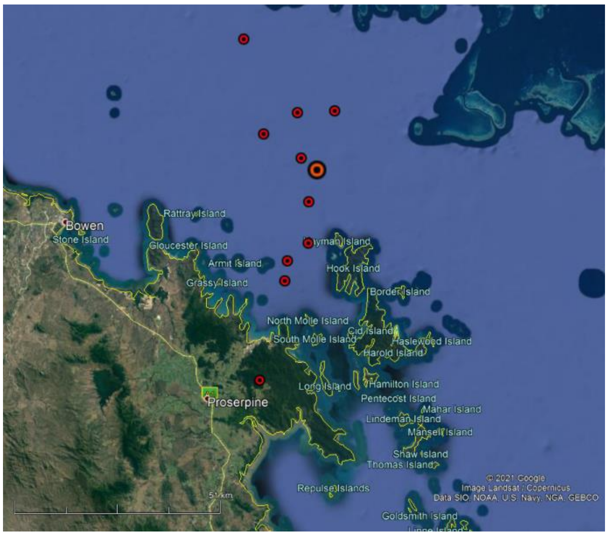

Figure 2: Bowen aftershocks that occurred in 2019, and were located by CQSRG, in relation to the August 2016 ML 5.8 earthquake (shown as orange marker).

During the 2019 calendar year 38 aftershocks ranging in magnitude from ML 2.8 down to ML 0.7 were detected by CQSRG; only 10 of which were located, due to lack of sufficient instrumental records.

Of those events that were detected, 10 provided sufficient recordings to be reliably located. A map showing locations of aftershocks that were located by CQSRG during 2019 is presented in Figure 2. This figure also shows the location of the main ML 5.8 August 2016 event.

Figure 3 shows a graphical plot of the 2016 Bowen sequence up to the end of 2019.

During the 2019 calendar year both the BW1H and BW2S monitoring stations in Bowen suffered from equipment failures; and this resulted in much fewer earthquake detections than what was expected based on previous observations.

BW1H, the more sensitive of the two stations, failed completely on 29 June, 2019. For the rest of the year the less sensitive BW2S station was used to detect events of ML 2.0 or greater. During this period it was not possible to reliably detect events of lower magnitude.

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

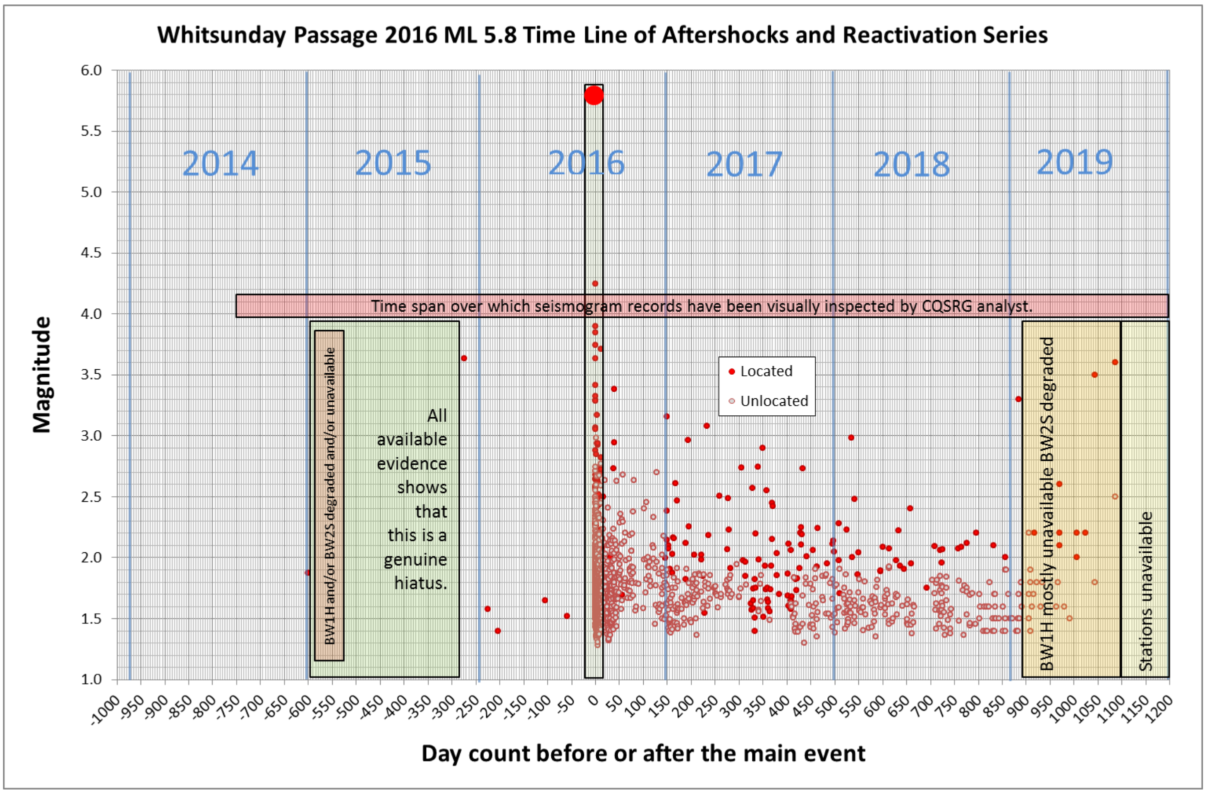

Figure 3: Events associated with the 2016 Bowen ML 5.8 earthquake, as detected and located by CQSRG.

It is clear from Figure 3 that the Bowen 2016 sequence is ongoing; and all indications are that it will continue into the 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 3. 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 38 Bowen earthquake events detected by CQSRG in 2019 is given in Table 1. Due to lack of available data only 10 of the listed events had mathematical locational analysis performed.

The method used 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 Whitsunday Passage area detected by CQSRG in 2019.

Magnitude (ML)	Date (UTC)	Time (UTC)	Latitude	Longitude
3.6	2019-08-09	02:55:16.67	-19.608	148.667
3.5	2019-06-28	06:17:54.88	-19.766	148.880
3.3	2019-01-18	17:24:04.14	-19.870	148.802
2.6	2019-04-14	19:58:34.00	-19.817	148.714
2.5	2019-08-09	02:55		
2.2	2019-02-21	20:41:12.56	-19.770	148.793
2.2	2019-04-14	08:20:17.27	-19.966	148.820
2.2	2019-05-20	07:10:49.02	-20.140	148.764
2.2	2019-06-07	10:11:35.62	-20.057	148.819
2.2	2019-02-10	11:01		
2.1	2019-04-15	14:44:55.58	-20.359	148.705
2.0	2019-05-20	07:20:14.59	-20.096	148.770
1.9	2019-02-13	11:36		
1.8	2019-01-24	05:14		
1.8	2019-02-13	00:07		
1.8	2019-02-27	13:51		
1.8	2019-03-10	19:37		
1.8	2019-04-11	11:39		
1.8	2019-06-28	16:03:30		
1.7	2019-01-20	13:59		
1.7	2019-02-09	08:24		
1.7	2019-02-20	19:52		
1.6	2019-01-26	05:06		
1.6	2019-02-17	18:08		
1.6	2019-03-06	18:31		
1.6	2019-04-08	15:17		
1.6	2019-04-24	23:12		
1.5	2019-01-02	20:43		
1.5	2019-01-04	21:17		
1.5	2019-01-05	05:01		
1.5	2019-01-07	19:56		
1.5	2019-01-18	21:58		
1.5	2019-01-21	22:07		
1.5	2019-02-09	08:13		
1.5	2019-05-06	04:42		
1.4	2019-01-15	18:55		
1.4	2019-01-17	14:04		
1.4	2019-01-18	19:24		
1.4	2019-02-13	17:10		

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 initiation of a new long-term seismicity regime for the Whitsunday Passage area.

Although the 28 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 2019

During 2019, 55 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 55 events listed in Table 2 include the 10 Bowen aftershock events that were sufficiently well recorded to have been located.

An additional 28 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 28 events have not been included in the main CQSRG Earthquake Catalogue, but are included in a CQSRG Supplementary Catalogue, listed in Table 1, and shown in Figure 3.

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, numerous 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).

Table 2: Earthquake Events Detected, Located, and Catalogued by CQSRG during 2019.

Date (UTC)	Time (UTC)	Longitude	Latitude	Depth (km)	Magnitude (ML)	Place	Comment
2019-12-29	20:42:19.39	151.460	-25.243	10	1.9	Mt Perry	20 km SW Mt Perry. Reviewed 2020-01-02.
2019-12-28	17:04:14.49	152.906	-24.751	10	1.9	Bundaberg	58 km E Bundaberg. Reviewed 2020-01-02.
2019-12-27	09:34:24.31	152.073	-25.486	10	1.0	Biggenden	4 km NE Biggenden. Reviewed 2020-01-02. Ambiguous 2 station location.
2019-12-27	09:29:55.47	152.073	-25.486	10	0.9	Biggenden	4 km NE Biggenden. Reviewed 2020-01-02. One station location. Same characteristics as 0934 event.

