PREESE HALL
SHALE GAS FRACTURING

REVIEW & RECOMMENDATIONS FOR INDUCED SEISMIC MITIGATION

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SUMMARY

A series of studies were commissioned by Cuadrilla Resources Ltd to examine the possible relationship between hydraulic fracture operations at the Preese Hall well, near Blackpool, and a number of earthquakes which occurred in April and May 2011, the largest of which had a magnitude of 2.3 M_L. The reports from these studies conclude that the earthquake activity was caused by direct fluid injection into an adjacent fault zone during the treatments, but that the probability of further earthquake activity is low. The reports analyse the earthquake activity and use available geological and geophysical data, including background geology, well logs and core samples, along with fracture treatment data, to develop a conceptual geomechanical model. A numerical model consisting of a single fault plane in a rock matrix was used to simulate the induced seismicity, compare with observations, and estimate maximum magnitudes for induced earthquakes. A critical magnitude at which damaging ground motions might occur was estimated using the German DIN4150 standard, and a simple relationship suggested for ground motions as a function of magnitude and distance. Finally, a protocol for controlling operational activity is proposed. This builds on extensive Enhanced Geothermal System experience and uses a traffic light system based on real-time monitoring of seismic activity.

We have been asked by DECC to review these reports, and the further studies and information provided by Cuadrilla; and to make appropriate recommendations for the mitigation of seismic risks in the conduct of future hydraulic fracture operations for shale gas.

We agree with the conclusion that the observed seismicity was induced by the hydraulic fracture treatments at Preese Hall. However, we are not convinced by the projected low probability of other earthquakes during future treatments. We believe it is not possible to state categorically that no further earthquakes will be experienced during a similar treatment in a nearby well. The analyses failed to identify a causative fault, and detailed knowledge of faulting in the basin is poor. In the present state of knowledge it is entirely possible that there are critically stressed faults elsewhere in the basin. It is possible that a 3-D seismic reflection survey could help better characterize faulting within the basin.

We also consider that the use of the numerical simulations to estimate maximum likely magnitude of any further earthquake should be treated with some caution, mainly because the model is necessarily simplistic due to lack of data to constrain parameters. Additionally, the numerical simulations fail to model some of the features of the seismic activity such as the low B-value. (On B-values, see background note on seismicity.) However, we consider that the historical record of maximum observed magnitudes from coal-mining induced earthquakes in the UK can be used to provide a realistic upper limit. This leads to a maximum magnitude of ~ 3.0 M_L. An event of this size at an expected depth of 2-3 km is unlikely to cause structural damage. There are examples of mining induced earthquakes of similar magnitudes in the UK that caused superficial damage, for example, minor cracks in plaster, but these occurred at shallower depths. Such an event would be strongly felt by people within a few kilometres from the epicenter and could cause some alarm. The critical magnitude suggested by Cuadrilla's consultants to prevent the occurrence of damage is a conservative estimate. An earthquake with a magnitude of 2.6 M_L is also unlikely to cause structural damage, even at a shallow depth, though again it may be strongly felt by people close to the epicentre.

Nevertheless, we consider that the maximum magnitude threshold of 1.7 M_L, initially proposed for the traffic light system, is undesirably high from the viewpoint of prudent conduct of future operations. Based on this limit, no action would have been taken before the magnitude 2.3 M_L event on 1 April 2011. Instead, we recommend a lower limit of 0.5 M_L.

We recommend the following specific measures to Department of Energy and Climate Change (DECC) to mitigate the risk of future earthquakes in the Bowland Basin.

1. *Hydraulic fracturing procedure should invariably include a smaller pre-injection and monitoring stage before the main injection.*

   Initially, smaller volumes should be injected, with immediate flowback, and the results monitored for a reasonable length of time. Meanwhile, the fracture diagnostics (microseismic and prefrac injection data) should be analysed to identify any unusual behaviour post-treatment, prior to pumping the job proper.

2. *Hydraulic fracture growth and direction should be monitored during future treatments.*

   This should be done with industry standard microseismic monitoring using either an array of surface or down-hole sensors. Tiltmeters should also be used, if possible. Monitoring of upward fracture growth and containment by complementary diagnostics such as temperature or tracer logs, should also be carried out.

3. *Future HF operations in this area should be subject to an effective monitoring system that can provide automatic locations and magnitudes of any seismic events in near real-time.*

   The system should employ an appropriate number and type of sensors to ensure reliable detection, location and magnitude estimation of seismic events of magnitude -1 M_L and above. The number of sensors should also provide an adequate level of redundancy.

4. *Operations should be halted and remedial action instituted, if events of magnitude 0.5* M_L *or above are detected.*

   We consider that this would be a prudent threshold value, to reduce the likelihood of events perceptible to local residents, and to offer a higher margin of safety against any possibility of damage to property. This threshold value can be adjusted over time, if appropriate in the light of developing experience.

