Summary report of the scientific analysis of the data gathered from Cuadrilla's PNR2 hydraulic fracturing operations at Preston New Road

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Executive Summary

In March 2020, the Oil & Gas Authority (OGA) commissioned four studies to investigate seismicity resulting from the Preston New Road 2 (PNR2) hydraulic fracturing operations. These were the continuation of studies into epidemic-type aftershock sequence (ETAS) modelling by the British Geological Survey (BGS), a subsurface and geomechanical study by Outer Limits Geophysics LLP, a study into the surface impacts of ground motion by Intraseis Ltd, and a new study to investigate magnitude conversion relationships by the BGS.

The purpose of these studies was to repeat the scientific analysis previously commissioned on the data collected from the hydraulic fracturing operations on the Preston New Road 1Z (PNR1Z) well[1] with the recently acquired PNR2 data. The studies were designed to further understand the subsurface and surface impacts of the induced seismicity experienced during the operations, and to investigate predictive techniques that could be used as a future mitigation against induced seismicity. This work was not intended to review any existing regulatory controls such as the Traffic Light System (TLS), nor is it a comprehensive review of the current scientific landscape following the effective moratorium[2] on high-volume hydraulic fracturing announced by the government on 2 November 2019.

The reports (summarised below) reinforce the conclusions made from the PNR1Z studies. In particular, whilst recently-identified novel methods offer some potential, it is not yet possible to accurately predict the seismic response to hydraulic fracturing, if any, in relation to variables such as site characteristics, fluid volume, rate or pressure. Where induced seismicity has occurred, mitigation measures have shown only limited success, and there can only be low confidence in their effectiveness currently.

> A study by **Outer Limits Geophysics** found that the potential geomechanical mechanisms for the cases of felt seismicity were complex and different for each site, which is especially noteworthy given the close proximity of these wells. This high variability and uncertainty make it challenging to make generalised conclusions of the causal mechanisms.
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> The **BGS** study into the relationship between downhole and surface magnitudes found that the recorded moment magnitudes (M_w) from the PNR1Z and PNR2 downhole catalogues were lower than the surface local magnitudes (M_L) as derived from the BGS surface array. Each downhole catalogue had a different relationship with the surface local magnitudes, so a consistent conversion factor could not be identified. Recorded downhole M_w values are significantly less than the expected value of M_w, with this discrepancy being greater in PNR1Z than for PNR2. This underestimation may be in part due to limitations in the downhole geophones used.
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> The results of Ground Motion Modelling by **Intraseis** were that a 2.9 M_L scenario, like that of the 26 August 2019 event, may cause sparse cases of low (DS1) superficial damage to buildings within the Fylde region, which corresponds with a few of the observations collected by the BGS. However, in modelling the 'unlikely' scenario of a 4.5 M_L event, ground motion models show that the likelihood of damage to buildings in the region could be high.

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[1] https://www.ogauthority.co.uk/exploration-production/onshore/onshore-reports-and-data/preston-new-road-pnr-1z-hydraulic-fracturing-operations-data/

[2] https://www.gov.uk/government/news/government-ends-support-for-fracking

Mechanical modelling demonstrated that the ground motion from such an event would be below the damage thresholds needed to induce damage to the well or its integrity.

The **BGS's** study of the statistical modelling of hydraulic fracturing-induced seismicity found that integrating injection volume data from operations improved the quality of seismicity rate forecasts, but that more work was needed to reduce the uncertainty introduced from model input parameters.

This report gives a summary of these studies, a background into the operations at Preston New Road, and reviews the conclusions from both PNR1Z and PNR2 datasets.

Introduction and Objectives

Following completion of hydraulic fracturing operations by Cuadrilla Resources on the PNR1Z well at Preston New Road in December 2018, the first hydraulic fracturing conducted in England since 2011, the OGA announced in February 2019 our intention to carry out a scientific analysis of the data gathered during these operations.

During August 2019, while the PNR1Z studies were continuing, Cuadrilla Resources hydraulically fractured the second well at the site, PNR2, which again experienced induced seismicity throughout the operations, leading to the early cessation and demobilisation of operations at the site. Due to the monitoring and reporting regulatory requirements for the site, a unique and significant volume of data was collected during these operations, including surface and downhole microseismic measurements, and operational datasets for pumping volumes, pressures and other well data.

