Interim report of the scientific analysis of data gathered from Cuadrilla's operations at Preston New Road

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Executive Summary

This paper describes the work and findings of the studies commissioned by the OGA in February 2019 the purpose of which were to understand and learn from the induced seismicity observed at PNR1Z in 2018. The results of OGA's work on the experience of other jurisdictions is also described.

Together, the studies indicate that the rupture of a previously unidentified strike-slip fault is the likely cause of the larger Preston New Road (PNR) events. The ground motion generated by those events was close to that predicted prior to operations. For future operations, the possibility of larger events could not be excluded and these could cause damage and disturbance unacceptable under the current BEIS policy guidance. The methods for predicting event maximum and magnitude need further testing and cannot be viewed as reliable for PNR.

A summary of the four studies and the OGA work on experience is included below:

> The **Outer Limits** study concludes that a moderately sized, previously unidentified, strike slip fault intersected with the PNR1Z well. Ruptures on that fault generated the majority, if not all, of the larger observed events. The mechanism for rupture was likely to be the very rapid transfer of stress introduced by preceding injection. Such stress transfers are highly dependent on the specific orientation of the fractures and receiving faults and so cannot easily be generalised to other sites. The modelling approach used in the study could be used by operators before or during operations to identify whether their planned program is likely to re-activate identified faults.
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> **Ben Edwards et al** found that the ground motions and impacts on buildings of the PNR1Z well conformed to expectations. The predictions of ground motion and potential damage from future operations found that for a 3.5 M_L, "possible" scenario, perhaps 1 percent of all buildings would sustain cracked plasterwork, 0.2 percent sustain slight structural damage or moderate non-structural damage with perhaps 0.1 percent of buildings sustaining chimney failure. In an "unlikely" 4.5 M_L scenario, there could be widespread building damage with cracked plasterwork affecting approximately 10 percent of buildings with 6 percent likely to suffer chimney failure. The study also noted that larger seismic events are often reported as 'loud bangs' or 'crashes' and that a combination of possible felt and heard effects may be frightening to people with particularly concern about the possibility of future, stronger, events. In reviewing the risk to well integrity, the study found that even in an "unlikely" 4.5 M_L scenario, there is an "very low" probability that the well could be damaged.
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> The study recommends that for future operations it would be important to model both the range and maximum magnitude of likely induced seismicity and that the experience from PNR shows that there is very limited tolerance to seismic events that are felt, and that even very few events are likely to be considered a public nuisance.
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> The **Nanometrics** study found that none of the four "real time" maximum magnitude prediction models were very successful when applied to each fracturing stage separately. However, combining all stages as if they were one large stimulation improved performance and the models gave warnings of between 1 to 16 days for the main events. We consider these findings should be treated with caution at this stage until the PNR2 data is incorporated.
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> **BGS** applied a technique shown to have met with a degree of success for predicting natural earthquakes to the PNR data and found the model captured some, but not all the important

features of the data. Further research using independent datasets (such as PNR2) and the modelling of the hydraulic fracturing is needed to improve performance.

If successful, it may be possible to use this technique before future operations commenced as a forecasting tool for the potential range and distribution of seismicity generated from the hydraulic fracturing, or, during operations or following a significant seismic event, to better understand the rate and distribution of the resultant seismicity, providing an approach to determine the appropriate pause duration in a TLS.

The **OGA** work found that susceptibility to seismicity depends strongly on a location's specific geology with the mere presence of faulting or the parameters of the injection possibly of less importance. There is some evidence that susceptibility correlates to geological characteristics such as nearby basement faulting or high pore pressure. Further work may show these or other indicators to be generally applicable predictors. Methods for predicting the maximum magnitude that adopt a link between injected volume and the maximum magnitude of induced events lack convincing empirical evidence or proven theoretical basis.

PNR2 data should now be used to test and improve all four studies with work on maximum magnitude prediction given high priority. Further work on correlating seismic susceptibility to local geological characteristics could be undertaken. The current reports should be treated as interim.

Introduction and study objectives

In December 2018, Cuadrilla Resources Limited (Cuadrilla) completed the Hydraulic Fracturing operations on the PNR1Z well at PNR. Operations were interrupted several times by seismic events which exceeded the 0.5 M_L pause threshold set out in Cuadrilla's Hydraulic Fracture Plan (HFP) and Traffic Light System (TLS).

During those operations, the underground location and magnitude of some 38,000 induced seismic events were recorded. This high-quality data set provided an opportunity to study, in far more detail than previously, the origin of the events, the mechanisms by which they were generated, the models that seek to predict seismicity, the ground motion that resulted from the larger events and the potential damage and disturbance from seismicity generated by future operations. The results of these studies could be used to develop or refine the methods already adopted to avoid or reduce the chance of inducing significant seismicity during future operations.

History of fracturing operations in Lancashire

Cuadrilla's April 2011 fracturing operations at the Preese Hall 1 well induced a number of poorly recorded seismic events with maximum magnitudes up to 2.3 M_L. DECC suspended operations partly to investigate the management of those operations but also to allow an Expert Panel to investigate this, at that time, unexpected seismic response.

Following a public consultation on the conclusion of the Experts' Report, the way forward for operations was set out in a Written Ministerial Statement in December 2012. This required operators to submit an HFP setting out their proposed measures to avoid and mitigate induced seismicity and prescribed a deliberately cautious TLS that paused fracturing if a ≥ 0.5 M_L event was induced.

In 2017, Cuadrilla Resources drilled two horizontal wells, PNR1Z and PNR2, at the PNR site some 2.5 miles from Preese Hall. The HFP for the first well to be fractured, PNR1Z, indicated that it was located some distance from known large faults, provided for microseismic monitoring that enabled fractures to be located as they were created during operations and applied the strict, 0.5 M_L, TLS threshold. Fracturing of the well ran from 15 October until 17 December 2018 and induced 38,000 recorded microseismic events. Six of these exceeded the 0.5 M_L threshold and the largest, 1.5 M_L, event occurred after pumping had ceased and was felt by a few residents near to the well site. Cuadrilla, facing an unrelated operational problem and concerned about their ability to operate within the 0.5 M_L threshold, ceased hydraulic fracturing having attempted only 17 of their planned 41 injection stages and with limited amounts of proppant being placed. The well was then tested.

While the studies summarised in this report were underway, Cuadrilla commenced hydraulic fracturing at the adjacent PNR2 well. The hydraulic fracturing at that well induced further seismic events of a different character to, and which exceeded the magnitude of, those of PNR1Z (up to a 2.9 M_L event). Those events came too late to be included in the studies. PNR2 operations are currently suspended.

A more detailed account of Cuadrilla's operations and the development of the mitigation approaches is provided in Annex 1.

The Studies and their conclusions

The operations at PNR1Z generated microseismic and operational data of an unprecedented quantity and quality. In February 2019, the OGA commissioned four studies to analyse this data. Although at that time there was considerable public debate as to whether the TLS threshold was appropriate, these studies were not commissioned as a review of the TLS and BEIS were very clear that they were not contemplating a review.