Based on the induced seismicity analysis done by Cuadrilla and ourselves, together with the agreement to use more sensitive fracture monitoring equipment and a DECC agreed induced seismic protocol for future operations, the authors of this report see no reason why Cuadrilla Resources Ltd. should not be allowed to proceed with their shale gas exploration activities and recommend cautious continuation of hydraulic fracture operations, at the Preese Hall site.

In respect of future shale gas operations elsewhere in the UK, we recommend that seismic hazards should be assessed prior to proceeding with these operations. This should include:

1. Appropriate baseline seismic monitoring to establish background seismicity in the area of interest.
2. Characterisation of any possible active faults in the region using all available geological and geophysical data.
3. Application of suitable ground motion prediction models to assess the potential impact of any induced earthquakes.

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1 INTRODUCTION

On 1 April and 27 May 2011, two earthquakes with magnitudes 2.3 M_L and 1.5 M_L were detected in the Blackpool area. These earthquakes were immediately suspected to be linked to hydraulic fracture injections at the Preese Hall well 1 (PH1), operated by Cuadrilla Resources Ltd. This well was hydraulically fractured during exploration of a shale gas reservoir in the Bowland basin. As a result of the earthquakes, operations were suspended at PH1 and Cuadrilla Resources Ltd commissioned a number of studies (Eisner *et al.*, 2011; Harper, 2011; GMI, 2011; de Pater and Pellicer, 2011 and Baisch and Voros, 2011) into the relationship between the earthquakes and their operations. An overall summary or synthesis of the findings was also published (de Pater and Baisch 2011).

In total, six hydraulic fracture treatments were carried out at different depths (Table 1). Seismicity was observed both during and after stages 2, 4 and 5. The largest magnitude event was 2.3 M_L and occurred approximately 10 hours after shut-in, following the stage 2 treatment. (The magnitude 1.5 M_L event on 27 May was approximately the same period of time after stage 4.) These events were found to be located in close vicinity to the point of injection and the signature of the events suggests that they all had similar locations and mechanisms.

Well-bore deformation was also observed following the first event in April, after stage 2. A caliper log run on 4 April showed that the extent of the deformation was greater than 0.5 inches over a depth range between 8480-8640ft MD.

Table 1: Preese Hall #1 Treatment Summary

Stage	Description	Date	Perforations					Slickwater Volume			Proppant	
			Depth			Length	Number					
			Top	Bottom								
			ft MD RKB	ft MD RKB	ft TVD SS	ft		Gallons US	m^3	bbls US	lbm	mton
1	DFIT	26 March 2011	8,841	8,850		9	27	34,314	130	817		
	Job	28 March 2011	8,841	8,949	8,730	36	108	485,856	1,839	11,568	226,240	101
2	DFIT	30 March 2011	8,700	8,759	8,583	27	81	24,780	94	590		
	Job	31 March 2011						593,040	2,245	14,120	262,080	117
		01 April 2011	Magnitude 2.3 seismic event									
		04 April 2011	Deformed casing confirmed with caliper 8480-8640ft MD (just below zone 3)									
3	DFIT	08 April 2011	8,420	8,489	8,340	27	81	10,668	40	254		
	Job	09 April 2011						200,634	759	4,777	116,480	52
4	DFIT	25 May 2011	8,020	8,259	8,052	27	81	21,084	80	502		
	Job	26 May 2011						423,696	1,604	10,088	183,680	82
		27 May 2011	Magnitude 1.5 seismic event									
5	DFIT	27 May 2011	7,970	7,819	7,823	27	81	11,760	45	280		
	Job	27 May 2011						402,780	1,525	9,590	248,640	111
6	DFIT	31 May 2011	7,670	7,789	7,666	27	81	10,290	39	245		
TOTALS							**513**	**2,218,902**	**8,399**	**52,831**	**1,037,120**	**463**

Data from the British Geological Survey (BGS) regional seismic monitoring network, along with data from two temporary stations installed close to Preese Hall by BGS and Keele University after the first event, were used to determine locations, magnitudes and mechanisms of the seismic events (Eisner *et al*., 2011). A total of 50 seismic events in the magnitude range -2 to 2.3 M_L were detected in the period 31 March to 27 May 2011.

Laboratory measurements of core samples, including uniaxial and triaxial testing, along with down-hole measurements, were used to determine elastic rock properties, rock strength and bedding plane strength (Harper, 2011). The laboratory measurements of rock strength were also used, along with density and image logs and minifrac data, to determine the magnitude of the minimum, maximum and vertical stresses and pore-pressure as a function of depth in the Preese Hall well (GMI, 2011). These results were used to develop a detailed geomechanical model of the reservoir (Harper 2011; GMI, 2011), Surface pressure matching from the fracture treatments was also used to estimate fracture size and geometry using a hydraulic fracture simulator (de Pater and Pellicier, 2011).