After publication of the PNR1Z studies and reports in November 2019, the OGA commissioned four further studies to investigate the datasets from the PNR2 operations. The objective of these studies was to better understand both the subsurface causes and surface impacts of the felt seismicity at PNR2, and to explore further predictive methods for induced seismicity.

Following the seismicity induced during the operations on PNR2, the government announced an effective moratorium on high-volume hydraulic fracturing in November 2019. The objective of this series of studies remains to repeat the scientific analysis with the recently acquired PNR2 data, not to address the need for the considerable body of new evidence which would be required to demonstrate that hydraulic fracturing can be conducted safely, sustainably and with minimal disturbance.

Hydraulic Fracturing Operations at Preston New Road

A detailed account of shale gas exploration in Lancashire using hydraulic fracturing, including at Preese Hall and Preston New Road, can be found in the OGA's 2019 interim report[3] on PNR1Z.

The PNR2 well, located approximately 200m north of PNR1Z, was hydraulically fractured by Cuadrilla in August 2019. The objective was a horizon within the Upper Bowland Shale, around 200m shallower than was targeted in PNR1Z.

A total of up to 45 stages were planned for these operations, with pumping operations scheduled to commence on 13 August. Seven sleeves were hydraulically fractured up to 22 August, before

[3] https://www.ogauthority.co.uk/media/6149/summary-of-pnr1z-interim-reports.pdf

operations were suspended after a series of red Traffic Light events were recorded, including the 2.9 M_L earthquake on 26 August 2019.

A moratorium on high-volume hydraulic fracturing with immediate effect was announced by the government on 2 November 2019. This included a presumption against issuing any further Hydraulic Fracturing Consents, citing the disturbance caused to residents living near Cuadrilla's Preston New Road site, and the OGA's scientific analysis that found that it is not currently possible to accurately predict the probability or magnitude of earthquakes linked to hydraulic fracturing operations.

Summary of the PNR2 Studies

Outer Limits – Geomechanical Interpretation of Induced Seismicity at the Preston New Road PNR2 Well, Lancashire, England

Following the earlier study which evaluated the microseismic data from PNR1Z, the objective of this study was to examine and interpret the microseismicity induced by hydraulic fracturing in the PNR2 well, with a focus on understanding the interaction between the hydraulic fracturing and any pre-existing faults, and in particular to identify the structure that generated the 2.9 M_L event of 26 August 2019.

The microseismic data gathered from PNR2 was very different in character from that at PNR1Z, noting that injection was only located approximately 200m shallower, and 200m further north than the first well. It was hoped that integrating the injection, pressure and other data from both operations could provide greater insight into what may have caused the seismicity at PNR2.

The study compared the microseismic event locations from the PNR1Z and PNR2 wells and found almost no overlap between them (Figure 1).