Ideally these studies would have included data from the PNR2 operations described above but, when commissioned, it was unclear on what timescale Cuadrilla would commence those operations, if at all. It was decided to proceed without further data since, if PNR2 were to be delayed for some time, this early analysis might assist in planning and managing those operations. In fact, Cuadrilla decided to move forward with PNR2 shortly after the studies were initiated and commenced fracturing in August 2019 but the data was gathered too late to form part of these studies.

The suite of studies was not intended to be comprehensive but they do focus on those areas where new data would most usefully add to understanding. The purpose of each study, their authors and conclusions are summarised below. The studies are technically complex and a thorough reading of the reports is required for a full understanding of the conclusions.

Outer Limits: Geomechanical Interpretation of Microseismicity at the PNR1Z Well

This work used the observed location and magnitude of the PNR1Z events to identify the physical mechanisms that caused the induced seismicity on pre-existing faults[1], sought to locate the faults that were ruptured and establish their size. To test their findings, a simple geomechanical model of the hydraulic fractures and the interaction of these with the faulting was constructed.

As background, it is generally thought that induced seismicity of significant magnitude is generated by the reactivation or rupture of pre-existing faults close to the fracked well rather than originating from the fracturing of "new" rock (which, of itself, generates only very low magnitude seismicity). To generate events of significant magnitude, the injected fluids are thought to reactivate the faults by

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[1] The pre-existing feature on which the seismicity is induced could be a single fault plane or a zone of natural fracturing. None of the studies seek to distinguish between these and "fault" is used to describe these features both in this summary and in the studies themselves.

one or both of two physical mechanisms. The first mechanism is that the injected fluids enter a fault and cause the pressure within it to increase, thereby reducing the forces which normally clamp the two faces of the fault together and allowing it to slip or "rupture". If the fault is already "critically stressed", as many are thought to be, a relatively small change in pressure will be sufficient to cause the fault to rupture (see Figure 1 case 1 and 2). The second possible mechanism is that the new fractures created by the injected fluid compress or "stress" the rock around them (rather as additional passengers entering an over-crowded train compress the passengers already standing all along the carriage). This additional stress is transmitted through the rock and, if it encounters a suitably orientated and critically stressed fault, will force it to rupture (Figure 1 case 3).

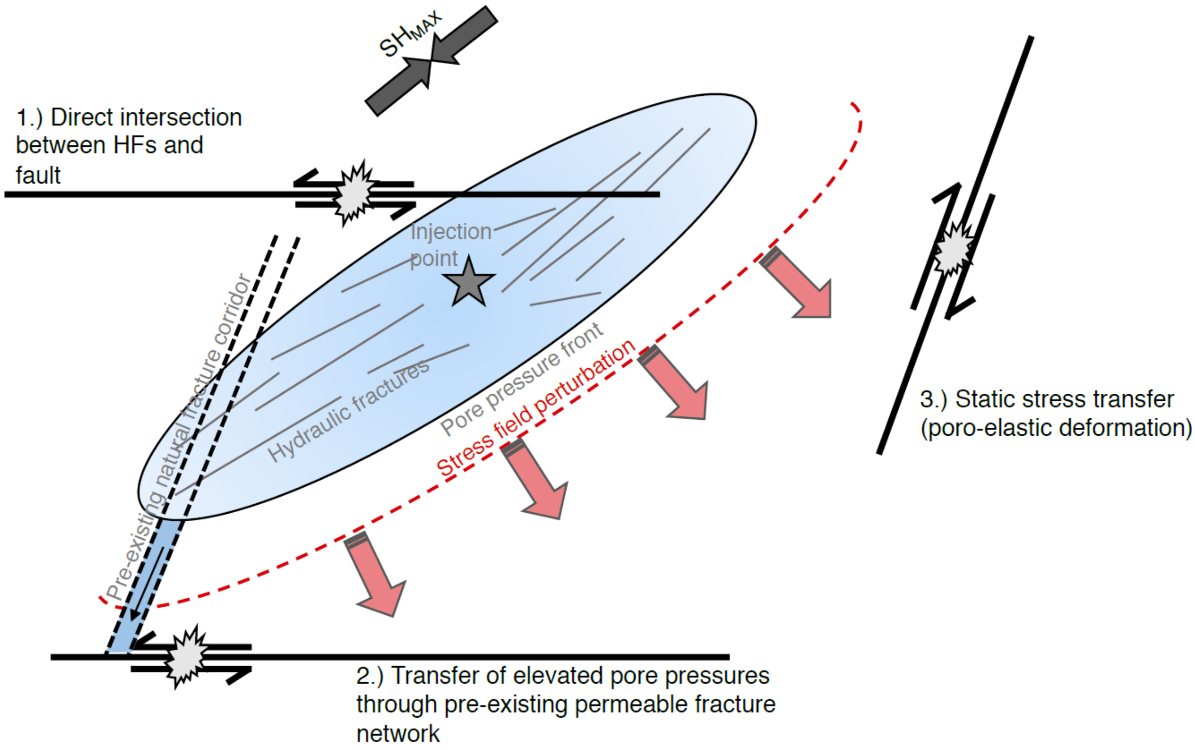

Figure 1 - Schematic showing the various mechanisms by which hydraulic fracturing can reactivate faults. Adapted from Igonin et al. (2019)

To see whether faults could be identified, the study looked in detail at the timing, magnitude and characteristics of the events at PNR, and the structure of these events when they were plotted in three dimensions. The study concluded that that most of the larger seismic events occurred along a, previously unidentified, pre-existing fault running to the northeast from the well and which appeared to be intersected by many of the staged fractures along the well (see Figure 2).