A simplified model consisting of a single fault plane was used to numerically simulate the geomechanical processes in the reservoir during the fracture treatments using a 3-D finite element model (Baisch and Voros, 2011). Simulated seismicity was compared with the observations and this method was also used to estimate the maximum expected magnitude for a similar fracture treatment. A critical magnitude for damaging ground motions was estimated, using the German DIN4150 standard, and a simple relationship for ground motions as a function of magnitude and distance (Baisch and Voros, 2011).

These studies examine seismological and geomechanical aspects of the seismicity in relation to the hydraulic fracture treatments, along with detailed background material on the regional geology and rock physics. They also estimate future seismic hazard and provide some recommendations for future operations and mitigation of seismic risk.

The key findings of their studies are as follows:

1. The earthquake activity was caused by direct fluid injection into an adjacent fault zone during the treatments. The fluid injection reduced the normal stress on the fault, causing it to fail repeatedly in a series of small earthquakes. The fault location is yet to be identified.
2. The Bowland Shale is a heterogeneous, relatively impermeable, stiff and brittle rock.
3. Bedding is pronounced throughout the reservoir and the structural dip of the bedding is variable and high. The bedding planes have low shear strength and show signs of previous slip.
4. Stresses are anisotropic and the in-situ stress regime is strike-slip. The difference between the maximum and minimum horizontal stresses is high and the orientation of maximum horizontal stress agrees with the regional stress orientation.
5. The maximum likely magnitude resulting from a similar treatment is estimated as 3.0 M_L. An event of this size is not expected to present a significant hazard.
6. There is a very low probability of other earthquakes during future treatments of other wells.
7. The injected volume and flow-back timing are an important controlling factor in the level of seismicity, as evidenced from the lack of seismicity during and after stage 3.
8. The potential for upward fluid migration is considered low. In the worst case, fluid could migrate along the fault plane, but this would be limited due to the presence of impermeable formations above the Bowland shale.
9. Though some casing collapse was found in the lower reservoir section, well integrity has not been compromised.

For future operations, they recommend

a) A conservative estimate of the minimum size of earthquake that could cause damage is 2.6 M_L, based on German standards. This should be the maximum allowable limit for seismic activity.

b) Seismicity can be mitigated by modifying job procedure, principally by reducing injected volume and rapid flow back.

c) Seismicity can be mitigated by deploying a real-time seismic monitoring "traffic light" system, to take action when observed seismicity reaches certain levels.

The authors of the present report were asked by DECC to provide advice on the reports commissioned by Cuadrilla (Eisner *et al.*, 2011; Harper, 2011; GMI, 2011; de Pater and Pellicer, 2011 and Baisch and Voros, 2011) and advise on what additional information was deemed necessary in order to allow this independent technical review of the final reports to be as comprehensive as possible. We were also asked to provide general recommendations for future operational good practices, to mitigate seismic risk, if future hydraulic fracture treatments are to be permitted in this area.

It has to be noted that given the sparse nature of the available seismic data for detailed analysis, the work commissioned by Cuadrilla can only address the major questions and provide some useful insights into the relationship between operations and seismic activity.

Overall, we generally agree with the main conclusions about the nature and mechanism of the seismic activity, although we have the following concerns:

- The stated low probability of future earthquakes during future treatments. There is not enough data to justify from a simple statistical analysis of potential realizations of the geomechanical situation that there is a low probability of encountering a similarly unique scenario in any future wells.
- The potential for upward fluid migration seems overstated, based on microseismic shale gas data from the main US plays. Further analysis in this report seems to indicate that fracture containment was good, with little vertical height growth. However, it is difficult to reach any concrete conclusions without confirmatory information from fracture diagnostics.

We conclude that an effective mitigation strategy is a necessary pre-requisite for commencing operations and offer in section 7 below our own recommendations for future operational best practice and monitoring.

2 MECHANISM OF INDUCED SEISMICITY

The aim of hydraulic fracturing is to improve fluid flow in an otherwise impermeable volume of rock, previously considered as source rock for more conventional (higher permeability) reservoirs. Stimulation is carried out to enhance well production, and is achieved by injecting fluid at a sufficient pressure to cause tensile failure (cracking of the rock) and develop a network of connected fractures to increase permeability and provide conduits for gas flow from the strata. Hydraulic-fracture induced micro-seismicity has been widely used in the oil and gas industry over the past decade to image fracture networks and estimate the orientation and size of a stimulated volume (Rutledge and Phillips, 2003). The dominant mechanism for creation of the microseismic events is shear slippage, induced by increased pore pressures along pre-existing fractures (Pearson, 1981).

We agree with the conclusion that the observed seismicity at Preese Hall was induced by the hydraulic fracture treatments. The detection and analysis of the seismic events (Eisner *et al.*, 2011) is comprehensive and, despite the sparse data, it is clear that the events are located close to the point of injection and the timing clearly corresponds to the treatment schedule. We also agree that the similarity of seismic events suggests a highly repeatable source, i.e., a fault that failed repeatedly resulting in a number of small earthquakes. There appear to be two possible scenarios: (1) the fault intersected the well-bore and fluid was directly injected into the fault during the treatment; (2) the fault may be at a distance of up to a few hundred metres from the well-bore, but that fluid was able to flow into the fault through bedding planes in the reservoir that opened during stimulation as a result of the high pressures. There is little evidence for the former from any of the existing data, although this scenario is used in the numerical modelling. There is evidence both for bedding planes opening and for previous slip on the bedding planes (Harper, 2011). Consequently, this seems to be the more probable mechanism.