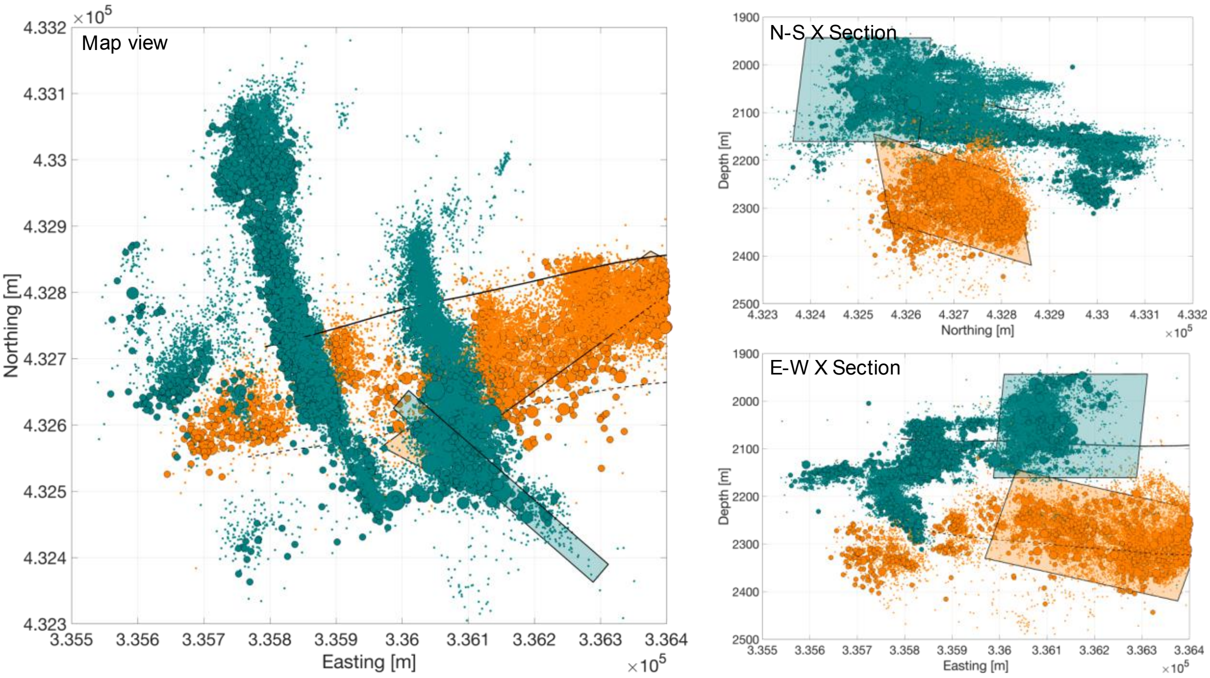

Figure 1 - Comparison of microseismic event locations during stimulation of the PNR1Z (orange) and PNR2 (teal) wells, showing identified fault planes. (from Outer Limits Geophysics)

During the hydraulic fracturing of PNR2, the microseismic data revealed that the early stages of injection created a large north-south extending hydraulic fracture system, which interacted with several natural structures but did not cause any notable seismicity.

As injection continued, a second zone of hydraulic fractures propagated to the east of the active sleeves, interacting with an unseen pre-existing near vertical fault with a south-east strike (the 'PNR2 fault'). This fault was responsible for the largest seismic events and was clearly delineated in the microseismic data by the aftershocks following the 2.9 M_L event. This fault is a different structure to the fault trend believed to be responsible for the seismicity induced during stimulation of PNR1Z.

This study concluded that the spatio-temporal evolution of microseismic events from PNR2 are indicative of a pore pressure diffusion-driven process, that is to say that the progressive growth of hydraulic fractures from the well was driven by the migration of the injected fluid. This is different from the PNR1Z case, where microseismic events occurred across a range of distances nearly instantaneously during injection (interpreted to be indicative of a static stress transfer process, where fractures compress the rock around them, and this additional stress is transmitted through the rock which may then trigger failure of a critically stressed fault).

Other factors such as stress transfer from tensile fracture opening may have contributed to seismicity and by modelling the stress transfer effects during fracturing, the study found that these effects would have also promoted slip on the identified fault.

Finally, the study investigated potential reasons for the difference in the levels of fault reactivation between the two wells. The previously undetected PNR2 fault was found to be extremely well orientated for slip. The in-situ stress conditions, and the fault orientation within the stress field appeared to have a significant impact on the rate of seismicity and the magnitude of the resulting events. In comparison, the PNR1Z fault was only moderately well oriented for slip, and although it received a higher volume of injected fluid, it produced less seismicity.

Intraseis – Impacts of Seismicity: Transmission to People, Property and Well Integrity

This study aimed to improve the understanding of the induced seismicity at PNR and potential future events in terms of its impacts on people, the built environment and well integrity. This work expanded upon the original PNR1Z study by integrating data from the subsequent hydraulic fracturing operations on PNR2 and made a direct comparison between reported effects and modelled damage for the largest recorded event.

It was observed that some near-surface geological deposits such as wind-blown sands can amplify ground motion, and this effect can be seen by comparing the shallow geology with the location of reports and their European Macroseismic Scale (EMS)[4] intensity rating from the BGS' "Did you feel it?" data after the 2.9 M_L event on 26 August 2019. The group characterised the near-surface geological deposits across the region for use as a proxy for site amplification effects (where there can be an increase of seismic amplitude due to near-surface geological conditions i.e. soft soil or sand), which were then used in ground motion predictions and subsequent risk calculations.

A site-specific predictive ground motion model was developed and calibrated using ground motion data recorded from events at both PNR1Z and PNR2.