Date (UTC)	Time (UTC)	Longitude	Latitude	Depth (km)	Magnitude (ML)	Place	Comment
2019-12-27	10:24:02.48	151.873	-25.230	10	0.5	Mt Perry	24 km E Mt Perry. Reviewed 2020-01-02. Ambiguous 2 station location.
2019-12-26	13:23:47.56	152.906	-24.751	10	1.5	Bundaberg	58 km E Bundaberg. Reviewed 2020-01-01. Foreshock of 2019-12-28 1704.
2019-12-26	09:56:50.86	152.852	-24.770	10	1.4	Bundaberg	52 km E Bundaberg. Reviewed 2020-01-01. Foreshock of 2019-12-28 1704.
2019-12-22	07:13:38.10	151.425	-25.056	10	1.8	Mt Perry	26 km NW Mt Perry. Reviewed 2019-12-24.
2019-10-24	16:27:55.96	141.182	-24.755	10	3.2	Betoota	115 km NNE Betoota. Reviewed 2019-10-25.
2019-10-16	14:36:30.50	151.456	-25.399	10	1.6	Mundubbera	26 km NE Mundubbera. Reviewed 2019-10-17.
2019-10-04	01:07:05.48	152.747	-21.861	10	3.6	Coral Sea	250 km NE Yeppoon. Reviewed 2019-10-04.
2019-09-21	20:51:07.62	151.876	-24.934	10	0.6	Gin Gin	10 km NW Gin Gin. Reviewed 2019-09-21
2019-09-12	17:53:12.31	151.824	-25.033	10	0.4	Gin Gin	15 km W Gin Gin. Reviewed 2019-09-13.
2019-09-12	17:52:30.00	151.824	-25.033	10	-0.1	Gin Gin	15 km W Gin Gin. Reviewed 2019-09-13.
2019-09-10	04:37:30.18	152.600	-24.300	10	2.2	Lady Elliot Island	Off shore NE Bundaberg. Reviewed 2019-09-10.
2019-09-10	12:16:09.61	151.850	-25.002	10	1.4	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:16:31.00	151.850	-25.002	10	0.9	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:45:08.15	151.848	-25.015	10	0.8	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:44:02.00	151.848	-25.020	10	0.0	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-08-26	12:29:12.18	151.997	-25.226	10	1.6	Wallaville	17 km S Wallaville. Reviewed 2019-08-27.
2019-08-22	11:39:50.95	150.763	-24.789	10	1.7	Monto	37 km WNW Monto. Reviewed 2019-08-23.
2019-08-09	02:55:16.67	148.667	-19.608	10	3.6	Bowen	63 km NE Bowen. Reviewed 2021-02-05.
2019-08-03	17:38:40.68	151.091	-25.012	10	1.8	Monto	17 km S Monto. Reviewed 2019-08-04.
2019-08-01	01:22:10.90	133.665	-19.961	10	5.3	Tennant Creek	65 km SW Tennant Creek. Reviewed 2019-08-01. MW Mag provided by GA.
2019-07-29	01:56:49.46	151.361	-25.231	10	1.8	Eidsvold	29 km NE Eidsvold. Reviewed 2019-07-29.
2019-07-24	18:21:43.05	151.594	-25.164	10	0.9	Mt Perry	5 km NW Mt Perry. Reviewed 2019-07-25.

Date (UTC)	Time (UTC)	Longitude	Latitude	Depth (km)	Magnitude (ML)	Place	Comment
2019-07-24	18:20	151.594	-25.164	10	0.0	Mt Perry	5 km NW Mt Perry. Foreshock of 18:21 event. Reviewed 2019-07-25.
2019-06-28	06:17:54.88	148.880	-19.766	10	3.5	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 58 km NNE Airlie Beach. Reviewed 2019-06-29.
2019-06-24	01:40:25.16	151.610	-25.015	10	0.8	Mt Perry	2 km W Mt Perry. Reviewed 2019-06-29.
2019-06-10	17:01:14.94	151.158	-25.344	10	1.3	Eidsvold	5 km NE Eidsvold. Reviewed 2019-06-13.
2019-06-07	10:11:35.62	148.819	-20.057	10	2.2	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 26 km NNE Airlie Beach. Reviewed 2019-06-30.
2019-05-25	02:37:40.06	151.605	-25.195	10	1.4	Mt Perry	4 km SW Mt Perry. Reviewed 2019-06-01.
2019-05-20	07:10:49.02	148.764	-20.140	10	2.2	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 15 km NNE Airlie Beach. Reviewed 2019-05-21.
2019-05-20	07:20:14.59	148.770	-20.096	10	2.0	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 20 km NNE Airlie Beach. Reviewed 2019-05-21.
2019-05-13	11:46:55.04	152.304	-26.595	10	2.4	Nanango	31 km ENE Nanango. Reviewed 2019-05-14.
2019-05-09	14:03:42.59	151.538	-25.217	10	1.9	Mt Perry	12 km SW Mt Perry. Reviewed 2019-05-10.
2019-04-24	01:03:08.01	151.519	-25.223	10	0.5	Mt Perry	14 km SW Mt Perry. Reviewed 2019-04-24.
2019-04-18	11:23:28.68	151.553	-25.108	10	1.2	Mt Perry	12 km NW Mt Perry. Reviewed 2019-04-21.
2019-04-15	14:44:55.58	148.705	-20.359	10	2.1	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 10 km S Airlie Beach. 14 km NE Proserpine. Reviewed 2019-05-03.
2019-04-14	19:58:34.00	148.714	-19.817	10	2.5	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 50 km N Airlie Beach. Reviewed 2019-05-03.
2019-04-14	08:20:17.27	148.820	-19.966	10	2.2	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 35 km NNE Airlie Beach. Reviewed 2019-05-03.
2019-03-26	11:43:56.83	151.489	-25.234	10	1.3	Mt Perry	17 km SW Mt Perry. Reviewed 2019-03-28.
2019-03-26	11:42:48.57	151.491	-25.233	10	0.7	Mt Perry	17 km SW Mt Perry. Reviewed 2019-03-28.
2019-03-22	16:24:01.02	151.542	-25.216	10	0.7	Mt Perry	11 km SW Mt Perry. Reviewed 2019-03-24.
2019-03-09	17:25:31.16	152.196	-27.475	10	3.3	Gatton	13 km NW Gatton. Reviewed 2019-03-10
2019-02-24	18:43:06.78	147.102	-27.435	10	3.4	Morven	112 km S Morven; 113 E Wyandra; 143 km SE Charleville. Reviewed 2019-02-25.

Date (UTC)	Time (UTC)	Longitude	Latitude	Depth (km)	Magnitude (ML)	Place	Comment
2019-02-21	20:41:12.56	148.793	-19.770	10	2.2	Bowen	Aftershock of 2016-08-18 04:30 event. 63 km NE Bowen. Reviewed 2019-02-22.
2019-02-16	07:23:44.57	151.533	-25.219	10	1.2	Mt Perry	12 km SW Mt Perry. Reviewed 2019-02-16.
2019-02-11	00:30:39.06	151.743	-25.148	10	1.0	Mt Perry	10 km NE Mt Perry. Reviewed 2019-02-12.
2019-01-22	08:55:34.09	151.629	-25.144	10	0.6	Mt Perry	4 km N Mt Perry. Reviewed 2019-01-23.
2019-01-18	17:24:04.14	148.802	-19.870	10	3.3	Airlie Beach	Aftershock of 2016-08-18 04:30 event. 45 km N Airlie Beach. Reviewed 2019-01-24.
2019-01-17	05:00:02.00	151.646	-25.165	10	1.1	Mt Perry	2 km N Mt Perry. Reviewed 2019-01-23.
2019-01-13	07:42:58.66	151.489	-25.234	10	1.4	Mt Perry	17 km SW Mt Perry. Reviewed 2019-01-23.
2019-01-12	20:46:52.11	147.965	-19.171	10	1.9	Ayr	74 km NE Ayr. Reviewed 2019-01-24.
2019-01-05	22:05:32.83	150.517	-25.405	10	2.8	Cracow	24 km SE Cracow. Reviewed 2019-01-23.
2019-12-29	20:42:19.39	151.460	-25.243	10	1.9	Mt Perry	20 km SW Mt Perry. Reviewed 2020-01-02.
2019-12-28	17:04:14.49	152.906	-24.751	10	1.9	Bundaberg	58 km E Bundaberg. Reviewed 2020-01-02.
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2019-12-27	10:24:02.48	151.873	-25.230	10	0.5	Mt Perry	24 km E Mt Perry. Reviewed 2020-01-02. Ambiguous 2 station location.
2019-12-26	13:23:47.56	152.906	-24.751	10	1.5	Bundaberg	58 km E Bundaberg. Reviewed 2020-01-01. Foreshock of 2019-12-28 1704.
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2019-10-24	16:27:55.96	141.182	-24.755	10	3.2	Betoota	115 km NNE Betoota. Reviewed 2019-10-25.
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2019-10-04	01:07:05.48	152.747	-21.861	10	3.6	Coral Sea	250 km NE Yeppoon. Reviewed 2019-10-04.
2019-09-21	20:51:07.62	151.876	-24.934	10	0.6	Gin Gin	10 km NW Gin Gin. Reviewed 2019-09-21