In two of the hydraulic fracture treatments, in zones 2 and 4, the largest earthquakes occurred approximately ten hours after the start of injection, while the well was shut-in under high pressure. These events were preceded by smaller events, which started immediately after injection, the largest of which was a magnitude 1.4 M_L event on 31 March. The numerical simulations of the seismicity (Baisch and Voros, 2011) capture this to some extent, but there is a discrepancy between the observed and modelled magnitude distributions, with considerably fewer smaller events observed, leading to a low B-value (Gutenberg and Richter, 1944). Interestingly, there are also very few events observed after the largest events in stages 2 and 4, which again are not apparent in the numerical simulations. This low B-value is unusual and is not fully explained, since induced earthquakes typically display higher than average B-values (Dorbarth, 2009). The catalogue is considered complete for magnitudes ≥ 0.4 M_L (Eisner *et al.*, 2011), which suggests that this is a real feature of the data rather than a detection issue, though it is possible that small events with a different mechanism (e.g. tensile failure) could remain undetected because of the design of the detection algorithm.

No seismicity was observed during stages 1 and 3, and only very weak seismicity occurred during stage 5. The lack of seismicity in stage 3 can be attributed to the smaller pumped volume and aggressive flow back. The pumped volume in stage 5 was similar to stages 2 and 4, but there was also flow back, which could explain the lack of larger events. However, the character of the small events is similar to the events in stages 2 and 4, which suggests that they also resulted from motion on the same fault and that fluid was injected into the fault.

The source mechanism obtained from the seismic data shows left-lateral strike-slip motion on a fault that strikes 50° from north and dips 70° from horizontal. Although the mechanism is poorly constrained by the sparse data, we agree that this is plausible, given that it is consistent with well breakout and other deformation results as well as with the regional stress orientation. Such a mechanism further confirms that the event was caused by shear-slip on an existing fault, i.e. the event was caused by the release of energy stored at a critically stressed fault, rather than tensile failure during opening of a hydraulic fracture.

Although we agree with the inference that the events are attributable to the existence of an adjacent fault, we note that the causative fault has not actually been identified, and more generally that there is only a limited understanding of the fault systems in the basin. Although some large scale structures have been mapped, earthquakes in the magnitude range 2 to 3 M_L require only relatively small rupture areas, and so can occur on small faults. The strength of an earthquake is related to the area of the rupture and the amount of slip on the rupture. A magnitude 2.3 M_L earthquake might require slip of up to 1 cm on a minimum rupture area of 10,000 m^2. There might be other comparable faults at reservoir depths throughout the basin, given the tectonic history. A comprehensive 3-D seismic survey might better improve understanding of the nature and orientation of fault systems in the basin.

3 HAZARD FROM INDUCED SEISMICITY

It is relatively well-known that anthropogenic activity can result in man-made or “induced” earthquakes. Although such events are generally small in comparison to natural earthquakes, they are often perceptible at the surface and some have been quite large. Underground mining, deep artificial water reservoirs, oil and gas extraction, geothermal power generation and waste disposal have all resulted in cases of induced seismicity. There are numerous examples of induced earthquakes in hydrocarbon fields related to oil and gas production (Suckale, 2010). For example, in 2001 a magnitude 4.1 M_w earthquake occurred in the Ekofisk field in the central North Sea (Ottemoller *et al.*, 2005). The earthquake was thought to be related to the pressure maintenance injection of around $1.9x10^6$ m^3 of water. Induced earthquakes with magnitudes as large as 3.5 M_L are well documented in Enhanced Geothermal Systems (EGS) (Majer *et al.*, 2007), where the injected volumes may be much larger than in hydrocarbon fields and the reservoir rocks are much stronger. In general, the number of fluid injection induced earthquakes above a given magnitude will increase approximately proportionally to the injected fluid volume (Shapiro, 2003 and 2010).

Magnitudes of the induced earthquakes during hydraulic fracture stimulation in hydrocarbon fields such as the Barnett Shale (Maxwell *et al.*, 2006) and the Cotton Valley (Holland, 2011) are typically less than 1 M_L, which means that these events are not detected, unless a local monitoring network is in place. These stimulations typically involve fluid volumes much greater than those used at Preese Hall. This would suggest that the earthquake activity observed at Preese Hall is unique. However, we note that both the tectonic history and the present-day stress regime in the British Isles may be rather different to many of these areas of exploration and production. Also, it should be noted that many US shale gas plays are in relatively remote locations, with no monitoring networks in place. It is only recently, after the events at Preese Hall, that evidence has come to light (Holland, October 2011) which suggests that hydraulic fracturing induced seismicity may be a potential issue for other reservoirs. There are also examples of seismicity induced by fluid disposal in deeper wells (e.g. Frohlich *et al.*, 2011).

