The Beetaloo Sub-basin Baseline Seismic Monitoring Project – Phase 1 Observations

Sharmin Shamsalsadati[1]; Trevor Allen[2]; Mustafa Çomoğlu[3]; Hugh Glanville[4]

1. *Corresponding Author. Email: Sharmin.Shamsalsadati@ga.gov.au*
2. *Email: Trevor.Allen@ga.gov.au*
3. *Email: Mustafa.Comoglu@ga.gov.au*
4. *Email: Hugh.Glanville@ga.gov.au*

Abstract

Public concerns have been raised about the potential for induced seismicity as state and territory governments lift moratoriums on hydraulic stimulation activities for the exploration and extraction of unconventional hydrocarbons. The Scientific Inquiry into Hydraulic Fracturing in the Northern Territory articulated the need for a traffic-light system "*to minimise the risk of occurrence of seismic events during hydraulic fracturing operations*" within the Beetaloo Sub-basin. A temporary seismic network (Phase 1) was deployed in late 2019 to monitor baseline seismic activity in the basin. Based on the data analysed herein (November 2019 – April 2021), no seismic events were identified within the area of interest suggesting that the Beetaloo Sub-basin is largely aseismic. Observations to date indicate that there is potential to identify events as small as M_L=1.5 within the basin. The recent installation of ten semi-permanent stations for continuous real-time monitoring will contribute to ongoing baseline monitoring efforts and support the implementation of an induced seismicity traffic-light system. The outcome of this study will be used to build knowledge about potential human-induced seismic activity in the region that may be associated with unconventional hydrocarbon recovery.

Keywords: Beetaloo Sub-basin, Seismic Monitoring, Traffic-Light System, Hydraulic Fracturing.

1 Introduction

Scientific studies have linked moderate-sized earthquakes to a number of shale gas provinces through the process of hydraulic fracturing; for example in the Western Canada Sedimentary Basin (2015 M_W 4.6 Fort St. John and other significant events) (Atkinson *et al.*, 2016), South Sichuan Basin (2018 M_L 5.7 and 2019 M_L 5.3) (Lei *et al.*, 2019), and Oklahoma (multiple events since 2010, M_W 3.0-3.5) (Skoumal *et al.*, 2018). In the United Kingdom (UK), the largest earthquake triggered by hydraulic fracturing activities to date (M_L 2.9) occurred at the New Preston Road operation near Lancashire on 26 August 2019, triggering a halt in production (Edwards *et al.*, 2021). The potential for induced seismicity in the Australian unconventional hydrocarbon sector remains relatively uncharacterised. Long-term seismic monitoring in regions associated with the exploration and extraction of unconventional hydrocarbons provides accurate, evidence-based information on the baseline seismicity of a region, as well as seismic activity that may be a consequence of the unconventional hydrocarbon sector.

The Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (hereafter referred to as “the Inquiry”) produced 135 recommendations for the development and regulation of an onshore shale gas industry in the Northern Territory (Pepper, 2018) Recommendation 5.7 expressed the importance of developing a traffic-light system, similar to that in the UK, to reduce the chance of seismic events taking place during hydraulic fracturing activities within the Northern Territory. The Northern Territory Government has agreed to support all of the 135 recommendations from the Inquiry, including the implementation of an induced seismicity traffic-light system. According to Recommendation 5.7 of the Inquiry, a UK-style traffic-light system should be completed in December 2021.

The Beetaloo Sub-basin is located in northern central Northern Territory and near the township of Daly Waters, approximately 300 km south-southeast of Katherine. The sub-basin is of considerable economic interest as a potential host for unconventional and conventional petroleum resources (Williams, 2020). The Australian National Seismograph Network (ANSN), which monitors seismicity in the Australian continent and the adjacent region, is relatively sparse in the Northern Territory and little is known about the potential for earthquakes in the Beetaloo Sub-basin. No earthquakes have been detected in or near the sub-basin in the modern instrumental era (Figure 1). The ANSN is not sufficiently dense to routinely detect earthquakes of approximately magnitude 2.8 and less in the Beetaloo Sub-basin region. As a consequence, the scientific community lacks the fundamental baseline data required to provide evidence-based information on the potential occurrence of induced seismicity in regions where unconventional hydrocarbon extraction may occur in the Northern Territory.