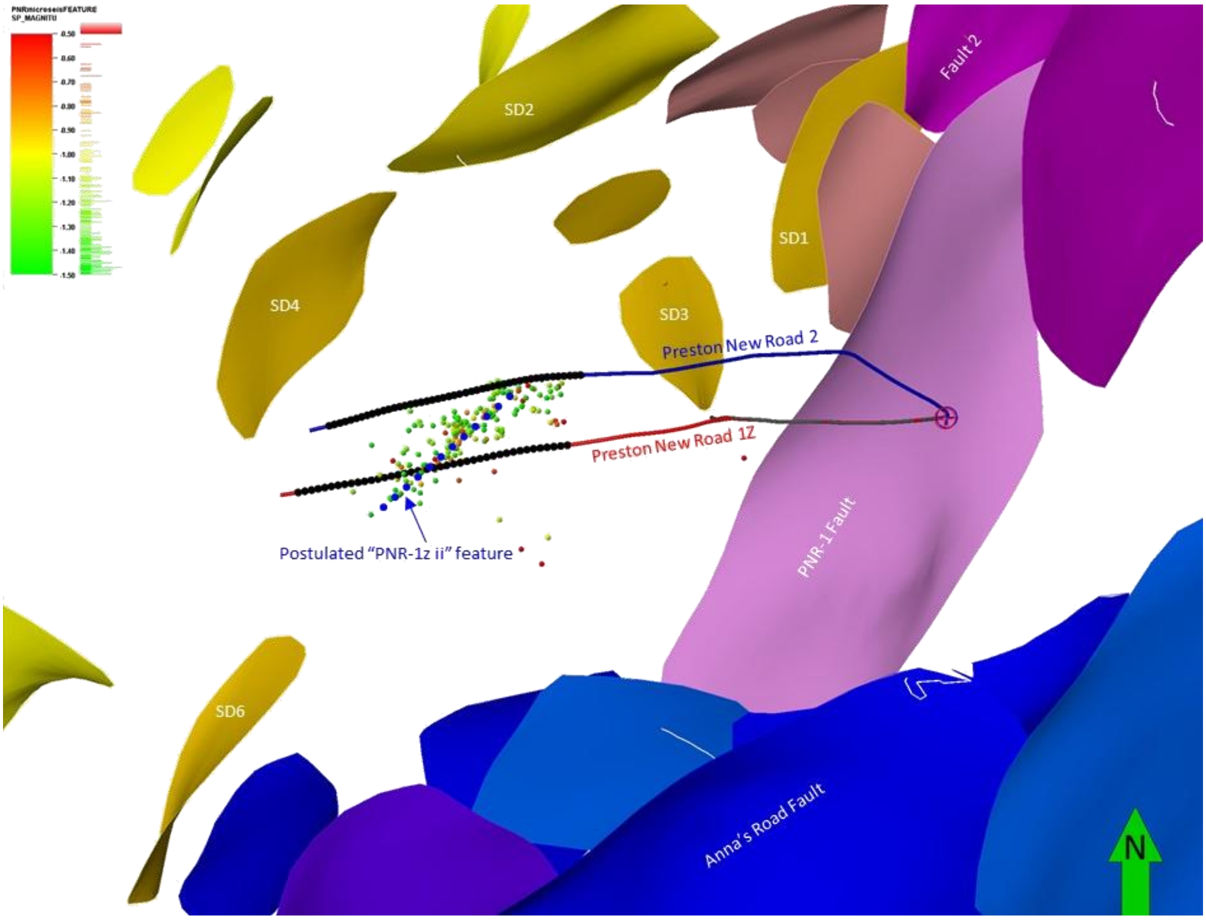

Figure 2 - Plan view of Preston New Road, regional faults, and the newly identified "PNR1Z ii" feature. Microseismic dots are coloured by magnitude, and filtered to the operational 'hiatus'

However, many aspects of the data were found to be difficult to explain even with the presence of this fault if the events were driven solely by pressures and fracture propagation (i.e. the first mechanism described above). Example difficulties being that clusters of events were spatially separated from the fluid injection points, that many events occur at large distances from the well for stages with only small injection volumes and that events occur near-instantaneously across a range of distances. To explore these unintuitive observations the study developed and applied statistical stress models of fractures and faulting and concluded that stress transfer (the second mechanism described above) could account for these observations and was thus likely to be an important mechanism in controlling fault reactivation at PNR1Z. The study used further modelling to conclude that the identified fault did not extend behind the heel of the well.

The authors caution that these stress transfer effects are highly dependent on the specific orientation of the induced fractures and receiving faults and so cannot easily be generalised to other sites. However, the report notes that the modelling approach used could be applied before or during operations in near real-time to enable operators to identify whether their planned program is likely to re-activate identified faults and to adjust their program accordingly.

Ben Edwards et al: Impacts of Seismicity: Transmission to People and Property, Environmental and Well Integrity

The purpose of this study was to examine the impact of the surface ground motion caused by induced seismicity at the PNR site on people, property and well integrity. The study reviewed the ground motion recorded at PNR1Z and then predicts the impact for a range of induced seismicity scenarios for future operations at the site. The study also provides an extensive review of ground motion, the methods for predicting its magnitude, the factors that influence its impact and relevant experience around the world.

The two largest events from PNR1Z (1.5 M_L, 1.1 M_L) were both assigned European Macroseismic Scale[2] intensity II, which equates to "Scarcely felt – Felt only by very few individual people at rest in houses". The study found that the ground motions experienced could be considered as almost imperceptible and well below the level of vibration that people experience going about everyday activities.

To estimate potential shaking and damage from future operations, and the associated macroseismic intensities[2], the study modelled five scenarios for earthquakes of magnitudes 2.5 to 4.5 M_L, with a focus on events with 2.5, 3.5 and 4.5 M_L which were considered as "likely", "possible" and "unlikely" respectively[3]. These scenarios were selected in the context of the geology and experience and in the absence of a reliable method for predicting maximum event magnitude. To improve the accuracy of the scenario predictions, fifty-seven of the PNR1Z events were analysed to identify the best ground motion prediction model, three measurements were taken of the geomechanical properties of the soil at locations around Preston New Road and a survey was made of the construction style and vulnerability to shaking of buildings in the local area.

The model estimates that the ground motion from a 2.5 M_L "likely" event would be felt for distances of about 2 km from the epicentre, but with no expected impact on buildings or structures[4]. The report notes however that seismic events occurring at shallow depths are often reported as 'loud bangs' or 'crashes' and that, even at this relatively low magnitude, a combination of possible felt and heard effects, coupled with the fear of possible future events, could be a cause for concern for at least some of the local population.

The 3.5 M_L "possible" scenario leads to a significant increase in the extent of shaking, with an event likely to be felt across the Fylde, including Blackpool and parts of Preston. As outlined in Figure 3, the model predicts that perhaps 1 percent of all buildings in the study area[5] would sustain cracked plasterwork, and 0.2 percent would sustain slight structural damage or moderate non-structural damage, with 0.1 percent of buildings possibly sustaining chimney failure.

The 4.5 M_L "unlikely" scenario would be widely felt, covering much of the region including all of Blackpool, Preston and beyond. The scenario indicated that there could be widespread building damage in the study area, with cracked plasterwork affecting approximately 10 percent of buildings, more serious structural damage (of varying degrees) affecting 5.4 percent of buildings, and 5.4 percent also likely to suffer chimney failure. Some damage would be caused to buildings outside of the study area.