Cuadrilla’s consultants conclude that the probability of further earthquakes during future treatments is low because it depends on three factors: (1) a critically stressed fault; (2) that the fault can store enough fluid to allow it to fail over a significant area; and, (3) the fault is brittle and can fail seismically. However, we believe it is not possible to state categorically that no further earthquakes will be experienced given a similar treatment in a nearby well. There is no evidence to suggest that the causative fault is unique and knowledge of faulting in the basin is poor, so it is quite possible that there are many such faults throughout the basin. A critical state of stress is widely expected at depth and observed throughout the Earth’s crust (Townend and Zoback, 2000) and numerous observations of mining induced earthquakes throughout the UK show that brittle failure can occur at shallow depths (c 1 km) in similar rocks. This means that the probability of further earthquakes, if similar treatments were repeated, may be higher than suggested, though this is difficult to quantify without detailed data to analyse.

The numerical modelling (Baisch and Voros, 2011) of the geomechanical processes during stimulation uses state-of-the-art software; however, we note that the model is necessarily simplistic as a result of data limitations. Although it provides useful insights into parameter dependencies, results such as the maximum magnitude should be treated with some caution. In our opinion, maximum observed magnitudes from coal mining induced seismicity (Bishop *et al.*, 1994 and Redmayne *et al.*, 1998), rather than the maximum magnitudes for tectonic events in the UK (Main *et al.*, 1999), provide a realistic upper limit for shallow injection induced events.

Coal-mining events occur in the same Carboniferous geological formations from which shale gas is now being sought, whereas the larger tectonic events tend to nucleate at much greater depths where the Earth's crust is significantly stronger. Magnitudes for mining-induced events typically range from magnitude -3 M_L, detectable only very close to the source, to events of magnitude greater than 1 M_L, which are detectable on seismic stations at greater distances. The maximum magnitude at which a statistically significant number of events have been recorded is magnitude ~3 M_L. We note that although an event of this size at a depth of 3 km is unlikely to cause structural damage, such an event at a shallow depth could be strongly felt at intensities[1] of 4-5 EMS and could cause some alarm to local residents. There are examples of mining-induced earthquakes of similar magnitudes in the UK that caused superficial damage (Westbrook *et al.*, 1980; Redmayne, 1998) including, minor cracks in plaster and harling, however these events occurred at shallower depths. There have been no reports of structural damage from mining-induced earthquakes in the UK in the past forty years.

Cuadrilla's consultants estimate a critical magnitude at which damaging ground motions might occur using the German DIN4150 standard and a simple relationship for ground motions as a function of magnitude and distance proposed (Baisch and Voros, 2011). We consider this estimate to be quite conservative. Structural damage occurring at this magnitude is unlikely, even for a shallow earthquake, although we note that minor superficial damage has been reported for mining induced events as small as 1.7 ML (Redmayne, 1988). Again, we note that such an event is likely to be perceptible to local residents, given that it is larger than the magnitude 2.3 M_L event on 1 April, particularly by a population who are now aware of the possibility of earthquakes. Structural damage is usually only observed for earthquakes with magnitudes greater than 4 or 5 M_L, which requires surfaces to slip on faults whose dimensions are several kilometres. In intraplate areas, such as the UK, such events are usually only generated at depths greater than 10 km in basement rocks.

We note that prediction of possible ground motions due to the up-scaling of observed motions from smaller events is problematic (Bommer *et al.*, 2007). In addition, we also note that the observed near field observations of the magnitude 1.5 M_L earthquake on 27 May are strongly variable at the two closest stations and differ by an order of magnitude. This highlights the variability of ground motions and shows that they can depend on a number of complex factors.