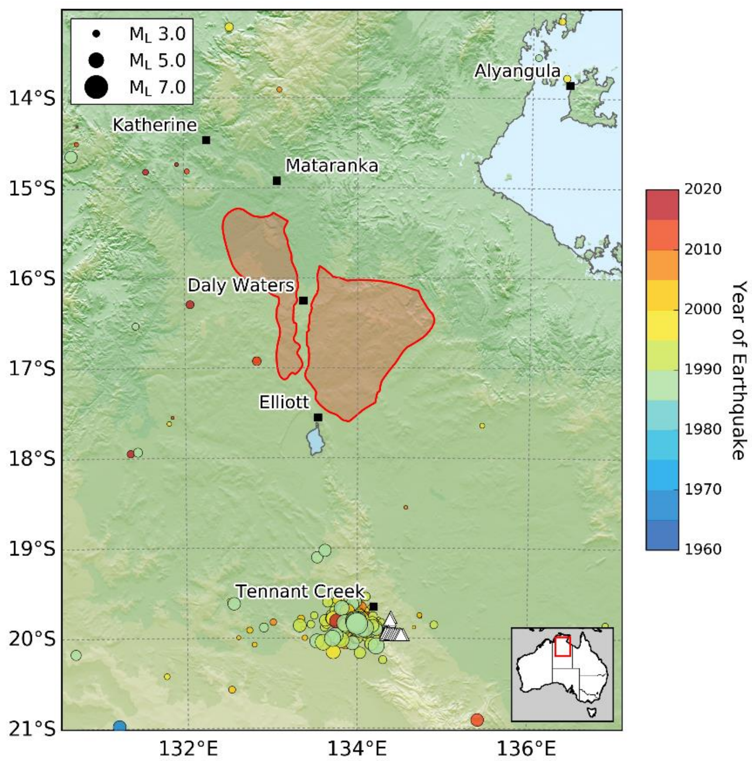

Figure 1. Earthquake history map around the Beetaloo region from 1960-2020. The extent of the Beetaloo Sub-basin GBA region is defined by the red polygons. White triangles indicate pre-existing Australian National Seismograph Network sites.

Geoscience Australia (GA) is partnering with the Department of Agriculture, Water and the Environment’s Geological and Bioregional Assessment (GBA) Program to provide information that will help assess the environmental impacts of shale and tight gas development in the Beetaloo Sub-basin region of the Northern Territory. This will provide new baseline data and information on induced seismicity to governments, industry, landowners and the community. It will provide regulators and industry with a common information base to help inform better decision-making and enhance the coordinated management of any potential impacts. Furthermore, the network's ongoing operation will support action towards Recommendation 5.7 of the Inquiry, i.e. supporting an independent traffic-light system for real-time risk management of hydraulic fracturing operations in the Northern Territory.

This manuscript provides a summary of the temporary Phase 1 network and describes the dataset collected from the sites within this network as of April 2021. The study describes the experimental design, challenges, quality controls and the preliminary analysis of the data collected to date. Finally, future plans for the enhancement and maintenance of the network are provided.

2 Network Design and Deployment

The installation of the Beetaloo Sub-basin seismic monitoring network has been split into two phases. When the project was first approved in late 2019, Geoscience Australia installed a 10-station temporary network to begin gathering important baseline data (Phase 1). The location of the Phase 1 sites are shown in Figure 2. This network was installed in late-2019 and was removed following the commissioning of the semi-permanent Phase 2 sites in September 2021 (Glanville, 2019). The Phase 1 sites envelop existing industry exploration wells in the Beetaloo Sub-basin. As the Phase 1 deployment was only intended to be temporary, the network consisted of two sensor types, which were available to Geoscience Australia at the time for immediate deployment. The deployment included seven broadband and three short period seismometer sensors (Table 1). An example of a Phase 1 recording site is shown in Figure 3.

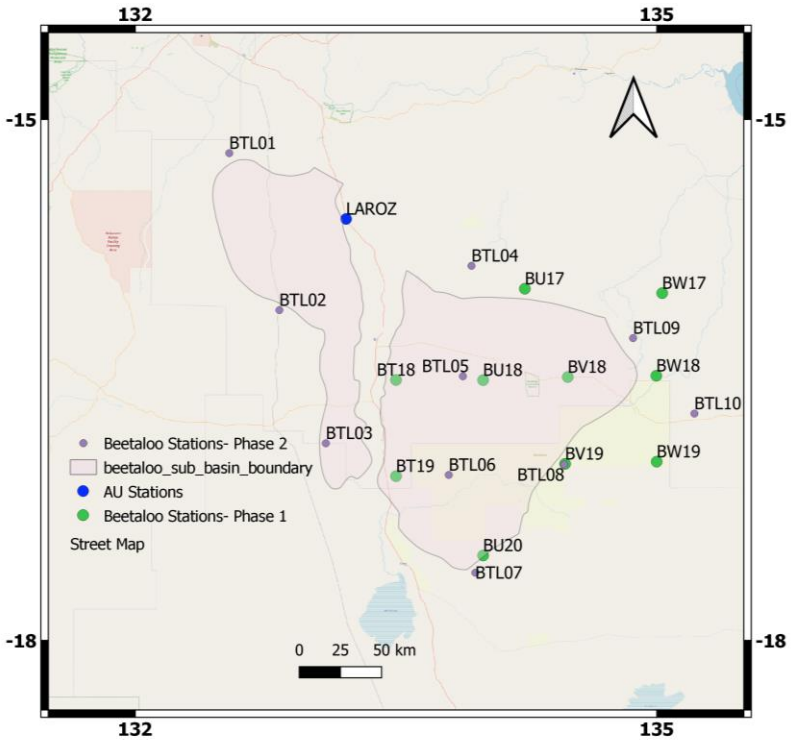

Figure 2. Locations for the Phase 1 and 2 seismic monitoring networks.