[4] https://earthquakes.bgs.ac.uk/education/education/ems_synopsis.htm

Using this ground motion model, a series of five hypothetical earthquake scenarios (2.5, 3.0, 3.5, 4.0, and 4.5 M_L) and the two largest earthquake events (2.1, 2.9 M_L) were modelled to generate PGV (Peak Ground Velocity) predictions and calculate the expected EMS intensity across the region from these events.

Based on these defined scenarios, a probabilistic framework was used to develop risk calculations for each scenario, from which the resulting damage due to these events was calculated.

For the 2.9 M_L scenario, a mean (which takes into account outlying events) of 52 buildings at DS1 state was calculated within the 16 x 15 km modelled region, which may correspond with some "Did you feel it?" reports to the BGS from the 26 August 2019 event.

The group also modelled an 'unlikely to happen' 4.5 M_L scenario. This model estimates that within 1km from the epicentre, ground motion intensities of VII ('damaging') may occur, and intensities of VI ('slightly damaging, cosmetic') could extend to around 3-4 km. Such an event would also be felt by many across the Fylde region.

Whilst it is important to note that hydraulic fracturing-induced seismicity at this 'unlikely' magnitude has only a few international precedents, it is within the range of UK tectonic events experienced in the past, and should such an event occur, there would be high likelihood of damage to buildings within the region.

This work highlights the importance of limiting the upper magnitude (e.g. < 2.5 M_L), since small increases above 3 will quickly lead to increased damage.

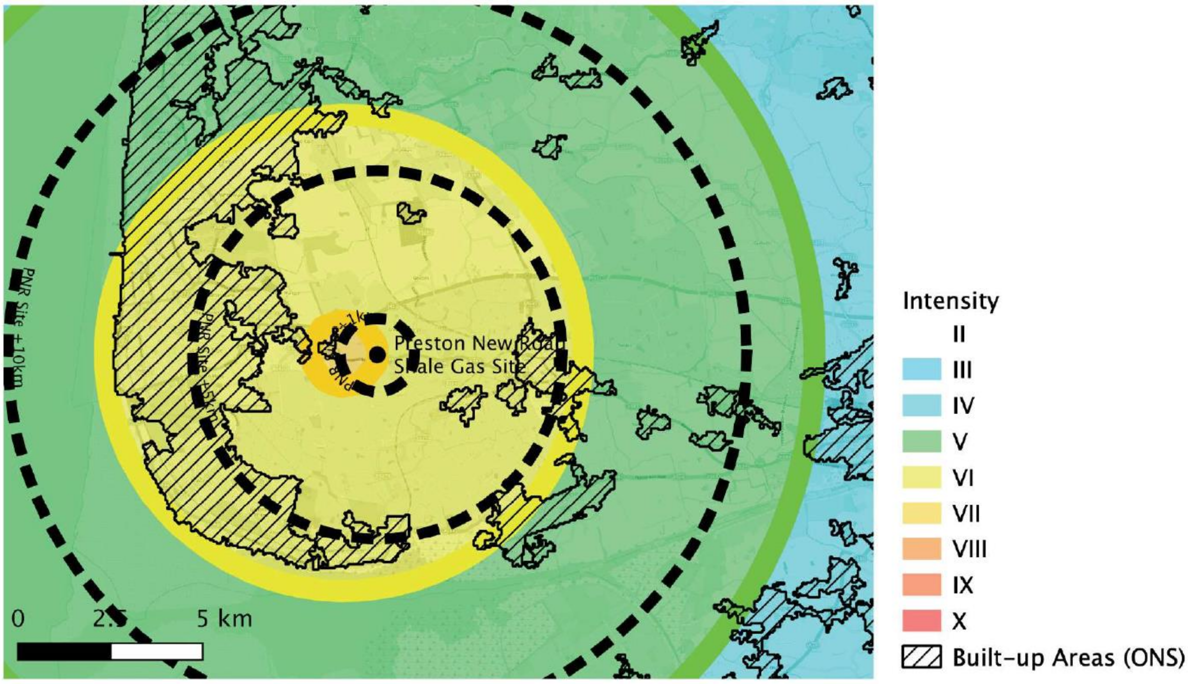

Figure 2 - EMS Intensity predictions for 'unlikely' 4.5 M_L scenario using median + one sigma mean PGV (from Intraseis)

An investigation into the impact of a significant event (i.e. 4.5 M_L) on the well and its integrity through deformation induced by motions, and bending and shear stresses on the well, concluded that the well could accommodate significant loading without the occurrence of damage, and that such an event would be unlikely to induce failure, with >98% of realisations being lower than the threshold for damage.