4 HYDRAULIC FRACTURING

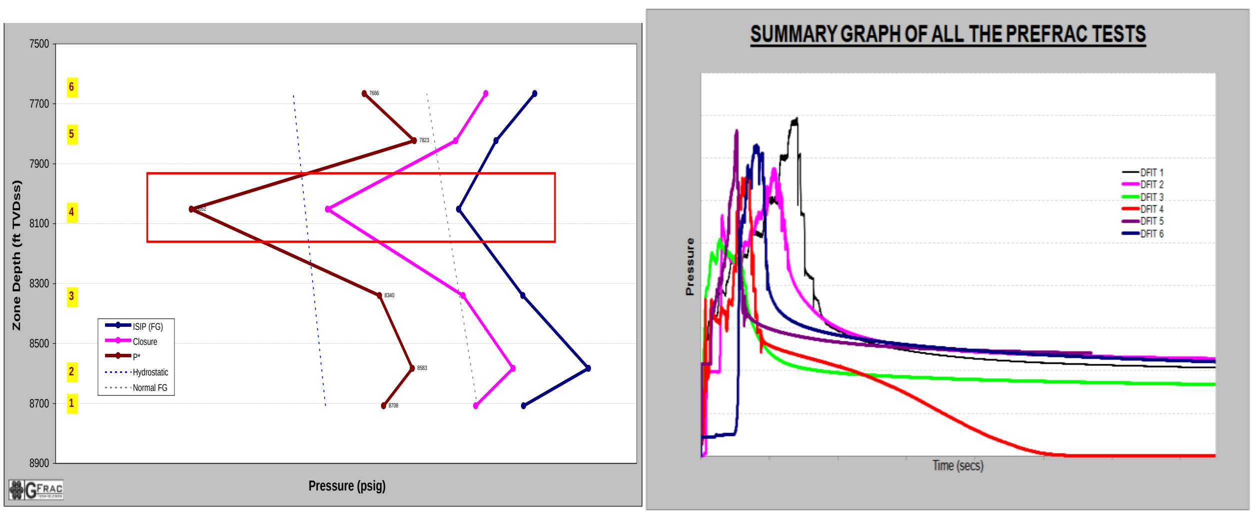
The analysis of the actual operations and discussion of the created hydraulic fracture is discussed in detail (de Pater and Pellicer, 2011) and further clarified in the synthesis report (de Pater and Baisch, 2011). The report discusses in detail the job fracture pressure analysis, with only a limited discussion of the prefrac testing analysis. Detailed prefrac test analysis is a necessary prerequisite, in order to properly discuss any subsequent job pressure analysis. However, any detailed discussion also requires diagnostic data to properly calibrate hydraulic fracture simulations, as matching of actual surface treating pressures with predicted values from the simulation is non-unique and can introduce significant error when determining how the created fracture grew (Green *et al.*, 2007). The standard process is to calibrate 3D simulators using all associated diagnostic and production data, as height growth is often overestimated, especially in heterogeneous, highly stressed reservoirs, such as the Bowland Shale.

[1] Magnitude is a measure of the energy released in an earthquake, intensity an expression of the perceived effects at the surface. See background note on seismicity.

4.1 Prefracture Injection Test Analysis

A detailed discussion of the prefrac injection test analysis is outside the scope of this report but G Frac Technologies has conducted closure (total minimum stress) analysis, which agrees with the results of de Pater and Pellicer (2011) but differs significantly from that used by Cuadrilla during the job. Incorrectly analysed stress data will lead to a misunderstanding of the in-situ stress and leakoff mechanisms, so that subsequent jobs are incorrectly designed. The calculated in-situ stress from zone 4 data was not analysed in the consultants' report, due to the data being considered not representative. However, we consider that the data was valid and it was therefore analysed as part of this review.

The plots of the treatment variations with depth are shown in Figures 1a) and 1b) and the only obviously exceptional zone is zone 4, as highlighted in Figure 1a. Zone 4 prefrac injection test analysis indicates that the fracture grew into a much lower stress zone and exhibited "fracture height recession" type leak-off characteristics, here probably representing the created fracture being forced into high-stress impermeable layers, which are forced to close first. We interpret this as possibly being at, or very near, to the fault, which is then proposed as a possible explanation of the subsequent immediate seismic events, while injecting into zones 4 and 5.



a) b)

Figure 1: Graphs showing a) variations of analysed parameters with depth and b) overlain prefrac surface treating pressure plots.

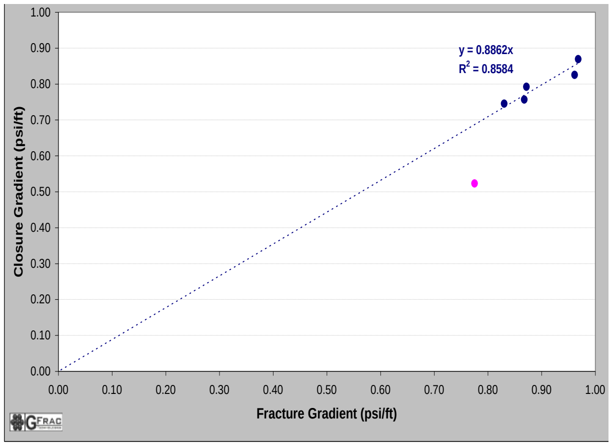


Figure 2: Graph showing fracture gradient vs closure gradient relationship.

Overall, the results indicate distinct and separate behaviours for each zone, interpreted as being representative of good containment of the created fracture growth in each zone. However, we consider that there is little additional useful information that can be concluded about the resultant fracture growth using only the surface job data, given the lack of complementary diagnostics.

4.2 Stress and Fracture Geometry

The prefrac injection tests indicate that the reservoir is overpressured and that fluid leak-off is unusually high for a shale. As can be seen in Table 2 the analysed time to closure indicates fluid leak-off several orders of magnitude higher than would be expected in most nanoDarcy shale formations, such as the Barnett. The reason for such high leak-off is correctly indicated as probably due to extensive natural fractures, or conductive bedding planes, but it should be noted that it was seen throughout all the lower section (zones 1-3), in particular.