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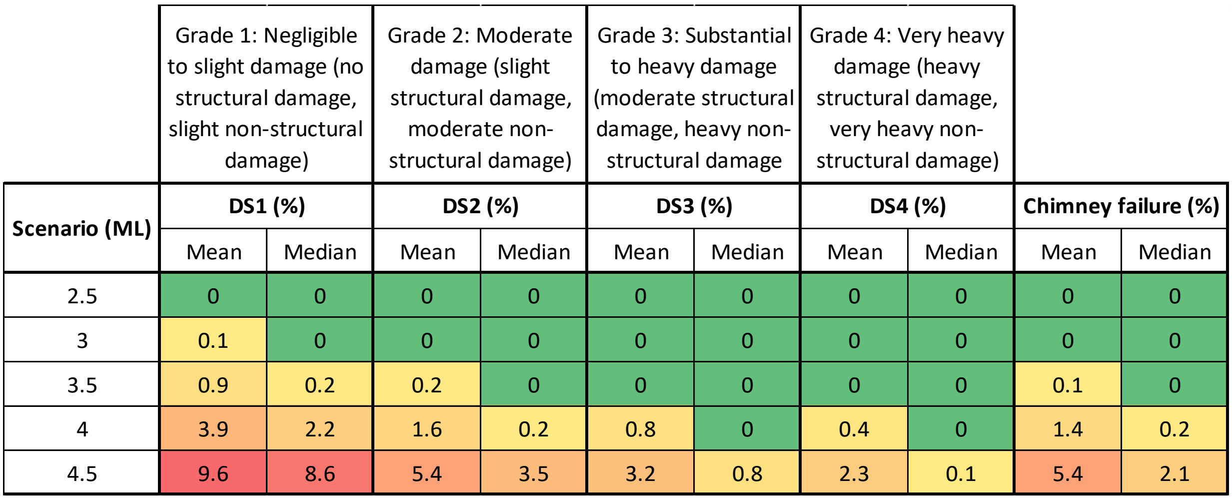
[2] The full EMS scheme which runs from I (Not Felt) to XII (Completely Devastating) is set out as table 3.1 of the full report, this summary uses only the descriptions.

[3] It had been intended that the BGS study described below would provide an estimate of the maximum event magnitude but this was found not to be possible. The 4.5 M_L "unlikely" event is based on the largest observed UK event seen as being possibly induced. The 2012 Expert Report considered a ~ 3.0 M_L event as the maximum based on coal mining induced seismicity.

[4] The estimates of damage summarised here are based on a "mid-case for shallow ground velocity" thought to best represent the study area as a whole. In fact, the estimates for the low and high cases are broadly similar.

[5] The study area is a 10 x 10 km area centred on the Preston New Road drill site.



	Grade 1: Negligible to slight damage (no structural damage, slight non-structural damage)		Grade 2: Moderate damage (slight structural damage, moderate non-structural damage)		Grade 3: Substantial to heavy damage (moderate structural damage, heavy non-structural damage		Grade 4: Very heavy damage (heavy structural damage, very heavy non-structural damage)			
Scenario (ML)	**DS1 (%)**		**DS2 (%)**		**DS3 (%)**		**DS4 (%)**		**Chimney failure (%)**	
	Mean	Median	Mean	Median	Mean	Median	Mean	Median	Mean	Median
2.5	0	0	0	0	0	0	0	0	0	0
3	0.1	0	0	0	0	0	0	0	0	0
3.5	0.9	0.2	0.2	0	0	0	0	0	0.1	0
4	3.9	2.2	1.6	0.2	0.8	0	0.4	0	1.4	0.2
4.5	9.6	8.6	5.4	3.5	3.2	0.8	2.3	0.1	5.4	2.1

Figure 3 - Summary of modelled scenario damage results using the mid-case for shallow ground velocity (V_{S30} = 240 m/s) throughout the study region against EMS macroseismic building damage states.

The study recommends that, ideally, a probabilistic seismic hazard assessment (PSHA) should be made at the PNR site, including fragility measurements of local buildings rather than analogues. The study found that for future operations it would be important to model both the range and maximum magnitude of likely induced seismicity. Experience from Preston New Road shows that there is very limited tolerance to seismic events that are felt, and that even very few events are likely to be considered a public nuisance. This is particularly relevant following the 2.9 M_L event in August 2019, which occurred as the authors were finalising the report where there were many felt reports, and some reports of cosmetic damage to buildings.

The potential impacts of seismicity on well integrity through two mechanisms were also considered: that the well is sheared by intersection with a fault that slips or that the well is damaged by strain caused by seismic waves near the surface.

Modelling of the design and construction of the PNR1Z well identified a 1.5 m section of the well with potential vulnerability to the shearing and deformation from fault slip from an “unlikely” 4.5 M_L event. As this section is a small proportion of the overall well, which extends for over 2,100 m, the probability of shear failure at this location is “very low”. It was also assessed that there was “extremely low” probability that the well could be damaged due to strain generated from seismic waves near to the surface, even under the largest 4.5 M_L scenario.

Nanometrics: Real-time forecasting to mitigate effects of seismicity

The purpose of this study was to identify the strengths and weaknesses of “real time” maximum magnitude earthquake prediction models and whether they could provide warning of imminent large earthquakes while operations were in progress.

The study used the downhole seismic data recorded at PNR1Z to test four published predictive models: Shapiro (2011), Hallo (2014), and two derived from Van der Elst (2016). Except for Van der Elst, all the models relate maximum induced seismicity to the volume of fluid injected.

The study found that when the four models were tested against the observed seismicity *using the injection volume and seismicity for each fracturing stage separately*, they were not very successful in forecasting maximum magnitude. While the largest event was, in most cases, forecasted by Hallo, that model overestimated the maximum magnitude in general. The tests also found that the notification time for many of the successful forecasts was very short giving insufficient warning to perform practical operational mitigations. There were also examples where the largest event occurred early in the sequence, before the occurrence of the c. 100 events required to start statistical analysis.

The study then considered analysing all stages together *as if they were one large stimulation* arguing that injection at each stage changed the stress conditions and that, by focusing on individual stages, the overall changes in the stress field would be ignored. Adopting that approach, the authors concluded that the study demonstrated that using the complete catalogue improved the forecasting outcome and the prediction models successfully forecasted all the four major events with advance notification varying between one and sixteen days. The study also found that, over time, the forecasts lose their sensitivity to the cumulative injection volume. The question of uncertainty in the predictions was not rigorously addressed.

OGA note. A degree of caution should be applied to these conclusions until they are tested against the PNR2 data. Both the Shapiro and Hallo models "cap" the maximum magnitude by, respectively, limiting the size of the earthquake rupture area or limiting the energy available to be released. Neither of these assumptions have a confirmed physical basis and both Shapiro and Hallo place caveats on the applicability of their methods. Further, the finding that the accuracy of the methods is improved by treating all stages of the operation as one, large, treatment may be a result of the statistics rather than a true improvement in prediction. The Van der Elst model makes fewer assumptions, simply adopting the limit on induced earthquake magnitude as that for natural tectonic events occurring in the same geological setting.

Action: Magnitude = 0.6
Probability of exceeding = 99.97%
Number of events equal or larger = 8

Red: Magnitude = 0.5
Probability of exceeding = 100.00%
Number of events equal or larger = 11

Amber: Magnitude = 0.4
Probability of exceeding = 100.00%
Number of events equal or larger = 14

Green: Magnitude = 0.0
Probability of exceeding = 100.00%
Number of events equal or larger = 47

Figure 4 - Nanometrics Dashboard for the entire recorded seismicity by the downhole array, showing Mmax predictions for Shapiro, Hallo and Van Der Elst methods using a 12 hour time interval. The forecasting notification time is highlighted.