Date (UTC)	Time (UTC)	Longitude	Latitude	Depth (km)	Magnitude (ML)	Place	Comment
2019-09-12	17:53:12.31	151.824	-25.033	10	0.4	Gin Gin	15 km W Gin Gin. Reviewed 2019-09-13.
2019-09-12	17:52:30.00	151.824	-25.033	10	-0.1	Gin Gin	15 km W Gin Gin. Reviewed 2019-09-13.
2019-09-10	04:37:30.18	152.600	-24.300	10	2.2	Lady Elliot Island	Off shore NE Bundaberg. Reviewed 2019-09-10.
2019-09-10	12:16:09.61	151.850	-25.002	10	1.4	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:16:31.00	151.850	-25.002	10	0.9	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:45:08.15	151.848	-25.015	10	0.8	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-09-10	12:44:02.00	151.848	-25.020	10	0.0	Gin Gin	10 km W Gin Gin. Reviewed 2019-09-11.
2019-08-26	12:29:12.18	151.997	-25.226	10	1.6	Wallaville	17 km S Wallaville. Reviewed 2019-08-27.

2019 Statistical Summary

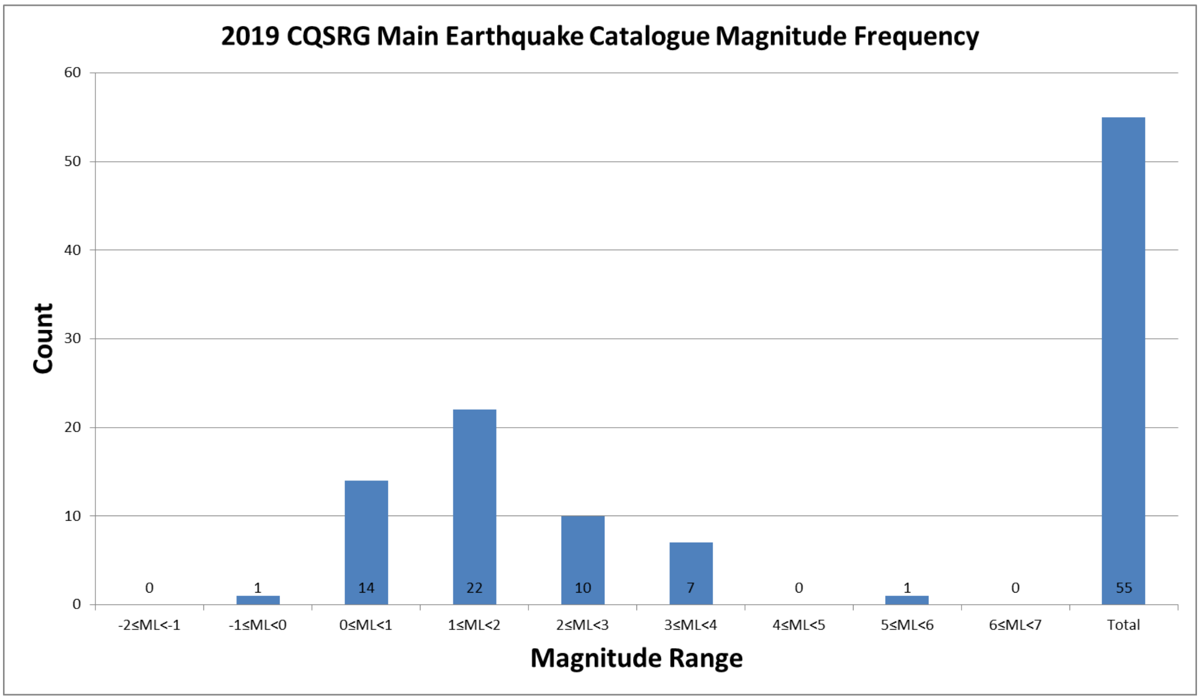

Figure 4: Magnitude frequency count for earthquakes in the main CQSRG 2018 Catalogue.

Figure 4 provides a graphical representation of the frequency of magnitude spread **for earthquake events listed in the main 2019 CQSRG Catalogue (Table 2)**.

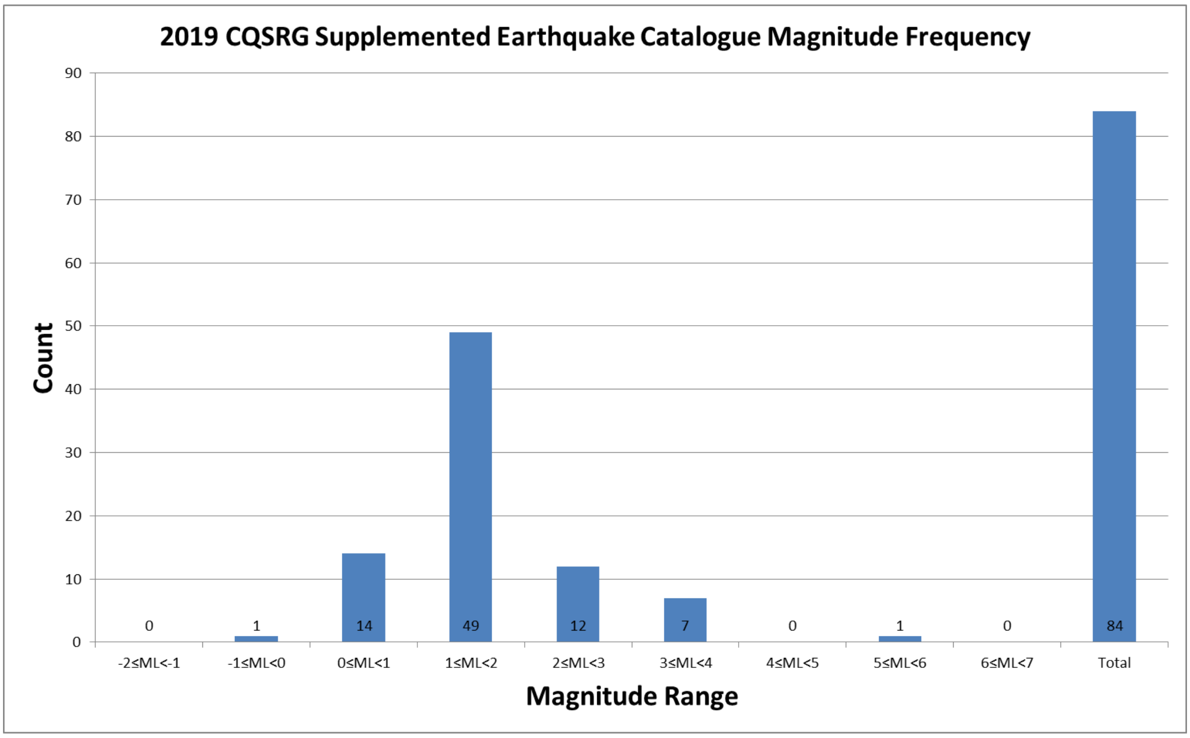

Figure 5: Magnitude frequency count for earthquakes in the supplemented CQSRG 2018 Catalogue, which includes the unlocated Bowen earthquakes.

Figure 5 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 shows the additional 28 unlocated earthquake events that were detected in the Whitsunday Passage, but omitted from the main CQSRG Earthquake Catalogue.

Figure 6 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 past five years 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 and 2016.