Table 2: Preese Hall #1 G Function Closure Time Summary

Stage	G_{time} Closure
1	0.79
2	0.64
3	0.72
4	3.29
5	2.84
6	1.03

Pressure increases were noted during the fracture jobs, which were matched in the consultant's simulator analyses by use of increased containment (de Pater, 2011). Whilst this may be one solution, increasing pressure has also been noted as an indicator of increasing fracture complexity (Cipolla *et al.*, 2009). The non-uniqueness of possible solutions further reinforces the need for a calibrating diagnostics (Barree *et al.*, 2007), such as microseismic monitoring, for future treatments.

There is also a confusing general discussion in their report of created hydraulic fracture growth in relation to bi-wing fractures and fracture networks, but as also indicated in their report, bi-wing fractures rarely occur in unconventional reservoirs, where complex, asymmetric growth is common. However, as stated, once the created fracture is propagating it is believed that most of the treating fluid is transported in a few branches at any one time, but trying to match this using "multiple fracture" simulations is of little use when there is no diagnostic data to constrain the model. At depth, fractures normally grow largely vertically, until about 4000ft TVD, at which point the fracture complexity (ratio of horizontal to vertical fracture volume distribution) begins to increase steadily. However, in strike-slip stress regimes where the overburden lithostatic pressure may be the source of the intermediate stress, horizontal fracture growth can result. This would mean that fractures created have both vertical and horizontal components i.e. T-shape type geometry, which can cause tortuosity and pinching effects, limiting upward growth. Similarly, horizontal components reduce the amount of fluid available for vertical fracture growth. The prefrac injection test leak-off behaviour indicates that fractures in several of the zones appear to have grown exclusively along bedding planes, lifting the overburden; such behaviour is also likely to be the explanation of the high hydraulic fracturing fluid returns after the job, also noted in the report. Therefore, we feel that the evidence indicates that more horizontal type growth occurred for the created fractures, which would severely limit any vertical growth component.

One of the major concerns with shale gas developments is answering the question of how the created hydraulic fracture grew, particularly in relation to shallower aquifers. A summary of US microseismic and tiltmeter data in shales has recently been published (Fisher and Warpinski, 2011) based on treatments carried out in the Barnett, Woodford, Marcellus and Eagle Ford shales. This work is of particular interest as it summarises how the fractures grew with respect to the overlying aquifers. Overall, the data indicate that in general for deeper shales (here classified as >4000ft TVD_{SS}), the created hydraulic fractures remain well confined to the target interval, even in the presence of faults, (see Figure 3 and also Figures 4-6).

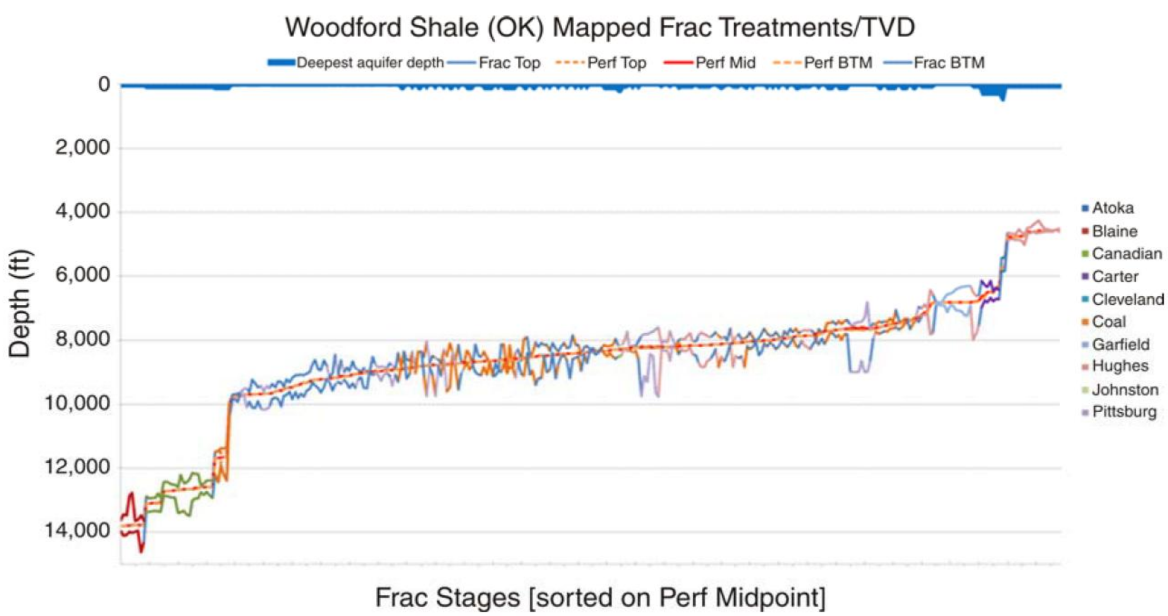


Figure 3: Woodford shale measured fracture heights compared to aquifer depths (copyright SPE)