BGS: Innovations in forecasting the distribution of seismicity

This study applied a technique for forecasting the aftershocks of natural earthquakes to the data from PNR1Z. The purpose of the work was to test the applicability of the technique to hydraulic fracture induced seismicity to provide a statistical forecast of seismicity during and after hydraulic fracturing. If successful, the modelling could be extended to provide a framework that could be used to better understand the rate and magnitude of seismicity that follows during and after operations at sites across the UK, to inform future real-time decision making and risk mitigation. With further work, in the future this could also be used before operations commenced as a forecasting tool for the potential range and distribution of seismicity generated from the hydraulic fracturing.

Mathematical models have been developed that predict the evolution of natural earthquake cascades (the series of aftershocks) with a degree of success. Such a model was used in this study - the Epidemic Type Aftershock Sequence Model (ETAS). This is a statistical approach which seeks to predict future earthquake probabilities. It has previously modelled earthquakes associated with geothermal energy and water injection and has robustly forecast the observed seismicity in terms of the number of events.

ETAS models use the statistical observations of previously observed seismicity to predict the occurrence of future events – a trail of aftershocks from each “new” event is predicted and then used to predict a further set of aftershocks and so on[6]. This creates a cascade of aftershocks statistically similar to those seen in nature. As the model runs, the magnitude of each of the events in the cascade is drawn independently from the statistical distribution of previously observed events. Consequently, the ETAS model is primarily aimed at calculating the number and timing (and if required, location) of events in an aftershock cascade. The magnitudes of these events, although a key part of the calculation, are an input. It had been intended that the study would provide a site-specific estimate of the maximum magnitude of induced seismicity possible, but the authors concluded that this was not currently possible within the timeframe of this project. For this application, the input used was drawn from Eurocode 8 seismic hazard maps for the UK which assumes the maximum natural earthquake magnitude to be 6.5 M_w.

To assess the suitability of the ETAS model to induced microseismicity at PNR1Z, a temporal ETAS model was calibrated to the microseismic catalogue (as shown in Figure 5) and then a retrospective forecasting experiment was performed on this data. The calibration consists of estimating the magnitude distribution and estimating five additional parameters of the ETAS model.

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[6] Each event can trigger further events according to its magnitude (large quakes trigger exponentially more events), and triggered events have a (small) chance of being larger than the parent event. This feature of the model is consistent with the observation that the largest magnitudes do not exclusively occur in early post-mainshock phases (natural seismicity) or at the beginning of hydraulic fracturing operations (induced seismicity). Triggered seismicity is modelled to decay in time and has as an input the “Omori *p*-value” which characterizes how fast seismicity decays over time and is calculated from the decay of observed aftershocks in the location.

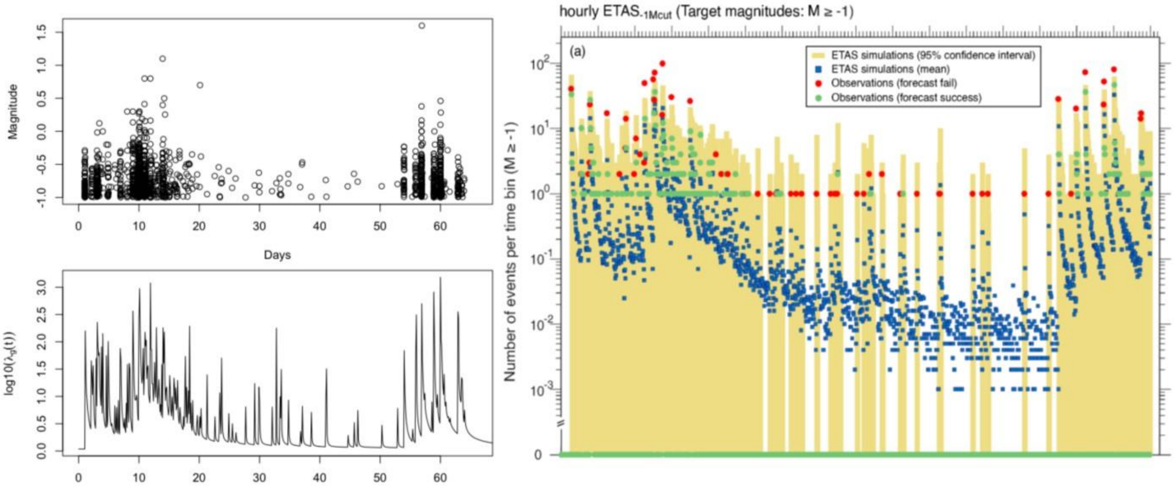

Figure 5 - Comparison of the observed PNR1Z seismicity against the calibrated conditional intensity function of ETAS-1Mcut, and ETAS simulation results.

The performance of the ETAS forecasts showed some successes particularly in the periods between fracturing stages but, during the injection stages themselves, the model underpredicted the observed seismicity, including the frequency or clustering of events. The results suggest that a different mechanism dominates the generation and type of seismicity during injection periods which is likely driven by the pore pressure changes caused by injection fluids.

The predictive capabilities of the model are closely linked to the quality of data on previous earthquakes (the catalogue), even for the smallest magnitudes. There should be a continuing focus on the collection of catalogues that feature high-resolution earthquake locations. Further research involving the independent dataset collected during subsequent hydraulic fracturing in 2019 at well PNR2 would allow for more confidence in the model performance. Further development of the model, particularly the modelling of injected volume and pressures is likely to improve predictive performance.

OGA: International Experience and Mitigations

There are now numerous international examples of significant felt seismic events induced by hydraulic fracturing. Figure 6 details the largest recorded seismic events by region, putting the events in Lancashire in context. While this illustrates that the Lancashire experience is not unique, it should be noted that other regions have seen significantly greater hydraulic fracturing activity.

Region	Country	Max. event	Year	Comment
Sichuan	China	5.2 M_W	2018	Changning
British Columbia	Canada	4.6 M_W	2015	Fort St. John
Alberta	Canada	4.1 M_W	2016	Fox Creek
Ohio	USA	3.7 M_L	2017	
Oklahoma	USA	3.2 M_L	2014	
Lancashire	United Kingdom	2.9 M_L	2019	Preston New Road 2
West Virginia	USA	2.7 M_L	2013	
Lancashire	United Kingdom	2.3 M_L	2011	Preese Hall 1
Pennsylvania	USA	1.9 M_L	2016	

Figure 6 - Examples of notable seismic events considered to be likely to have been induced by hydraulic fracturing operations (modified from The Human-Induced Earthquake Database (HiQuake), (www.inducedearthquakes.org). Last accessed 25/09/2019.