Table 1. Beetaloo Phase 1 station information

Station	Latitude	Longitude	Type	Property	Sensor Type
BT18	-16.50	133.49	BB	Kalala	Trillium Compact TC120-PH
BU18	-16.50	134.00	BB	Amungee Mungee	Trillium Compact TC120-PH
BU20	-17.51	134.00	BB	Tandyidgee	Trillium Compact TC120-PH
BU17	-15.97	134.02	BB	Nutwood Downs	Trillium Compact TC120-PH
BV19	-16.98	134.47	BB	Beetaloo Station	Trillium Compact TC120-PH
BW19	-16.97	134.99	BB	Beetaloo Station	Trillium Compact TC120-PH
BW17	-16.00	135.03	BB	Broadmere	Trillium Compact TC120-PH
BW18	-16.47	134.99	SP	Broadmere	Lennartz LE-3DLite
BV18	-16.48	134.48	SP	Tanumbirini	Lennartz LE-3DLite
BT19	-17.05	133.49	SP	Hayfield	Lennartz LE-3DLite

Figure 3. Example of a temporary Phase 1 instrument deployment in the Beetaloo Sub-basin.

3 Data Analysis and Quality Control

Seismic data recorded by the ten temporary stations were collected at two stages: one in October 2020 and the second in April 2021. The data comprise three orthogonal channels, recording at a sampling rate of 200 Hz.

The ISPAQ software released by the Incorporated Research Institutions for Seismology (IRIS) (Casey *et al.*, 2018) was used to inspect data quality through the generation of Probability Density Functions (PDF) of ambient noise at each site. ISPAQ is a Python client that allows users to run data quality metrics. We calculated monthly PDFs showing ambient seismic noise levels for all ten stations. Figure 4 demonstrates three representative PDFs for vertical components of stations BT18, BT19, and BW19 for a period of one month in March 2020. The blue line on the top of the PDF plot for BT18 station (top sub-plot) may indicate a mass recentre effect, which occurs automatically due to the drift in sensor mass position (similar behaviour is observed for BT19 and BW19 stations), while possible atmospheric pressure changes may introduce occasional seismic noise at mid-periods. The effect of using a short period seismometer is seen in longer periods for the BT19 station (middle sub-plot) which creates a large increase in spectral power density signal at longer periods. The bottom sub-plot demonstrates a loss of sensitivity at short periods for BW19, which suggests the sensor may have had levelling problems.