British Geological Survey – Robust Relationships for Magnitude Conversion of PNR Seismicity Catalogues

One of the common themes identified through the earlier PNR1Z studies, was that existing published local magnitude (M_L) to moment magnitude (M_W) conversion relationships were not appropriate to merge the downhole microseismic data and the surface 'traffic light system' microseismic data from PNR1Z operations into a single dataset. Using microseismic data from both PNR1Z and PNR2, the objective of this project was to compare the magnitude estimates from both seismicity catalogues and investigate new mathematical relationships that could be used to integrate microseismic data from both M_L and M_W magnitudes.

An initial comparison found that as the downhole microseismic array (located within the wellbore) was closer to the event sources and being buried deeper had higher signal to noise ratios, the downhole microseismic array had a far smaller event detectability limit, identifying events with magnitudes below those detected from the surface array. However, this geophone proximity was problematic at higher event magnitudes, when downhole geophones became saturated and clipped, not accurately measuring the magnitude for larger events versus the surface geophone records.

When comparing data from each well, it was found that the downhole moment magnitudes (M_W) from the PNR1Z and PNR2 catalogues were not consistent, each having a different relationship with the surface local magnitudes (M_L).

The downhole M_w values are significantly less than the expected value of M_w at the surface when compared against expected M_L-M_W relationships, with this discrepancy being greater in PNR1Z than for PNR2. This underestimation of downhole moment magnitudes may be partly due to limited dynamic range and frequency response in the downhole geophones used in both PNR1Z and PNR2.

The moment magnitudes (M_W) calculated from surface recordings broadly agreed with a number of empirical relationships between M_L and M_w but were found to be greater when compared to the same events determined from downhole data, again suggesting limitations in the acquisition of downhole data.

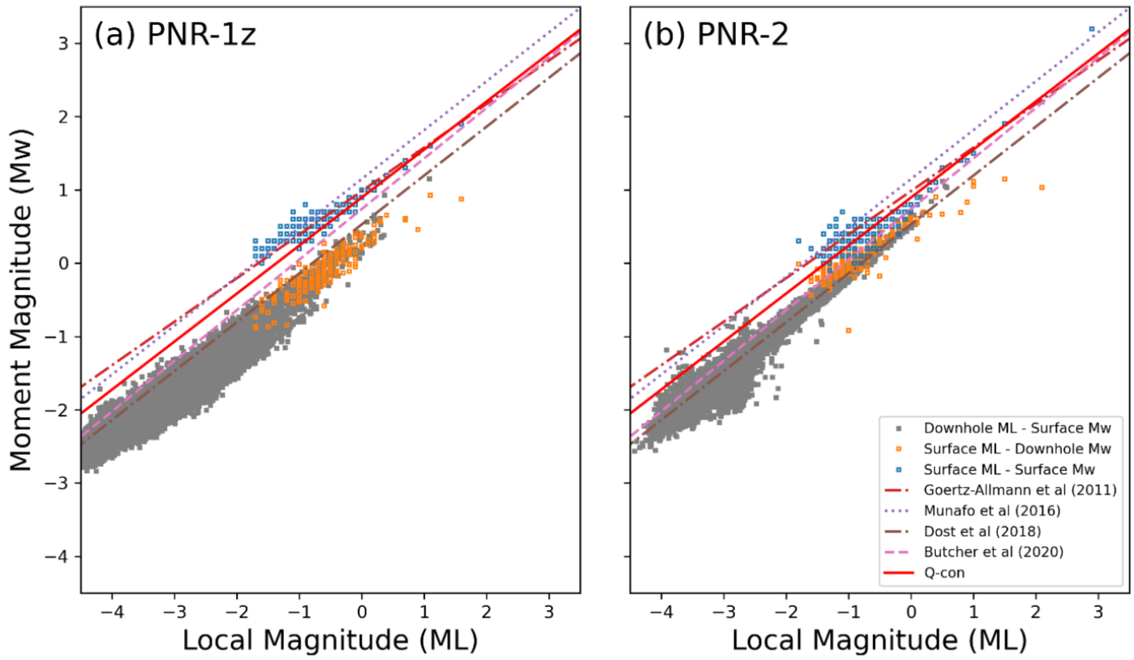

Figure 3 – Comparison between surface and downhole magnitude data from PNR1Z and PNR2 (from BGS)

The moment magnitudes in the downhole catalogues were corrected by referencing them to both an existing published relationship between surface M_W and M_L, and an observed relationship between surface and downhole M_W. Both methods result in an increase in activity rate, however, the two approaches result in differing *b*-values, particularly for PNR2, where a considerable reduction in *b*-value is observed using the first approach. This may suggest a change in the behaviour of the seismicity between PNR1Z and PNR2.