The paper presents a short overview of the experience of injection induced seismicity in other jurisdictions and is drawn from discussions with N. American regulators, operators and service companies and from recent relevant publications. It is not intended to be comprehensive but highlights some current thinking on topics with relevance to UK operations, specifically a description of other geological settings; the experience of seismicity caused by other applications of fluid injection including geothermal; the maximum magnitude of induced events in other geological settings; the various Traffic Light Systems that have been adopted and potential improvements; and the operational mitigations that have been tried and their success.

Two general conclusions are drawn. The first is that the tendency for injection to induce seismicity appears to be very location/geology specific with probably less dependency on the simple presence of faults or the engineering parameters of the injection operations themselves. The second conclusion is that, while the basic understanding of the physical processes that can cause seismicity are reasonably well understood, the application of those processes to specific operations or geology, the data on which is often sparse, is still in the early stage of development. In the light of this it is not surprising that few, if any, generally applicable rules have been established that can be reliably applied to eliminate or mitigate induced seismicity. This underlines the need to take every opportunity to improve the understanding of the geological setting prior to operations, conduct operations with caution, rapidly identify unexpected seismic responses and be prepared to react quickly, if necessary suspending operations to accommodate new information.

When relating seismicity to geological setting, in certain areas of Canada and the US there is some correlation between significant seismicity and the proximity, and even direct involvement, of deeper basement faulting - hydraulic fracturing in areas that are faulted but not in such close proximity to these deeper faults results in very much lower frequency and magnitude of events. In China, the presence of unexpected, very localised intense seismicity has been shown to arise from a large, previously unidentified, fault below the fracturing horizon, although a correlation with basement rock was not established. Canadian experience is also that there is a strong correlation between induced earthquakes and fracturing in areas of high in-situ pore pressure (elevated pore pressure is a feature of the Bowland Shale at Preston New Road). Further work on the correlation of seismicity and, particularly, event magnitude with deeper faulting and/or overpressure may show these are indicators that could be more generally applicable predictors.

Various approaches have been taken to mitigating seismicity either from the start of operations or at resumption following induced events. Much attention has been given to reducing injection rate and/or volume. While there are many hypothesises linking injected volume to the maximum magnitude of induced events, the empirical evidence or theoretical basis for this is inconclusive. Opinions on the benefit of immediate flowback of injected fluids are sharply divided over whether an immediate flowback limits the number and maximum magnitude of induced events or could indeed increase them. It may be that, in certain geological settings, both volume and flowback mitigations will work and in others they will not. Similarly, the effectiveness of skipping stages to avoid induced seismicity is inconclusive, again the effectiveness of such a strategy could be very dependent on the geological setting.

Many jurisdictions require some form of TLS which monitors for unusual seismic events and requires action, including mitigation or suspension of operation, should a certain magnitude threshold be exceeded. It has been observed that while these systems are beneficial, they may not be effective at preventing either large events or aftershocks. It should be noted however that for the largest (> 4 M_L) events identified in this paper either no TLS was in place, the TLS was not followed or the thresholds were so large as to be ineffective. As the understanding of induced seismicity has improved, several suggestions have been made for improvements to TLSs such as monitoring the real-time development of the magnitude or location of events, or incorporating the mathematical simulation of induced seismicity. It should be noted that the UK's TLS adopts the most precautionary thresholds of any jurisdiction and already incorporates real time monitoring of magnitude and location.

Recommendations and next steps

All four of the studies provide ample opportunities for testing or improving their findings against the recently collected data from PNR2 which shows several characteristics unlike those of PNR1Z. Some prioritisation of this work may be necessary.

Any further work should be delivered by the end of 2019. In the light of the above, all the studies could be considered interim reports.

In the longer term, focus should be placed on the accurate prediction of the maximum event magnitude for any future PNR operations (or elsewhere) both as a prior input for the HFP and as a real-time mitigation parameter.

There are some indications that induced seismic susceptibility can be correlated to the overall geological characteristic of a site more strongly than to the mere presence of faulting. A more detailed review of the literature could be undertaken as a preliminary step to undertaking UK focussed studies.

Annex 1

Early operations

In 2011, Cuadrilla Resources Limited completed drilling of Preese Hall 1; the first onshore shale gas exploration well in the United Kingdom to investigate the resource potential of the Bowland Shale.

The well was drilled vertically through the Bowland Shale strata to a total depth of 2740 metres, and following evaluation of the wireline logging through the shales, a number of potentially prospective shale horizons were identified, for which initial estimates indicated a potentially significant shale gas resource. A total of six zones in the Bowland shale were perforated for hydraulic fracturing, which commenced on 26th March 2011.

Six stages were hydraulically fractured during these operations, with the largest stage, stage 2 using treatment volumes using approximately 2250 m^3 of slick water, and placing 117 tons of proppant.

On the 1st April 2011, 10 hours after shut-in of stage 2, a magnitude 2.3 M_L seismic event was detected in the Blackpool area by the BGS regional seismic monitoring network, and was felt by local people.

Following the completion of stage 5, on the 27th May 2011, a further magnitude 1.5 M_L seismic event occurred. These events were suspected to be associated with the hydraulic fracturing at Preese Hall, and operations were therefore suspended, and a series of reports to investigate the induced seismicity were commissioned.

In response to these unexpected seismic events, the government imposed a temporary moratorium on hydraulic fracturing whilst these scientific investigations were conducted, and Cuadrilla Resources Ltd were requested to undertake a full technical study into the relationship between the earthquakes and their operations.

Resumption of Hydraulic Fracturing

Cuadrilla submitted to DECC a synthesis report with several technical appendices in November 2011. These reports examined the seismological and geomechanical aspects of the seismicity in relation to the hydraulic fracture treatments, and concluded that these seismic events were caused by the hydraulic fracturing operations. They also estimated future seismic hazard and proposed recommendations for future operations to mitigate seismic risk.

To evaluate these studies and recommendations, DECC asked three leading experts in the fields of seismology, induced seismicity and hydraulic fracturing to make an independent assessment of the Cuadrilla-funded studies; Dr. Brian Baptie, Professor Peter Styles, and Dr. Christopher A. Green.

The independent experts made recommendations to DECC for mitigating the risk of induced seismicity resulting from continued hydraulic fracturing operations, and DECC conducted a public consultation in April to May 2012 on the review of Cuadrilla's geotechnical report and recommendations by the panel of independent experts.

An independent review of the health, safety and environmental risks associated with hydraulic fracturing for shale gas was also carried out by the Royal Academy of Engineering and the Royal Society. The report, published in June 2012, concluded that the risks from hydraulic fracturing could be managed effectively in the UK so long as operational best practices are implemented, and enforced through regulation.

In response to the recommendations made in reports by the Expert Panel and the Royal Society, and following public consultation, in December 2012 Ed Davey, the Secretary of State for Energy, announced the lifting of the moratorium subject to the introduction of new regulatory requirements to ensure that seismic risks are effectively mitigated as recommended in these reports.

Before the OGA will consider proposals for hydraulic fracturing, operators are first required to review the available information on faults around the proposed well to minimise the risk of activating any fault by hydraulic fracturing, and are required to monitor background seismicity before operations commence.