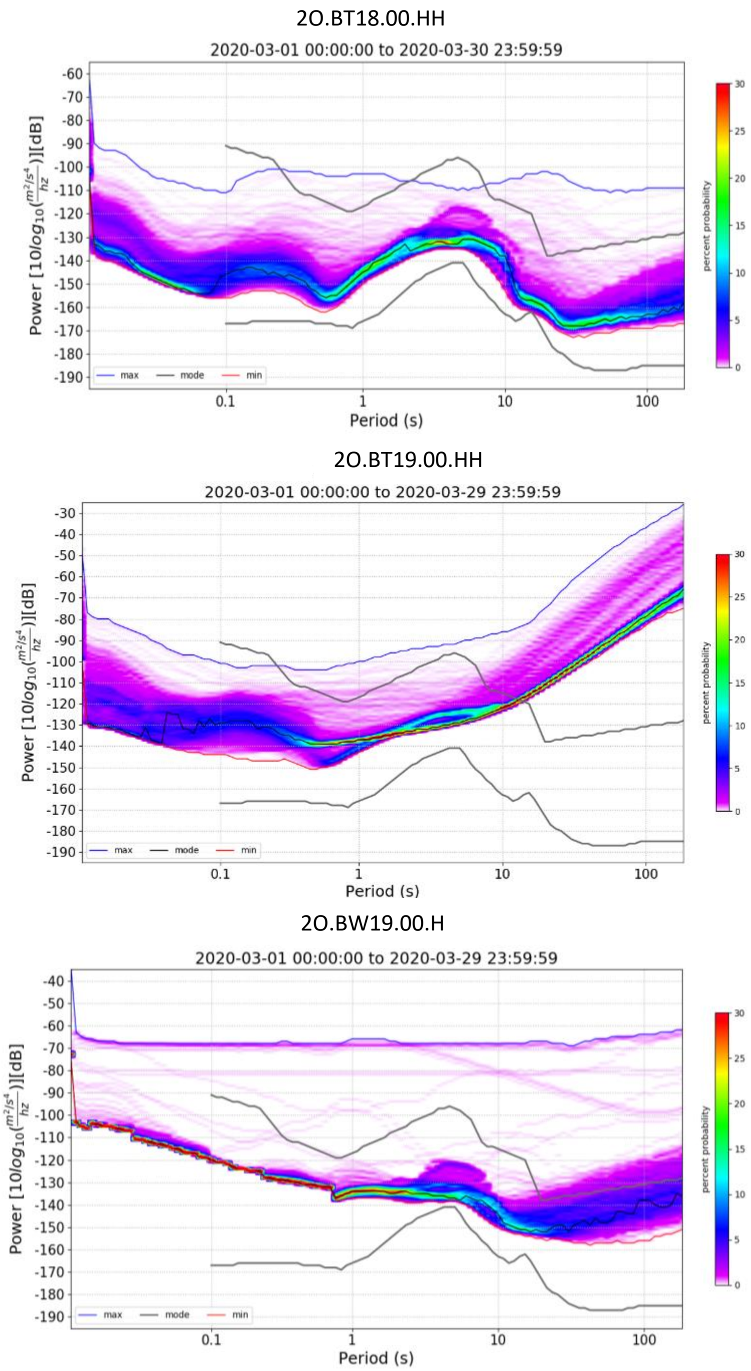

Figure 4. Noise probability density function recorded by vertical component of BT18, BT19, and BW19 stations during March 2020.

We also looked into the time gaps in data using ISPAQ and verified the output with the data gaps reviewed by ObsPy (Beyreuther *et al.*, 2010; Megies *et al.*, 2011). Data gap plots for the

Phase 1 datasets are shown in Figure 5. The top subplot demonstrates above 90 percent of data availability after the first phase of data collection in October 2020 for all stations excluding station BW19 which did not record any data beyond March 2020. The gaps in data collected between October 2020 and April 2021 (Figure 5-bottom) shows above 98-99 percent of data availability; although, BW19 station did not record beyond March 2021.

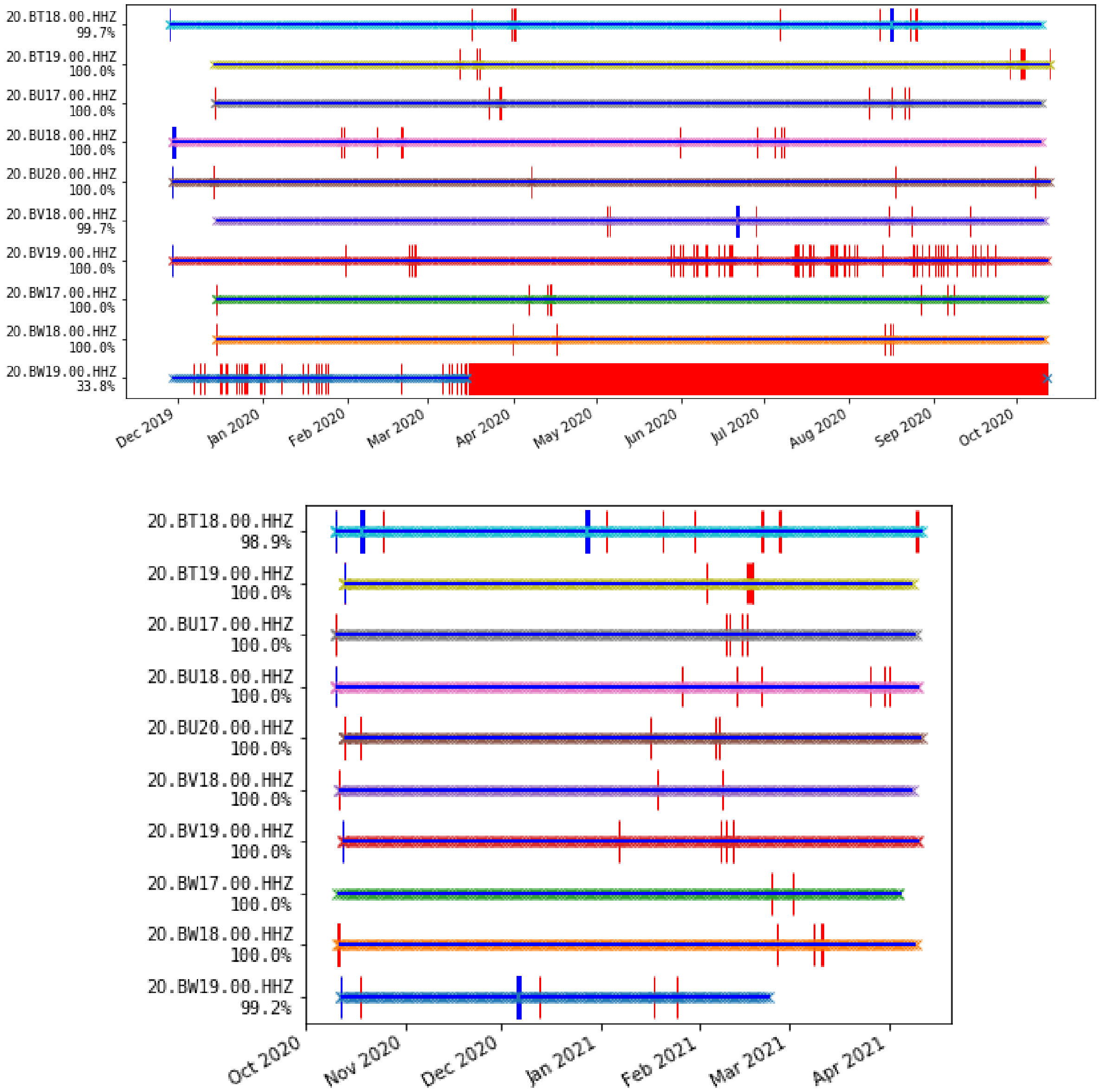

Figure 5. Data gaps plotted as horizontal lines for vertical component of all ten stations between November 2019 and October 2020 (top) and from October 2020 to April 2021 (bottom) data collections. Gaps are plotted as vertical red lines and start times of available data are plotted as blue crosses