Combining the surface and downhole datasets overcomes both the detectability limitations of the surface data and the saturation issues with the downhole datasets. The corrected dataset addresses much of the uncertainty introduced by the limitations of the individual datasets, in particular, for the estimation of activity rates and *b*-values, and for the reliable estimation of seismic moment release.

Comparisons between individual datasets and this combined dataset also highlights the limitations of using only a surface-based seismic monitoring network, for which the seismic catalogue may be incomplete near the TLS threshold[5] of 0.0 M_L and would limit effective real-time seismic forecasting using such a network.

This study concludes that for a full understanding of these results and to determine a reliable conversion relationship for the PNR1Z and PNR2 data, further work is needed to understand the differences between surface and downhole magnitudes, and it is recommended that M_w for both the downhole catalogues be re-calculated using the waveform data, and that a systematic analysis of the waveform data be conducted to understand its limitations.

Also noted is the importance of understanding the effects of instrumentation and calibration. Therefore, the study recommends that for future operations requiring microseismic monitoring, the Operator should assess the potential impact of the type of instrumentation on magnitude estimation, and that a denser network of (shallow borehole) sensors be used to improve event detection and the limited completeness of surface catalogues.

[5] https://www.ogauthority.co.uk/media/5110/oga_managing_onshore_induced_seismicity_infographic.pdf

British Geological Survey – Statistical Modelling of the Preston New Road 2 Seismicity

Using the microseismic data from PNR1Z, this study initially investigated the feasibility of statistically forecasting the microseismicity observed during and after hydraulic fracturing operations by developing an Epidemic Type Aftershock Sequence (ETAS) model.

The PNR2 dataset contains a greater sampling of larger magnitude events and magnitude of completeness than PNR1Z. This study extended the previous work in order to integrate and analyse the PNR2 data to validate the assumptions and parameter uncertainties used in the ETAS model, investigate relationships between operational parameters and seismicity, and test the predictive performance of injection-rate driven predictive ETAS models using this independent, out-of-sample dataset.

Analysis of the PNR1Z and PNR2 microseismic data found that the relationship between injected volume and released seismic moment is complicated and non-unique. The seismic moment released per unit injected volume varied dramatically between the wells, as well as between neighbouring sleeves. The high variability between seismic moment and volume is an indication that the seismic response is at least partially controlled by locally heterogeneous conditions.

None of the injections generated seismic moments that exceeded the McGarr (2014)[6] proposed relationship of moment release for a given injected volume, but the study concluded that the observed magnitude distribution for these wells is consistent with a maximum magnitude of 6.5 M_L, that is to say the upper bound of maximum event magnitude equivalent to the UK's tectonic setting.

The study also found that the relationship between earthquake counts and injection volume is non-unique and variable, but in general, increased seismicity rates tended to be associated with greater volumes, whilst smaller volumes were more associated with lower seismic rates.

[6] Maximum magnitude earthquakes induced by fluid injection, McGarr 2014 *(DOI: 10.1002/2013JB010597)*