A Hydraulic Fracture Plan is required to be agreed by the OGA, in which the operator sets out its operational measures to mitigate against abnormal seismicity and potential risks posed to the environment from those operations.

Real time seismic monitoring will also continue during operations, with these subject to a “traffic-light” regime, so that operations can be quickly paused and data reviewed if unusual levels of seismic activity is observed.

The remedial action level for the traffic light system (that is, the “red light” whereby injection is paused for at least 18 hours) will be set at precautionary level of magnitude 0.5 (far below a perceptible surface event, but larger than the expected level generated by the fracturing of the rock)

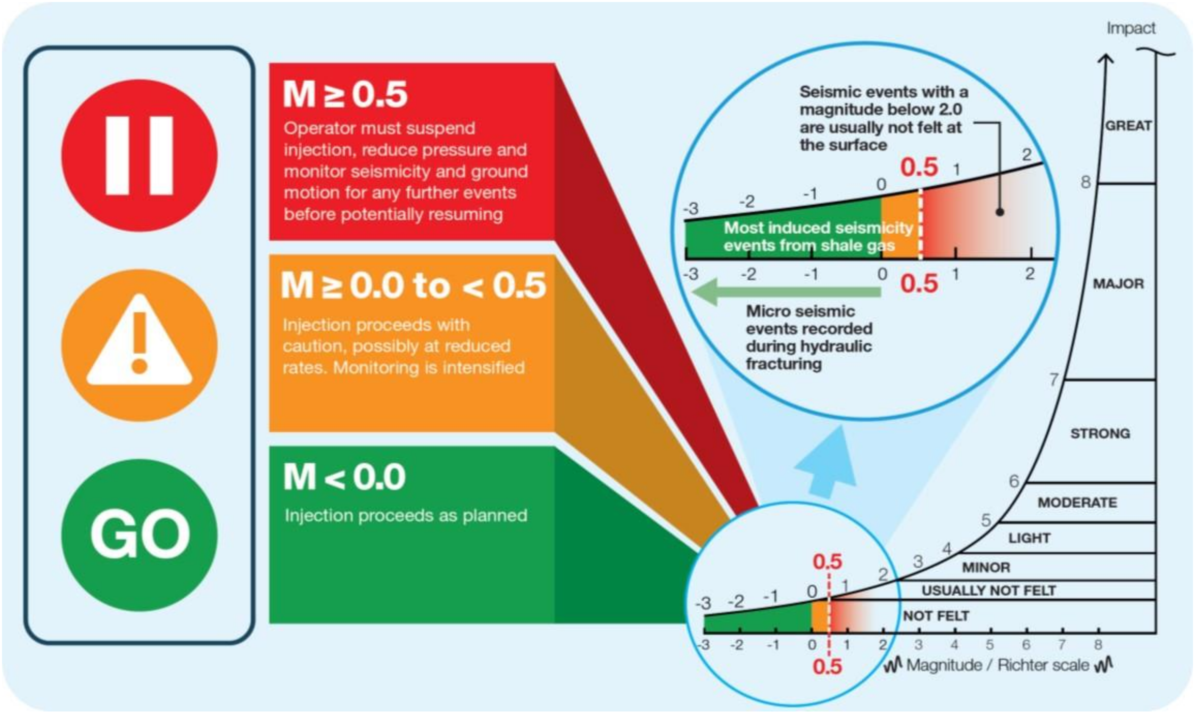

Figure 7 - Schematic of the Traffic Light System (OGA, 2018)

Operations at Preston New Road 1Z

In 2017, Cuadrilla Resources commenced exploratory drilling at a new site on the Fylde Peninsula, Lancashire, known as Preston New Road. The objective of the work was to drill a vertical pilot well (Preston New Road 1) through the Bowland Shale, and to collect data on the shale including wireline logging and core data.

Preston New Road 1 was then deviated horizontally from the pilot well through the upper-most section of the Lower Bowland Shale, and a second, horizontally deviated well known as Preston New

Road 2 was drilled through the lower-most section of the Upper Bowland Shale. Both horizonal wells were completed in the Bowland section with sliding sleeve casing, to allow for hydraulic fracturing to be tested with a flexible methodology.

In September 2018, the OGA agreed the required Hydraulic Fracture Plan for the hydraulic fracturing of the Preston New Road 1Z well, in which Cuadrilla proposed to fracture up to 41 stages along the horizontal well, using up to 765 m^3 of slick water fluid to place 75 tonnes of proppant per stage.

The required monitoring systems for the operations included a surface seismic array, a downhole microseismic array, and vibration monitors.

The Traffic Light System used 8 surface-based seismometers installed as a local array surrounding the site, also integrating seismic data from separate independent seismic arrays operated by the British Geological Survey and the University of Liverpool to detect traffic light events that may be associated with the operations.

The microseismic array consisted of 12 geophones located downhole in the adjacent Preston New Road-2 well, and was used to detect microseismic activity generated from the development of hydraulic fractures and to identify any interaction between these and pre-existing faults.

Based on at least 4 ground motion monitors, the vibration monitoring system compliments the Traffic Light System by measuring the ground motion of detected seismic events. The monitors are located adjacent to sensitive or vulnerable structures in the local area.

Hydraulic Fracturing in the Preston New Road 1Z well commenced on 15 October until the 17 December 2018. Local seismic events were detected throughout the operations, with the BGS reporting a total of 57 events. Nine of these events were reported as traffic light events (greater than 0 M_L) by the operator, with six of these seismic events exceeding the magnitude 0.5 M_L threshold. Six of the nine TLS events occurred during pumping, and four resulted in the premature termination of the associated stages. Three of these "Red" TLS events occurred after pumping, and were therefore trailing events, and extended the operational pause following a "Red" event by a minimum of a further 18 hours.

The largest event that occurred had a magnitude of 1.5 M_L, immediately following the completion of stage 38. This event was felt by some local residents near to the well site. Operations were paused for approximately 48 hours, during which time the operator, and the OGA reviewed the microseismic and operational data from the stage, and consulted with independent experts before operations were allowed to resume. All recorded TLS events induced by PNR1Z operations are set out in Figure 8.

Interpretation of the microseismic data recorded through the operations, showed that many of the TLS events that occurred during injection may have been associated with a fault plane or fractured zone that intersected with the well path. This potential feature was not identifiable from the 3D seismic data, but analysis of the microseismic data, particularly during the 30-day period where no operations took place revealed an area of microseismic activity that continued even without stimulation from injection. A working assumption for the repeated traffic light events was that the feature, named "PNR1z ii", was being reactivated by operations. In an attempt to avoid further seismicity, Cuadrilla skipped stages in proximity to the feature through the operations.