At the time of the analysis, the full integrity of the data for five of the sites could not be verified owing to missing metadata on GNSS timing accuracy following damage caused by livestock. However, teleseismic events recorded by Beetaloo stations were analysed and used to investigate possible time shifts in the waveforms due to the loss of GNSS timing lock. The two teleseismic earthquakes in the Banda Sea region occurred on 2020/5/6 and 2020/8/21 (M_W 6.8 and 6.9, respectively) demonstrated clear recordings on Beetaloo stations that were utilized as reference events. The result of the relocation analysis using temporary and network stations did not show any time shift for the ten stations used in this study. To demonstrate the general quality of the data from the Phase 1 temporary network, example waveforms are presented for an earthquake that occurred outside of the network, southwest of Nhulunbuy, NT (M_L 3.8; Origin Time: 20/12/2019 14:29:11). Figure 6 displays the seismic waveform data for several Phase 1 sites for the event near Nhulunbuy, which was well recorded by all stations except BW19, given its higher levels of ambient noise.

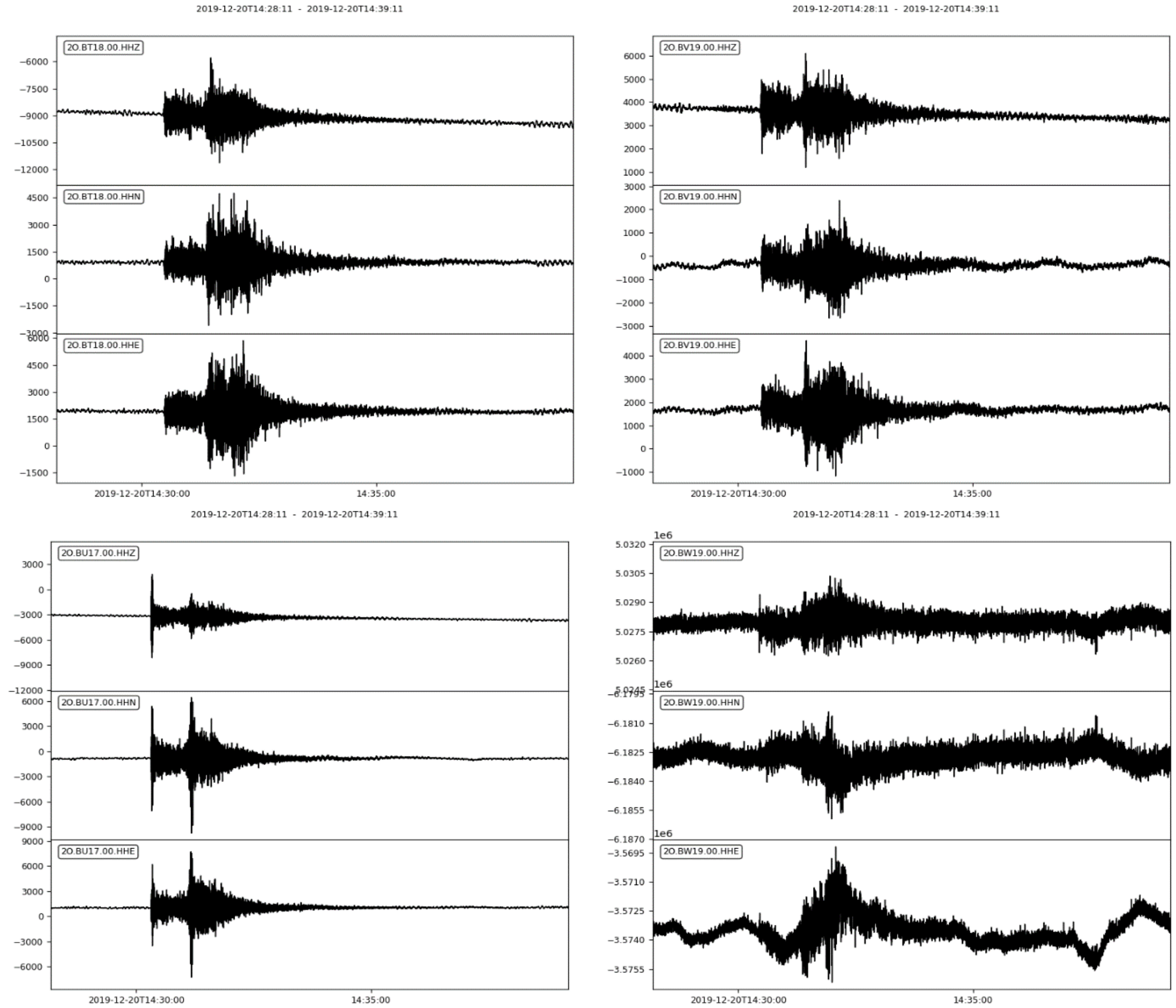

Figure 6. Waveforms for earthquake SW of Nhulunbuy, NT (M_L=3.8) recorded by the Phase 1 Beetaloo seismic network