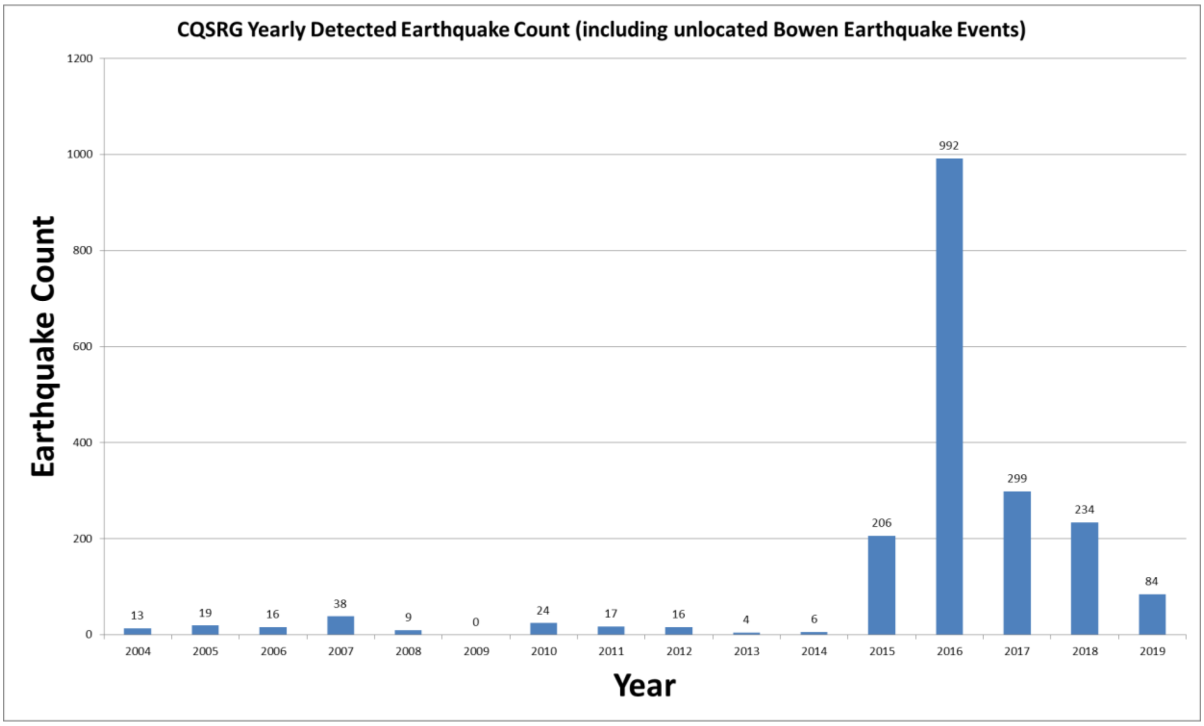

Figure 6: Yearly count of earthquakes detected by CQSRG

The five 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 is probably the second largest earthquake to have been recorded on the East coast of Mainland Australia in modern times.

2019 Earthquake Maps

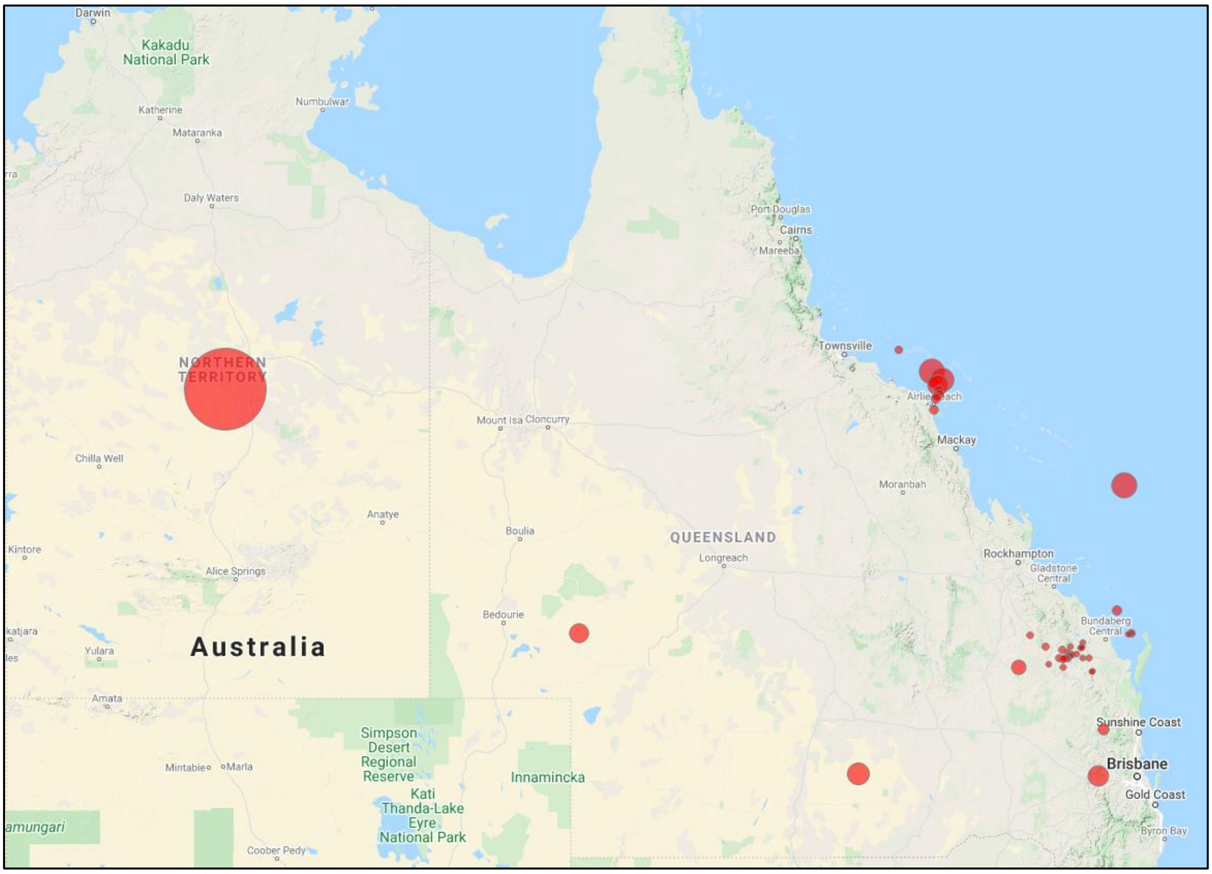

Figure 7: Broad view of earthquakes located in 2019 by CQSRG.

Figure 7 is a broad-view map of the 55 earthquakes located and entered into its Main Earthquake catalogue by CQSRG in 2019. An additional 28 unlocated events were entered into the CQSRG Supplementary Catalogue, and these are not shown in Figure 7.

It should be noted that the earthquakes located in the South-West and some in the North-East of the Queensland were not directly detected by CQSRG monitoring stations, but were notified by Geoscience Australia. These were, however, independently confirmed and located by CQSRG.

The events in the North-East (in the Bowen area, Cairns area, and in the Coral Sea) 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.

The two events in the South-West region were reported by Geoscience Australia and CQSRG subsequently gathered data from non-CQSRG monitoring stations to perform locational analysis.

It should not be inferred from the clustering and distributed nature of the earthquake events shown in Figure 7 that small earthquake events did not occur in other parts of Queensland. However, no other Queensland earthquake events other than those shown in Figure 7 were reported by Geoscience Australia during the 2019 calendar year.

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

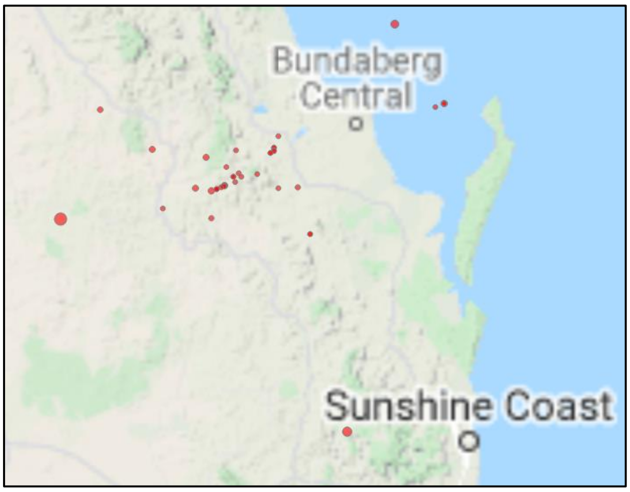

Figure 8: Earthquakes located by CQSRG during 2019 in the Central Queensland Coastal Area.

Figure 8 provides a focused view of earthquakes located by CQSRG in 2019 in the Central Queensland Coastal region.

None of these events are listed in Geoscience Australia's Earthquake database. The magnitudes of those events represented by the small markers range from ML -0.1 to ML 1.9. The three larger markers represent earthquakes of ML 2.2, ML 2.4, and ML 2.8.

The author regards this apparent clustering of earthquake events in this confined region as being an artefact caused by the earthquake detection efforts of the Central Queensland Seismology Research Group (CQSRG). 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 8 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 8, 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.

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

Where:

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

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 $\log_{10}A_0$ 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 9 shows the graph of $\log_{10}A_0$ plotted against the associated S-P time difference (extracted from Table 3).