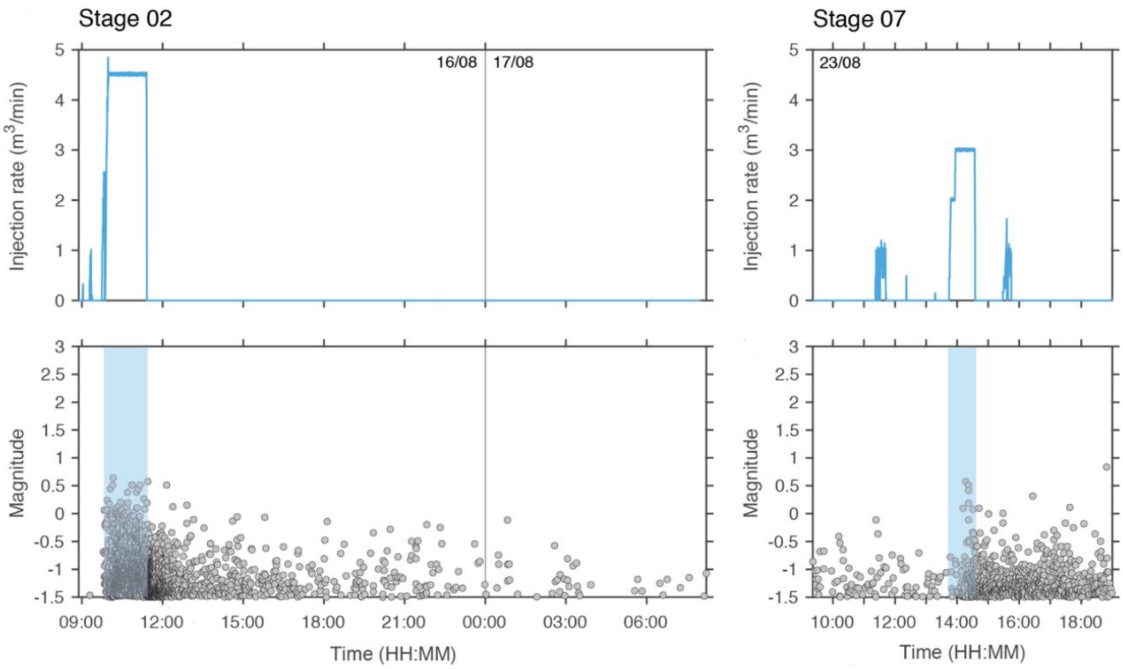

Figure 4 - Examples of the relationship between injection rates and observed seismicity at PNR2 (from BGS)

A standard ETAS model, used for naturally occurring earthquakes, was modified to integrate an assumed relationship that the background seismicity rate was proportional to the injection rate, and the resulting model provided much better earthquake rate forecasts than the standard model. In particular, the induced ETAS model captured the periods of high rates of seismicity due to injection.

This modified ETAS model calibrated on PNR1Z was then tested against the PNR2 dataset, where, the seismicity forecasting again performed better than a standard ETAS model, although not as well as a PNR2-specific model.

This testing demonstrates that where injection rates are known in advance, the injection-rate driven ETAS model can provide informative seismicity forecasts.

The study concluded that with further model development, injection-rate driven ETAS models may have some potential for probabilistic forecasting of seismicity rates using operational injection rates. The authors recommended that future work should focus on better capturing the relationships between injection rate and seismic response, and in reducing the uncertainty associated with estimating the real-time parameters required by the model.

Conclusions and Next Steps

These studies improved understanding of both the subsurface causes and surface impacts of the seismicity at PNR2, and there is potential to transfer many of the findings and knowledge from this work to other industrial applications where induced seismicity may pose a risk, such as geothermal, underground storage/disposal (i.e. methane, waste water, CO_2) and hydrocarbon production.

To build on these existing studies, a focus on understanding the differences between surface and downhole magnitudes is needed. M_w for both the downhole catalogues could be re-calculated using the full-waveform data, and a systematic analysis of the waveform data be conducted to understand its limitations. Using an improved and combined dataset, there could be opportunities to reduce the uncertainties in results when used in real-time statistical forecasting methods (i.e. ETAS), and potentially offer additional insights into the forecasting of induced seismicity.

Following the operations at Preston New Road and the issues raised within these studies, there remain significant uncertainties and challenges related to the prediction and management of induced seismicity from hydraulic fracturing.

Further work could usefully focus on addressing broader challenges, such as establishing the seismogenic nature of sites like Preston New Road, and whether certain geological settings or conditions are contributing factors to hydraulic-fracturing induced seismicity.

Improvements in the performance of predictive tools for the likelihood and magnitude of events are needed to support reliable mitigations and controls.

Finally, the limitations of reflection seismic surveys mean that there is a need to develop alternative or predictive methods that could predict and identify faults and fracture networks that lead to notable seismicity and aid planning operations to avoid these.

The OGA would like to acknowledge Cuadrilla Resources Ltd provision of this operational data, and to thank all the organisations and researchers who contributed to these studies.