Once data integrity was confirmed, the data were processed using SeisComP3 seismic analysis software (Weber *et al.*, 2007) which utilizes "playback" feature for automatic event detections and locations. Playback was run across the dataset for the purpose of automatic locating after testing for appropriate filtering parameters in SeisComP3. Inventories of station metadata required by SeisComP3 were generated through SMP (Station Management Portal), then instrument response files were created for each of the stations. All data were assigned with the International Federation of Digital Seismograph Networks (FDSN) network code created for the Beetaloo seismic network (2O; Glanville, 2019).

4 Analysing Local Events

The SeisComP3 software package was used for analysing seismic events or possible blasts recorded by Beetaloo stations, as well as nearby stations from the ANSN. The automatically detected arrival times for seismic signals (or phases) were verified and adjusted manually for all arrivals and the verified seismic events were relocated.

The location of the 144 located events for the period between 14th November 2019 and 9th April 2021 are mapped in Figure 7. The events detected by temporary Beetaloo sensors were mainly localised to two clusters. The first cluster identifies events near the Tennant Creek region. These events appear to be associated with the ongoing aftershock sequence from the 1988 Tennant Creek earthquake sequence (Jones *et al.*, 1991). The second cluster of events occurred in the vicinity of the McArthur River Mine. The events identified close to the mine all took place during the local working hours (see Figure 8) which is consistent with the common time windows of blasting operations in mines. Characterisation of the mine blasts outside the Beetaloo Sub-basin is beyond the scope of this study and hence, it was not investigated further.

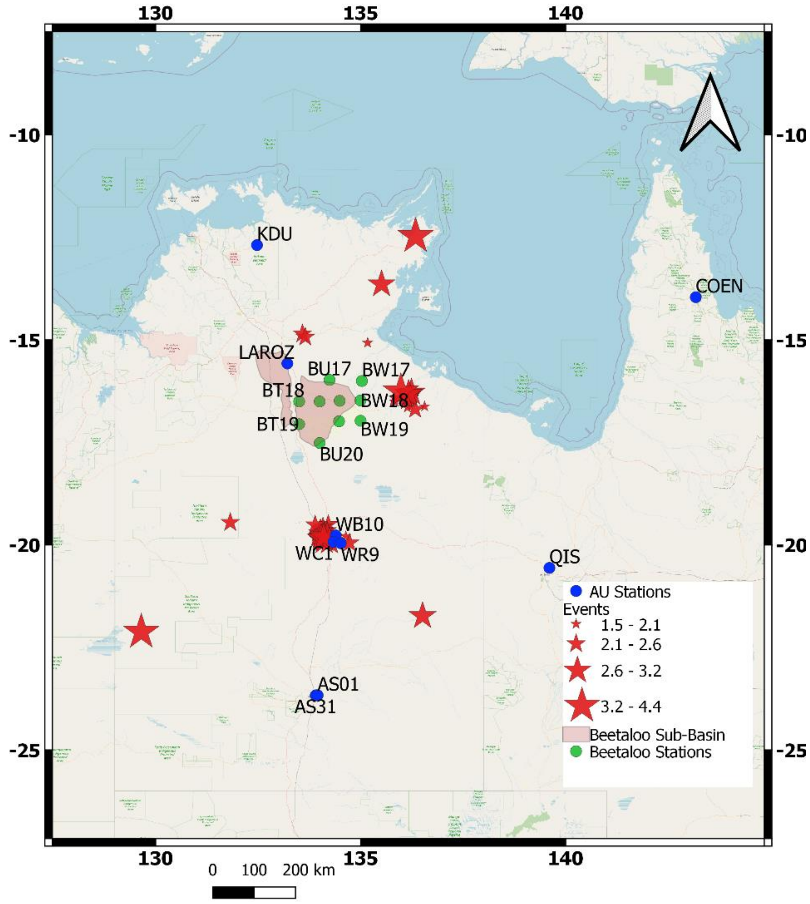

Figure 7. Location of the detected events and stations relative to the Beetaloo Sub-basin.

Specific information on the located events over the time period of interest will be summarised in a forthcoming report (Shamsalsadati *et al.*, in prep). In summary, this report will indicate that events of local magnitude (M_L) 1.5 and greater occurring 250 km from the network are well recorded by the temporary stations deployed in Beetaloo Sub-basin. Twenty out of the 56 events located in the Tennant Creek region are amongst earthquakes previously published at Geoscience Australia's catalogue using AU network stations only. The comparison between the observations from this study and those published in the catalogue shows close correspondence in terms of earthquake magnitudes and origin times. The default depth used by NEAC is 10 km for poorly constrained hypocentres with large location uncertainties; however, referring to the information available from previous studies (Choy and Bowman, 1990; Bowman, 1992), the default depth in our analysis was set to 5 km. Therefore, there are discrepancies in the locations due to respective assumptions in the default depth in cases where the hypocentres are not well resolved. Nevertheless, comparison of the calculated residuals in this study relative to those residuals evaluated by NEAC reveals generally lower values through the use of the Beetaloo Sub-basin seismic network (Shamsalsadati *et al.*, in prep). Figure 9 illustrates velocity waveforms for the event with M_L 1.9 occurred on Dec 20, 2020 near the McArthur River Mine.