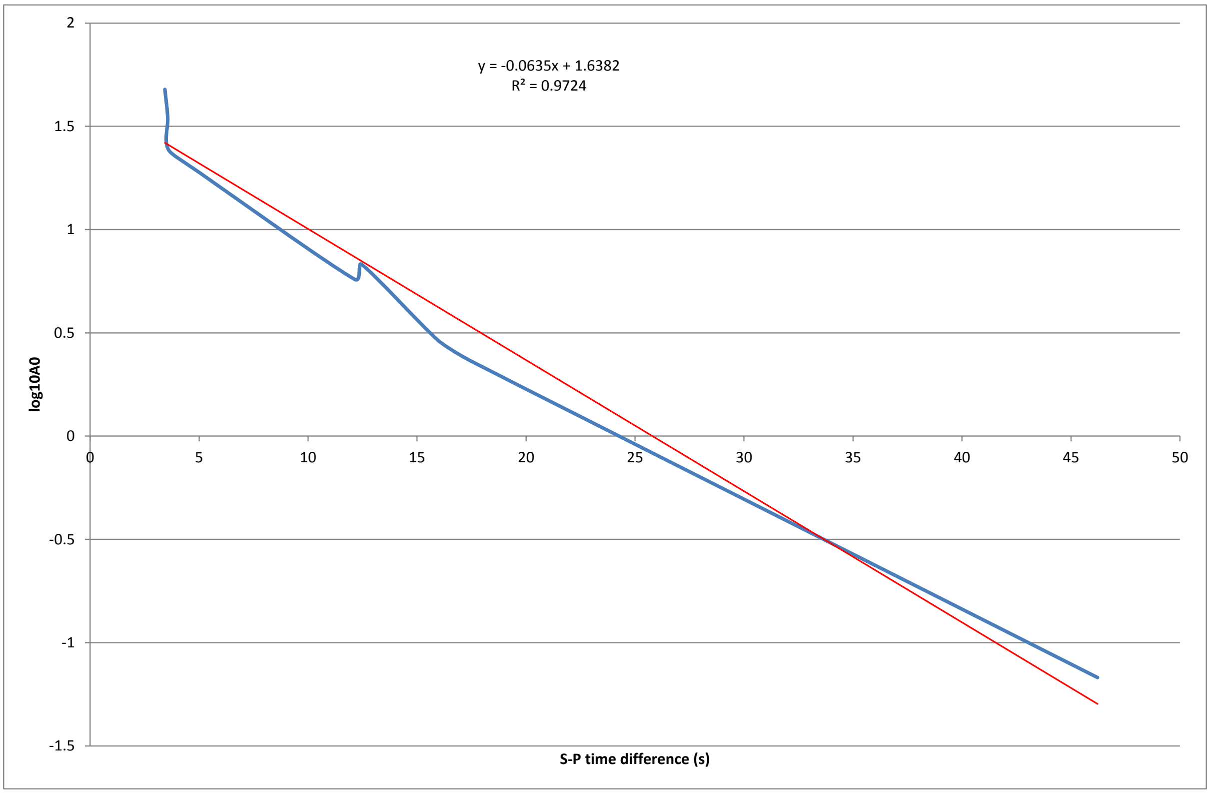

Figure 9: log10A0 Vs S-P.

Figure 9 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 9, 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 10 shows the seismogram of an earthquake that was recorded on station FS03 on 26 October 2012.

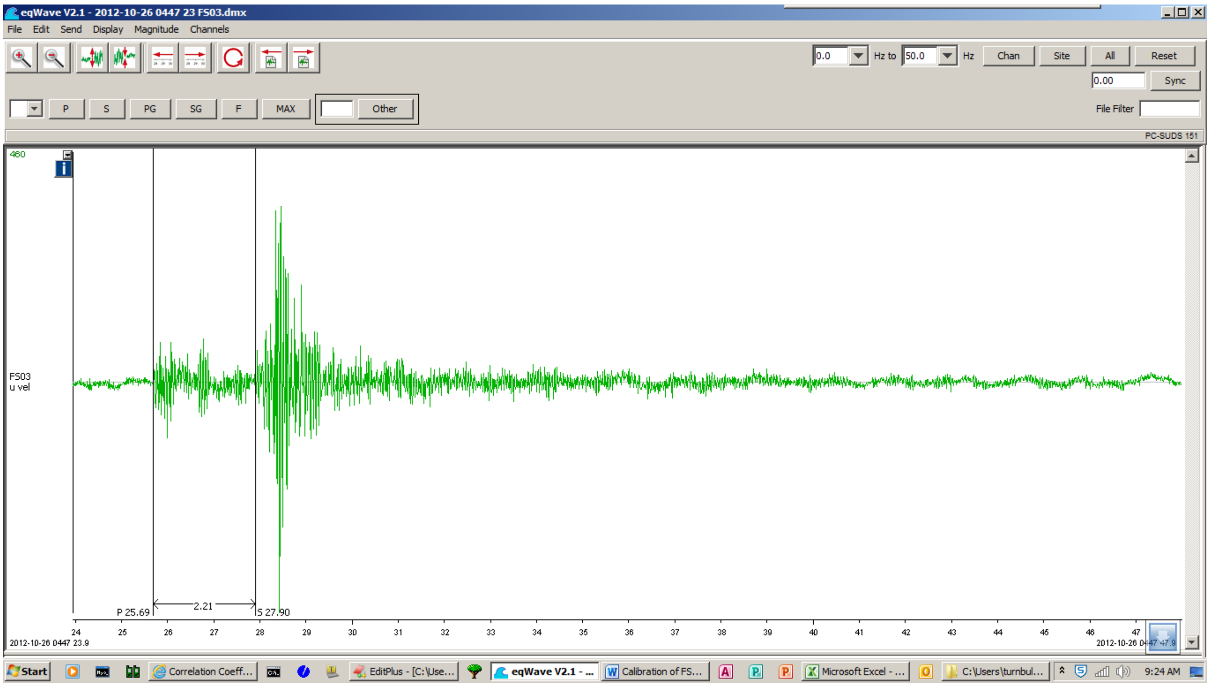

Figure 10: FS03 record of an earthquake.

From Figure 10 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 11, Figure 12, Figure 13, and Figure 14 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.

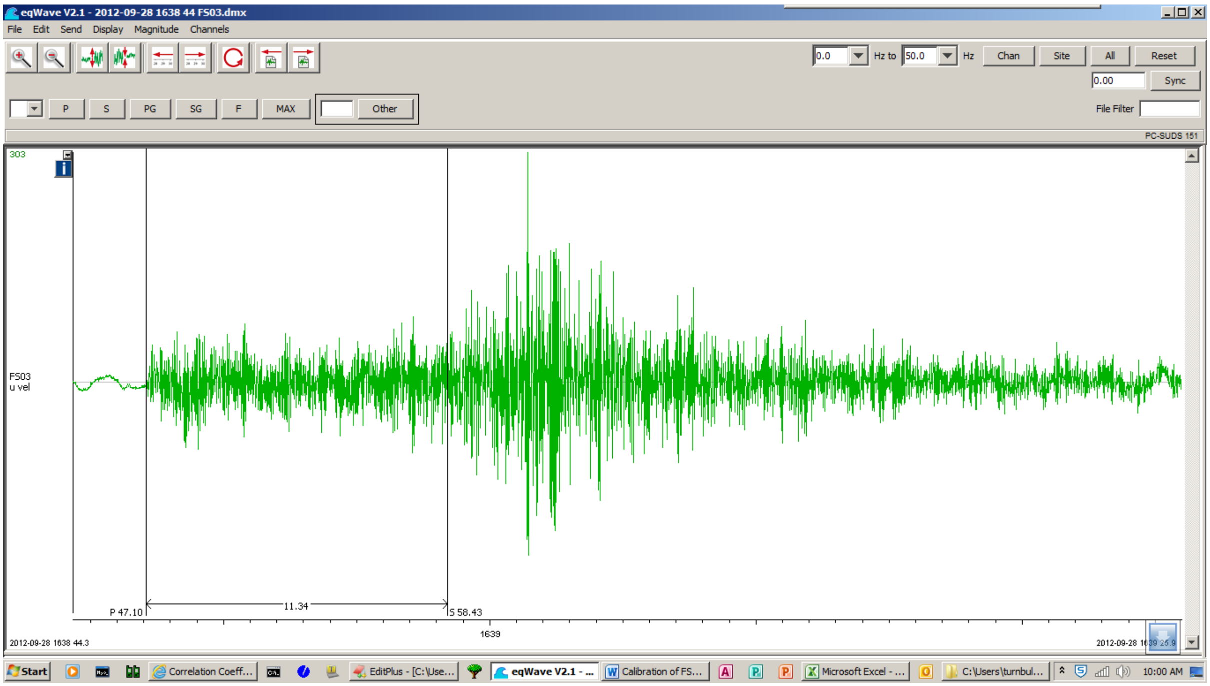

Figure 11: Earthquake recorded on FS03 on 28 September 2012.