Day	Date	Stage	Fluid (m^3)	Proppant (tonnes)	TLS Seismicity		Comments
					During	Trailing	
Tuesday	15-Oct	1	2	0			mini-frac
Tuesday	16-Oct	1	162	0			mini-frac and main-frac
Wednesday	17-Oct	2	317	22			mini-frac and main-frac
Thursday	18-Oct	3	394	51			mini-frac and main-frac
Friday	19-Oct	12	34	0	0.3 ML		mini-frac cut short
Saturday	20-Oct	12	222	7			main-frac cut short due to downhole data delay
Sunday	21-Oct		0				
Monday	22-Oct	13	385	37			mini-frac then main-frac cut short operational issue
Tuesday	23-Oct	14	129	2	0.4 ML		mini-frac, then main-frac cut short amber
Wednesday	24-Oct	18	11	0		0.48 ML	main-frac cut after minifrac due to trailing amber 0.48
Thursday	25-Oct	22	351	17	0.37 ML		main-frac cut short after amber pumping
Friday	26-Oct	30	142	4	0.76 ML		continued after 0.26 amber, but cut short after red
Saturday	27-Oct	31	112	2		0.78 ML	cut short due to downhole data delay, before trailing
Sunday	28-Oct		0	0			
Monday	29-Oct	32	119	5	1.0 ML		mini-frac, then main-frac cut short after red
Tuesday	30-Oct	41, 39	31	0			two mini-fracs only
Wednesday	31-Oct	37, 40	26	0			two mini-fracs only
Thursday	01-Nov		0	0			flowed back, no injection
Friday	02-Nov	35, 38	29	0			two mini-fracs only
Saturday	03-Nov		0	0			
Sunday	04-Nov		0	0		0.66 ML	
Monday	05-Nov		0	0			flowed back, no injection
------ FLOWED BACK; HIATUS IN OPERATIONS ------							
Friday	07-Dec		0	0			flowed back, no injection
Saturday	08-Dec	37	78	4			main-frac
Sunday	09-Dec		0	0			
Monday	10-Dec	37	107	3			main-frac
Tuesday	11-Dec	38	268	28		1.5 ML	main-frac, 0.1 and 0.0 amber trailing
Wednesday	12-Dec		0	0			
Thursday	13-Dec	39	261	27			main-frac
Friday	14-Dec	40	251	20	0.86 ML		main-frac cut short after 0.1 amber, 0.86 red
Saturday	15-Dec	41	18	0			mini-frac
Sunday	16-Dec		0	0			
Monday	17-Dec	41	431	50			main-frac
	TOTALS		3877	278			

Figure 8 - Summary of hydraulically fractured stages and Traffic Light Events recorded during 2018 operations on Preston New Road 1Z

Of the planned 41 injection stages (400m^3 fluid and 50 tonnes proppant), only 17 were hydraulically stimulated (mini and /or main frac), 15 of which placed proppant (ranging from 2 to 51 tonnes) by the conclusion of operations.

Operational issues with sleeves 30 and 31 led to a pause in operations between the 3rd November and 7th December to attempt to resolve this issue, but without success. The failure to resolve these issues meant that the operator was unable to return to any of the stages below sleeve 31 after 2nd November.

Mitigation methods applied by the operator to avoid further induced seismicity during operations, and to avoid further stimulation of the identified fault-like feature included early halting of injection stages in response to “Amber” TLS events or abnormally high downhole pressures. Further mitigations including an extended flow back period during the operational pause, and the skipping stages in response to abnormal TLS events.

As a result of the TLS events and the attempted mitigation methods in response, just 14 percent of the intended proppant was injected into the formation.

Hydraulic fracturing of the well ended on 17 December 2018, and the well was put onto an extended well test by opening all sleeves and flowing back to surface. Any gas that was then separated from the flowback, was then burnt in an enclosed flare.

Data release regulations from the OGA require information from hydraulic fracturing operations to be released 6 months following. The purpose of this data release is to promote best practice and lessons learned, and allow for public and academic scrutiny of the operations.

On 27 June 2019, the OGA made available a significant dataset from the PNR1Z operations. This data included micro seismic event data, pumping data, a summary of produced water, screen shots of the hydraulic fracturing operations, a seismic event video and the final hydraulic fracture report.

The public release of this dataset is unique, with the vast majority of international hydraulic fracturing operations remaining commercially confidential. The dataset also provided a significant opportunity for academic research, with much of the data such as the microseismic recordings actively being used in NERC-sponsored research.

Current Operations

On the 5th August 2019, the OGA announced that they had agreed a Hydraulic Fracture Plan for the hydraulic fracturing of the Preston New Road 2 well. The plan proposed to use the same mitigation measures and thresholds as in PNR1Z, including a traffic light system, and also integrated the learnings from those operations including the identification of geological features such as “PNR1z ii” from microseismic data, and updated modelling of the potential ground motion from an induced seismic event.

The planned operations for PNR2 were to hydraulically fracture up to 45 stages, using 765 m^3 of fluid to place 75 tonnes of proppant. The plan introduced options to use either slick water, gel or a hybrid frac fluid as a mitigation against induced seismicity.

Hydraulic fracturing commenced on the 15th August 2019, with both a mini-frac and full frac completed each day on the first three stages, with no detected traffic light events. Analysis of the microseismic data showed that the fractures generated had a good fit to those modelled.

Operations resumed on stage 4 following the weekend with a mini-frac and full frac, during which two minor TLS events were detected (0.03 M_L, 0.09 M_L) during pumping. Stage 5 was completed with no TLS events. Microseismic data showed that fractures were generated as expected, but that there was some additional microseismic activity away from the injected stage, near to stage 15.

Following the completion of injection at stage 6 on 21st August, three trailing red light events (1.55 M_L, 0.87 M_L, 1.0 M_L) were detected, and operations were paused for a total period of 48 hours. The largest event was reported to be felt locally. Before operations were allowed to resume, Cuadrilla wrote to the OGA and set out a series of steps that were to be taken during and after operations in order to mitigate against further felt events.

Stage 7 was conducted on 23rd August, using a hybrid frac-fluid, but was suspended during injection as a precautionary measure following observations of abnormal downhole treatment pressures. After the early halting of stage 7, a series of trailing red traffic light events (1.1 M_L, 0.5 M_L, 2.1 M_L, 2.9 M_L, 0.5 M_L) were detected over the following five days, during which all operations were paused.

The largest event occurred on 26th August at 08.30 BST, and was recorded as a magnitude 2.9 M_L event. Ground motion from the event was measured between 5-8 mm/second, and it was widely felt across the region, with reports to regulators and the operator of potential superficial damage to buildings. This event is believed to be the largest recorded induced seismic event from hydraulic fracturing in the United Kingdom.

Operations have been suspended since Friday 23rd August 2019, and on 2nd September 2019, the OGA announced that hydraulic fracturing would remain suspended whilst investigations were conducted into these events, including the consideration as to whether the assumptions and mitigations in Cuadrilla's PNR2 Hydraulic Fracture Plan continue to be appropriate to manage the risk of induced seismicity at the Preston New Road site.