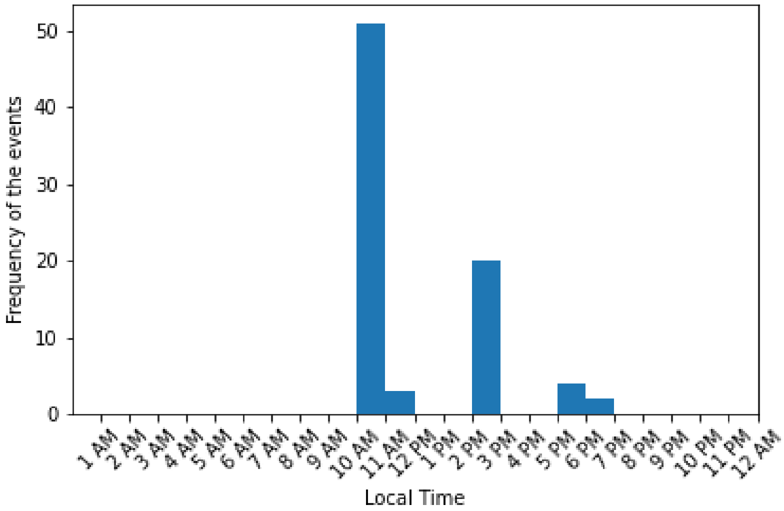

Figure 8. Histogram of the events proximal to the McArthur River Mine binned by local time.

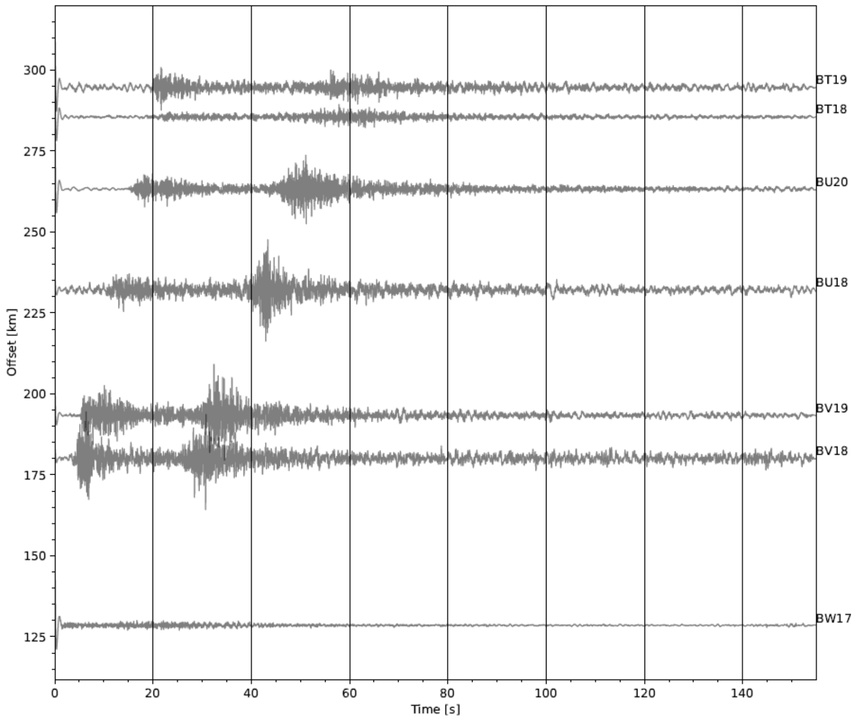

Figure 9. Selection of the vertical-component velocity waveforms for an event that occurred on 2020-12-20 01:03:12 near the McArthur River Mine (M_L=1.9).

5 Network Sensitivity

Analysis of the change in network sensitivity in the Beetaloo region was undertaken using software developed by Sandia Instruments called NetMOD (Merchant, 2015). NetMOD makes use of geophysical models to determine the source characteristics, signal attenuation along the path between the source and station, and the performance and noise properties of the station. These geophysical models are combined to simulate the relative amplitudes of signal and noise that are observed at each of the stations (Merchant, 2015). When the Phase 2

Beetaloo network is considered with five *P*-wave arrivals, a sensitivity can be obtained that can resolve an earthquake to a magnitude of m_b 1.8 (Figure 10-left) while using three *P*-wave arrivals, the magnitude sensitivity reduces to m_b 1.6. In contrast, when the Beetaloo network is not used, the resolvable magnitude for the region is in the order of m_b 3 (Figure 10-right). Results presented in Section 5 suggest that the Phase 1 network may have outperformed these estimates with the minimum magnitude event located being M_L 1.5.