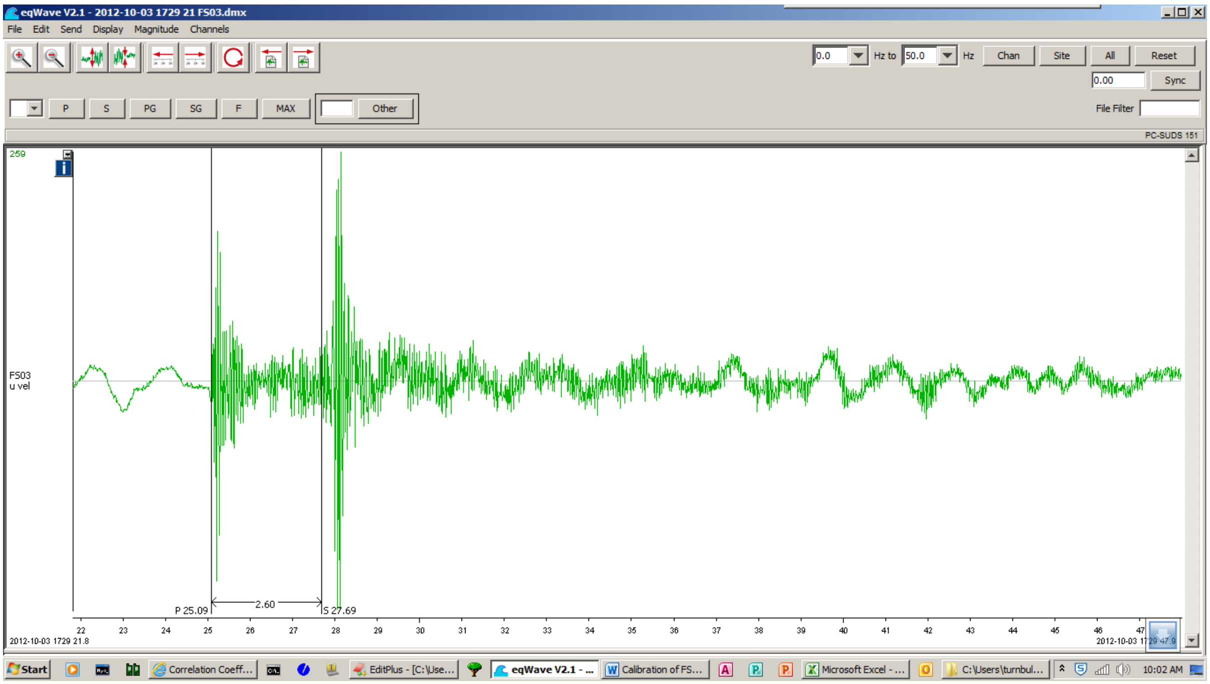

Figure 12: Earthquake recorded on FS03 on 3 October 2012.

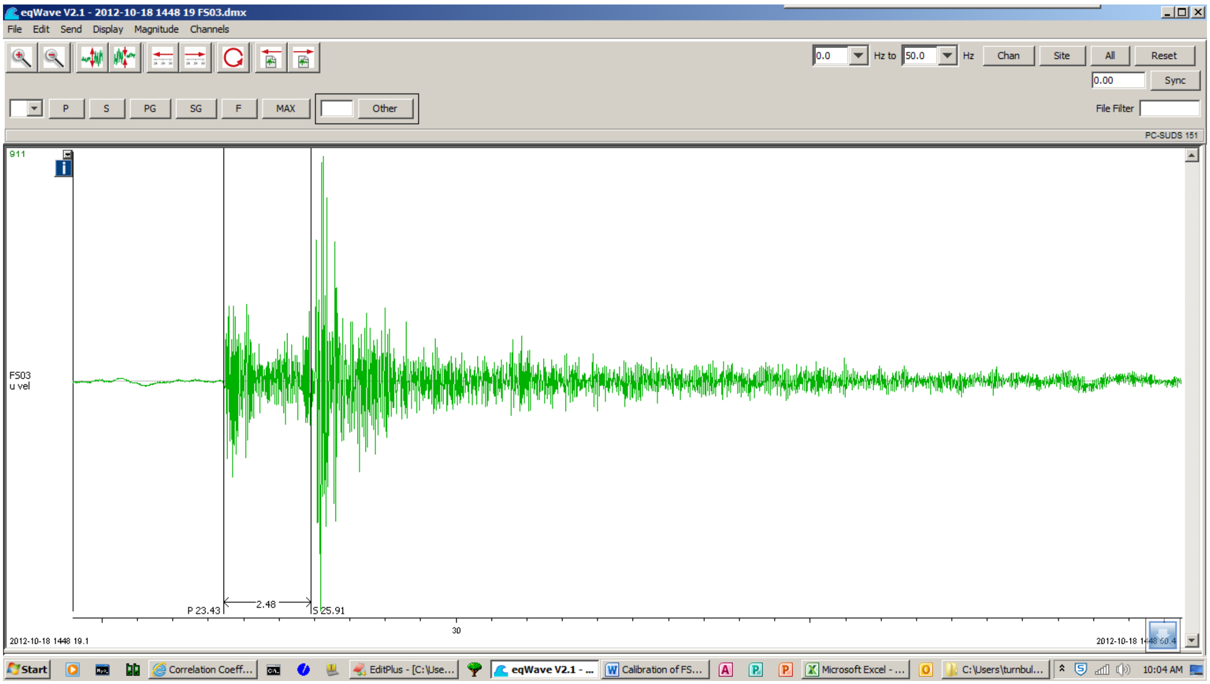

Figure 13: Earthquake recorded on FS03 on 18 October 2012.

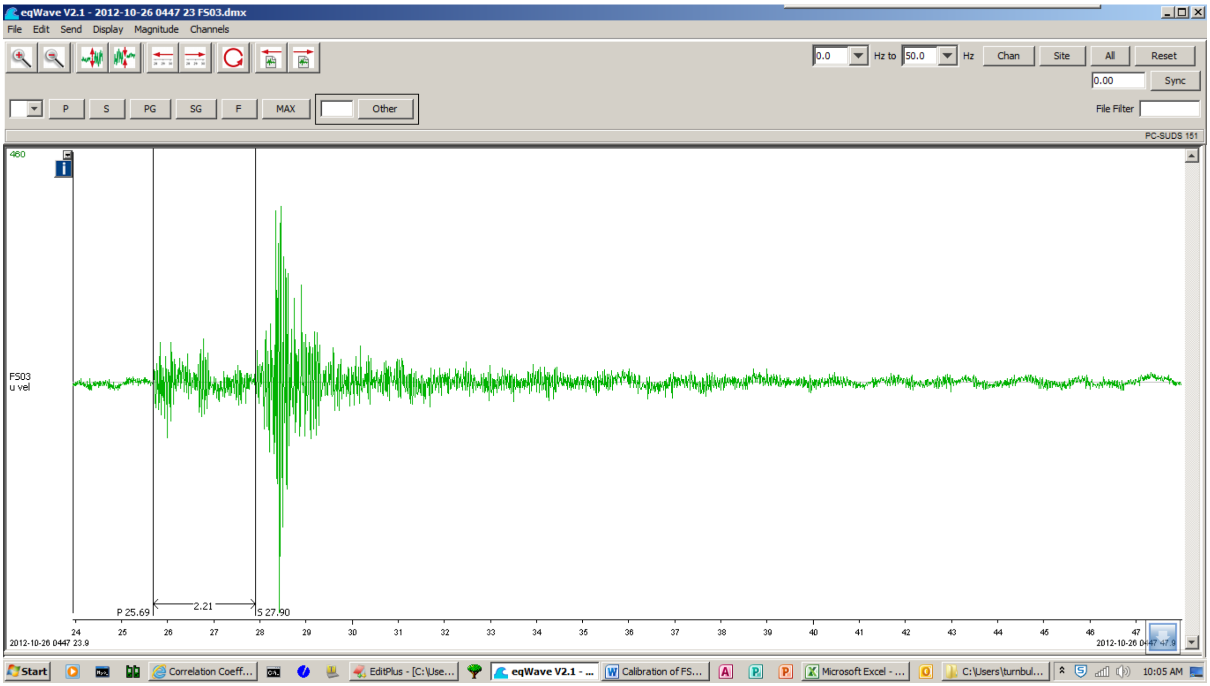

Figure 14: Earthquake recorded on FS03 on 26 October 2012.

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 15 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 15 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.**