It is worth noting here that International Association of Seismology and Physics of the Earth's Interior (IASPEI) recommends epicentral distance of 20-100 degrees for m_b (Bormann and Dewey, 2014), it is not possible for an event of m_b 1.6 to be detected using data at the distance ranges considered. Based on the 2018 National Seismic Hazard Assessment earthquake catalogue (Allen *et al.*, 2018) there is an approximate 1:1 relationship between m_b and M_L for earthquakes down to 3.5. However, it is unknown as to whether this relationship would hold to smaller magnitudes. Nevertheless, the NetMOD software does allow for the visualisation of the approximate improvement to the magnitude completeness given the densification of the seismic network. Future enhancements to the NetMOD software to enable it to consider Australian-specific local magnitudes should be considered.

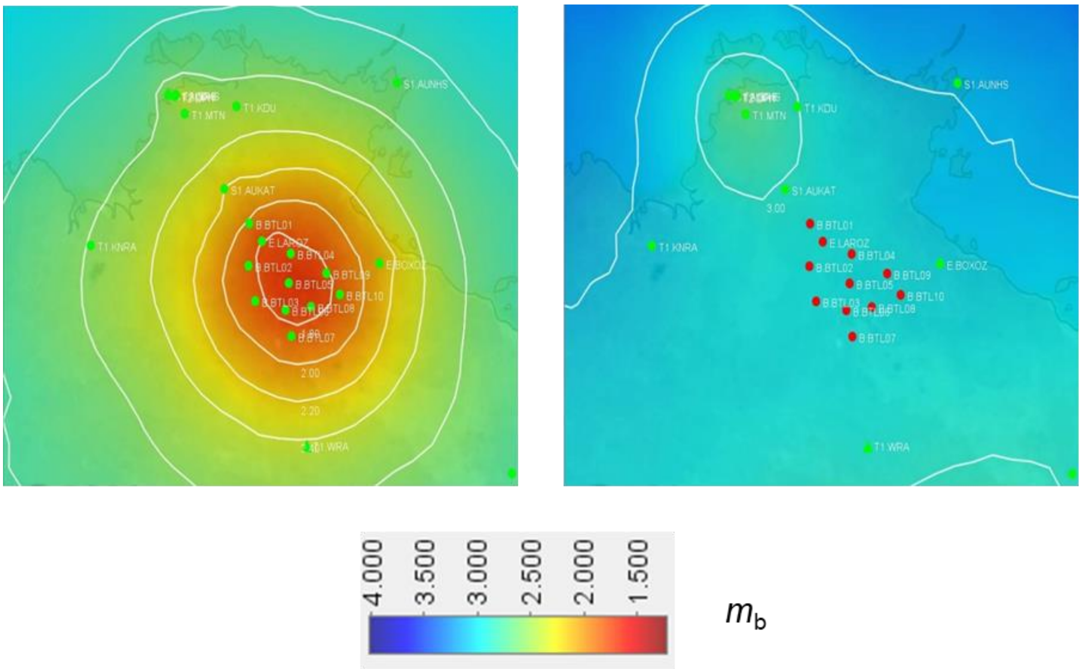

Figure 10. NetMOD output with detection threshold m_b 1.8 or better within the Phase 2 Beetaloo Sub-basin network assuming five P-wave arrivals (left) and a detection threshold of m_b > 3.0 in the region when the network is not considered (right)

6 Summary and Future Work

Ten temporary seismic stations were installed in Beetaloo Sub-basin (late-2019) to monitor baseline seismic activity in the region. The minimum magnitude detected was M_L 1.5, which was detected at a distance of 250 km from the nearest Beetaloo network site. Our new findings indicate that there is a potential to find smaller local earthquakes using temporary stations in the Beetaloo Sub-basin.

The introduction of the Phase 1 seismic network has significantly improved seismic monitoring capabilities in the region. Based on the data analysed herein, no seismic events were identified within the region of interest during the observation window suggesting that the Beetaloo Sub-basin is largely aseismic. This is an important observation given the lack of fundamental baseline data required to provide evidence-based advice on the potential for induced seismicity in regions of unconventional hydrocarbon recovery in the Northern Territory, and Australia more broadly.

Through Phase 2 of this project, nine of ten new semi-permanent seismic stations are installed in the region as of September 2021. These instruments will provide data to Geoscience Australia via satellite to monitor local and regional seismic activity in real time. The development of strong standards and guidelines for the mitigation of induced seismicity and for alerting will support the development of a safe and sustainable unconventional hydrocarbon resource sector. Furthermore, this initiative supports Recommendation 5.7 of the Final Report from the Scientific Inquiry into Hydraulic Fracturing in the Northern Territory (Pepper, 2018) to implement a traffic-light system similar to that in the UK to minimise the risk of occurrence of seismic events during hydraulic fracturing operations.

The outcome of this study will be used by GA, the public and other organisations to build knowledge about potential human-induced seismic activity in the region that may be associated with unconventional hydrocarbon recovery.

7 Acknowledgements

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