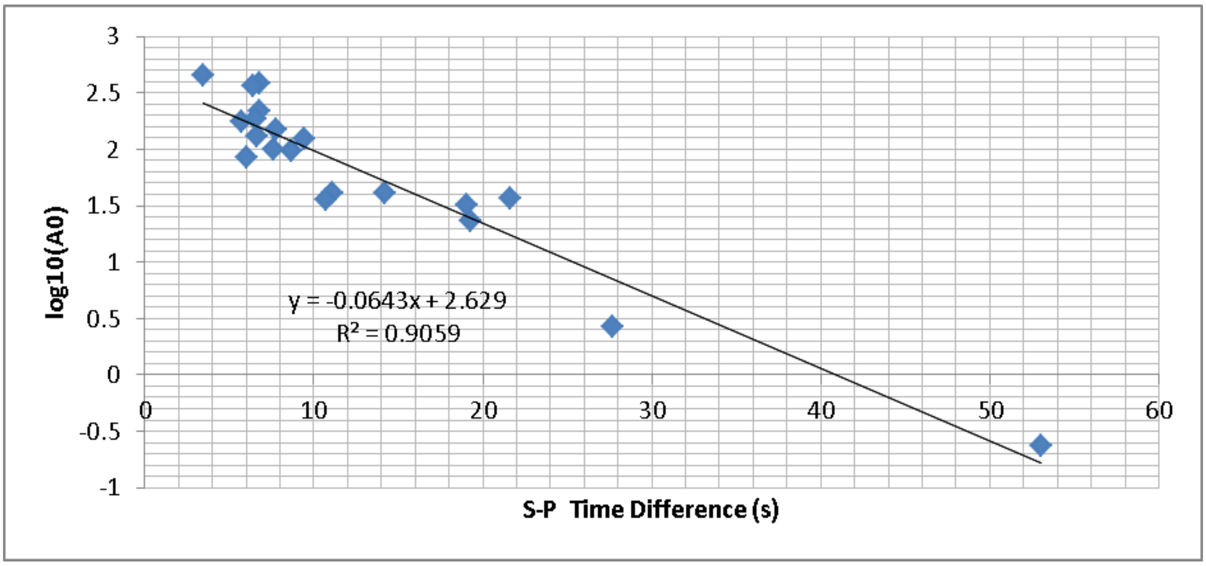

Figure 15: 23: $\log_{10}A_0$ Vs S-P

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

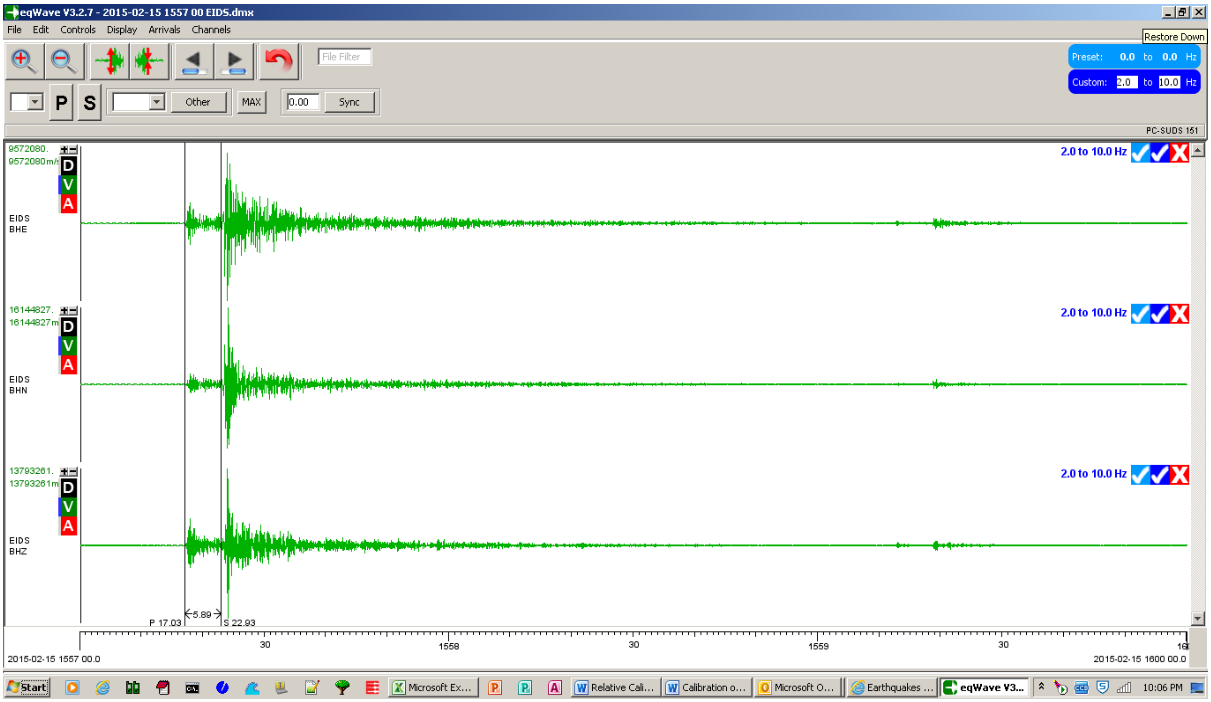

Figure 16: EIDS record of an earthquake.

From Figure 16 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 17 shows the grouping pattern.

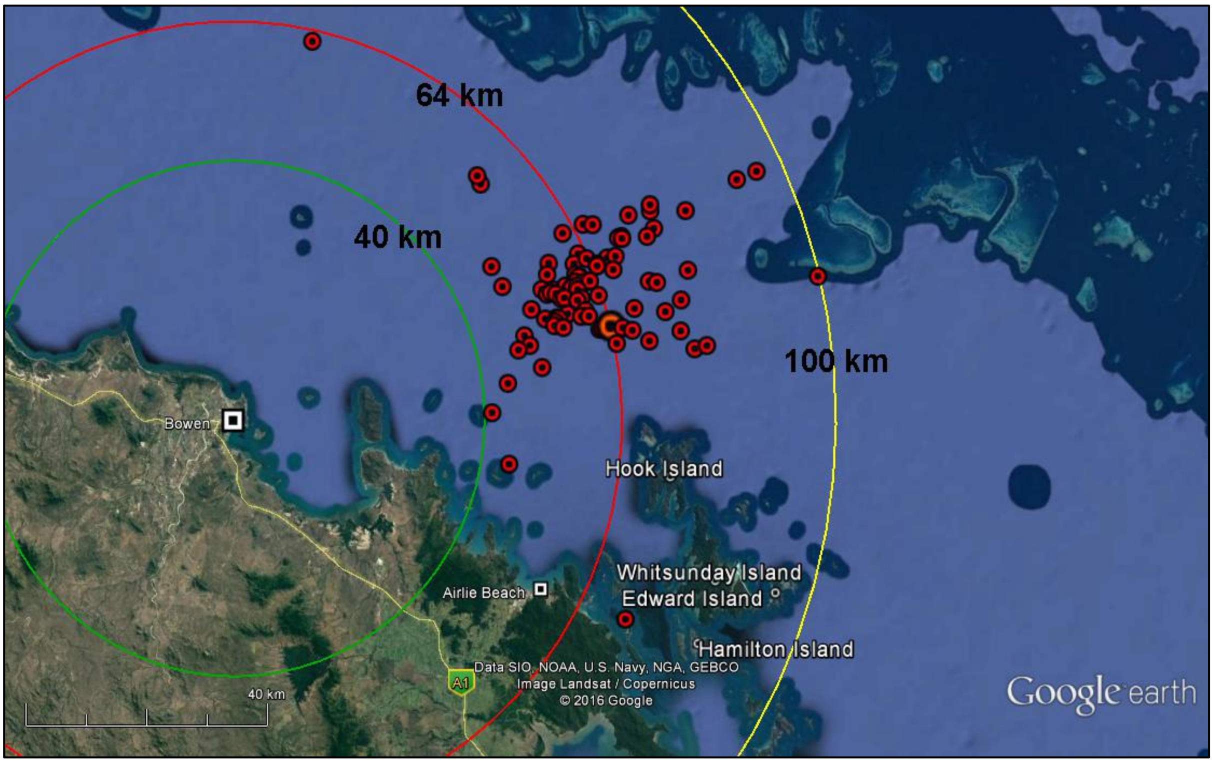

Figure 17: The grouping of the 2016 Bowen earthquake sequence.

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 18.

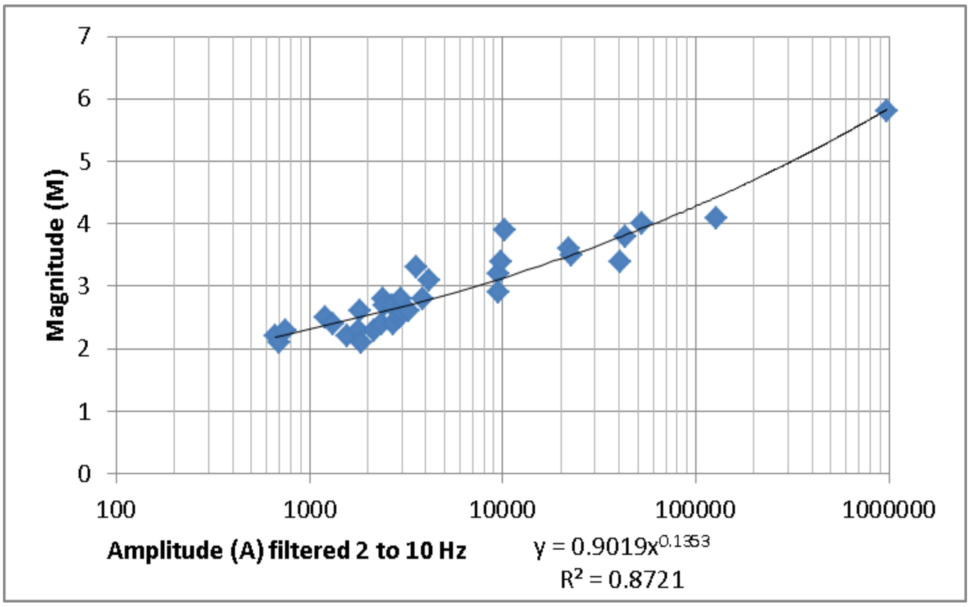

Figure 18: Filtered Amplitudes Vs Published Magnitudes.

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 18 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.

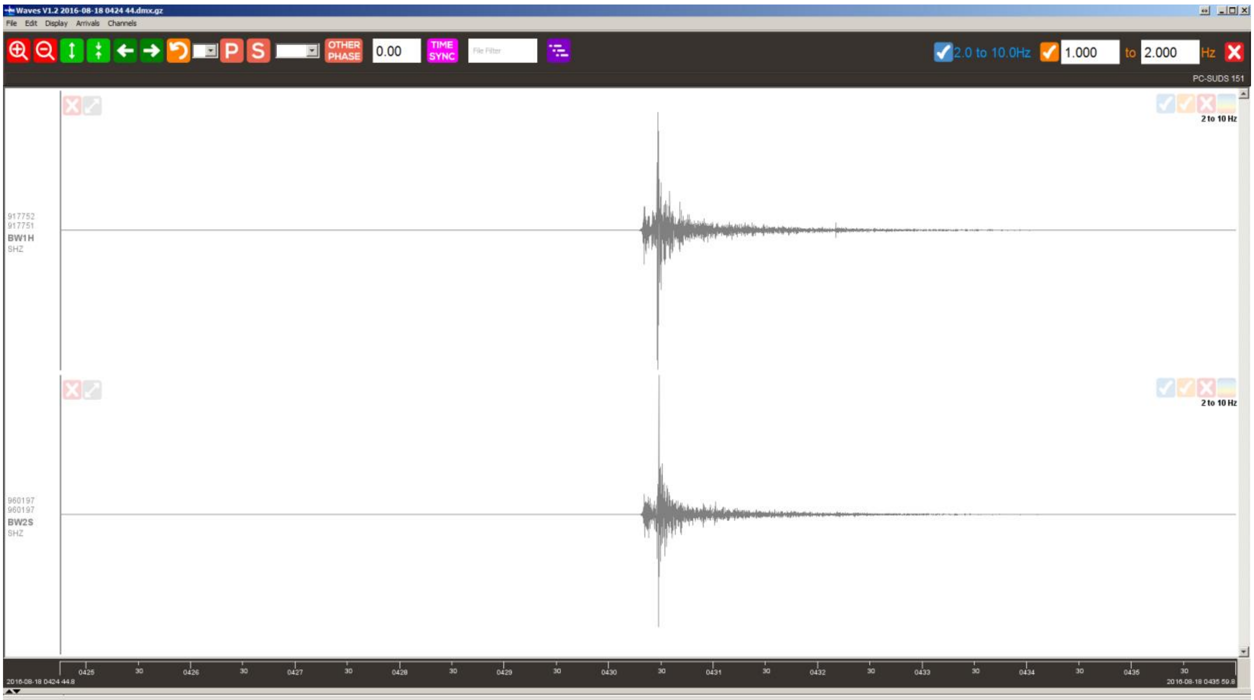

Figure 19: BW1H and BW2S Recordings of the Main ML 5.8 event.

The characteristic shape of the wave form

Figure 19 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 20, a BW1H/BW2S recording of an ML 1.3 aftershock.

Figure 20: 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 19 and Figure 20 represent the two extremes of the magnitude range, the following Figure 21 and Figure 22 provide examples of mid-range aftershocks of ML 1.8, ML 2.2 and ML 2.6.

All three of the events in Figure 21 and Figure 22 have been located using data from multiple stations and verified as being valid aftershocks.

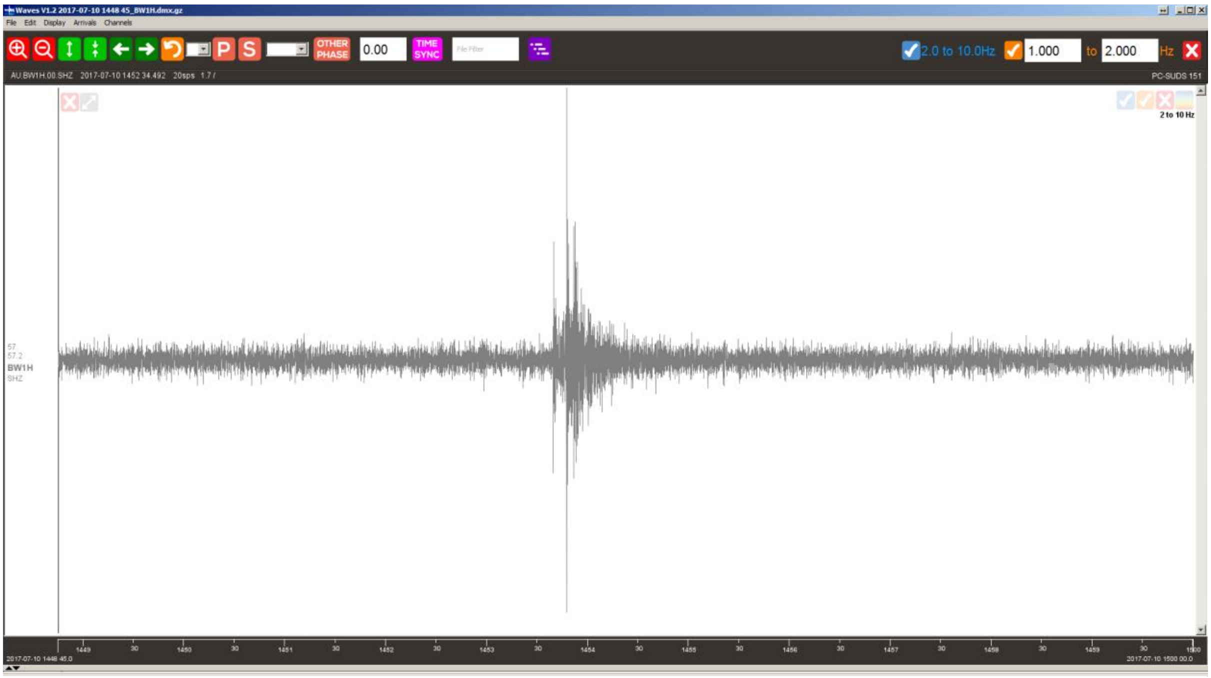

Figure 21: Example of an ML 1.8 aftershock

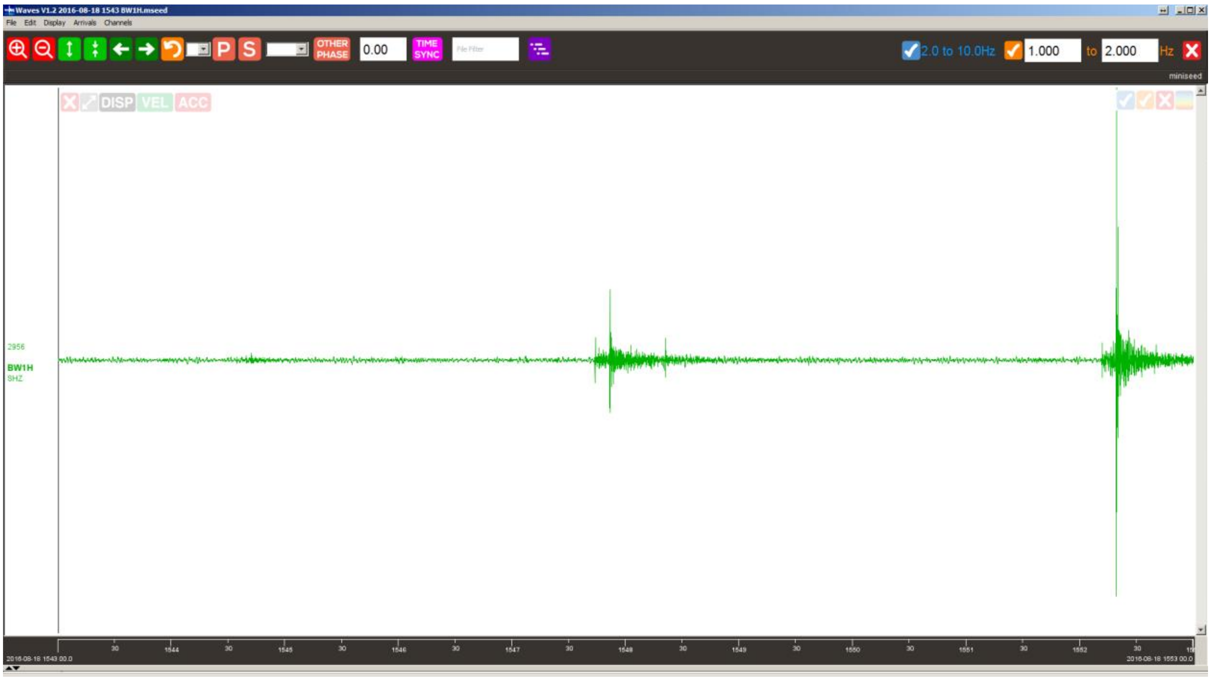

Figure 22: Example of ML 2.2 and ML 2.6 aftershocks.