Overall, the US data indicates that faults do not provide a mechanism whereby created fractures are able to propagate significantly upwards, towards the surface. The presence of faults is generally indicated by large upward and downward growth spikes, but overall vertical growth is still limited to several hundreds of feet. The Woodford shale is probably the best analogue for the Bowland shale, as it also has a very complex geology which also includes faulting and highly dipping or overturned bedding planes. However, interpretation of the

Woodford, in common with the Barnett, shows that created hydraulic fracture heights are well contained and separated from the local aquifers by at least several thousand feet. (In US regulatory practice, the focus would be on protection of aquifers used, or potentially usable, for drinking water supplies. It is our understanding that in the UK, the Environment Agency would aim to secure appropriate protection of all groundwater.)

Theoretically, upward growth is limited by calculations of the necessary volumes (volumetrics) but especially by what are termed "composite layering effects" (Veatch, 1983; Daneshy, 1978; Warpinski *et al.*, 1982 and Miksimins and Barree, 2003). These effects, together with the fact that a very low viscosity fluid is used for shale gas treatments, means that normally, height growth is very limited. In shale gas reservoirs it is difficult to replicate the growth and containment actually observed using microseismic monitoring, even using 3D hydraulic fracture simulators (see Figure A6 of the synthesis report for an overview of the containment stratigraphy).

4.3 Job Size and Induced Seismicity

There is a strong indication from the data in the consultants' reports that the strength of a seismic event is linked to the amount of fluid injected. This inference is consistent with the mechanism considered to be the most likely cause of most induced earthquakes, where the induced pore pressure reduces the effective stress and faults weaken, or are lubricated to move (Hubbert and Rubey, 1959). The size, rate and type of induced seismicity would therefore be dependent on:

1) Rate and amount of fluid injected
2) Orientation of the stress field relative to the pore pressure increase
3) Extent of the fault system
4) Deviatoric stress field in the subsurface

It is very difficult to predict what will happen in highly stressed reservoirs once hydraulic fracturing operations occur, especially where there are no local analogous fields for comparison, or historical data to analyse. Therefore, the standard procedure is to conduct small hydraulic fracturing operations, analyse the data, and if abnormalities are seen, suspend operations and determine a suitable protocol to mitigate any future risks.

Based on the above discussion it is considered necessary for future hydraulic fracturing operations in this basin, or elsewhere, to routinely perform smaller prefrac tests before the main treatment injection. A reasonable period of time (12-24 hours) should also be allowed to elapse after the injection, to be sure that no seismic activity occurs as the fluid diffuses away from the wellbore. The monitored results should be fully considered, to allow determination of not only reservoir parameters, but also the in-situ stress, before the design of the main injection operation is finalised. We consider that this should be standard practice, at least until more data are collected and a more thorough analysis undertaken.

5 CASING DEFORMATION AND WELL INTEGRITY

In general, wells are recommended to be constructed to Oil and Gas UK guidelines and API standards (refs 33 and 34) and, if necessary, problem zones isolated behind pipe, before drilling the next section. Cuadrilla has constructed the PH1 well in a way that complies with the API standards (see Appendix A Figure 7) and the integrity of the upper completion, as expected, indicated no problems from the two small seismic events that occurred. It should be noted that as a precaution to reservoir problems Cuadrilla did use an intermediate casing, the purpose of which is to isolate subsurface formations that may cause borehole instability or to offer protection from abnormally pressured, subsurface formations.

Production casing deformation is common in wells in highly stressed reservoirs and there are three main forms of well damage that have been observed:

1) Horizontal shear at weak lithology interfaces during reservoir compaction.
2) Horizontal shear at the top of a production or injection interval, due to temperature or pressure volume changes.
3) Casing buckling and shear within the producing interval due to axial buckling, when lateral constraints are removed or due to shearing at a lithological interface.

Once wellbore deformation is observed, a detailed analysis is required in order to use the correct mitigating strategy, which may include either strengthening the casing, or alternatively, allowing more room for greater compliance between the casing and formation.

The fact that the casing deformation was discovered on 4th April, after the initial seismic event on 1st April, indicates that it is clearly related to the event, which caused rock shear due to the changes in pressure and stress. Rock mass shear, or sideways movement, tends to be concentrated in planes and occurs as a relative lateral displacement across a feature such as a bedding plane, joint or fault. However, little more can be said about this event, due to the lack of available data on the fault or detailed ultrasonic log data taken in the well after the event.

However, this occurred in the lower section of the reservoir productive zone and subsequent prefrac injection test analysis did not indicate any communication problems between zones, such as cumulative stress or high tortuosity. Such indicators are what might usually be expected as indicators of containment issues due to poor cement. Therefore, well integrity was not considered a risk given the proven integrity of the upper completion, confirmed by surface gas measurements and annular pressure readings (see Figure 8). These tests demonstrate that the integrity of the casing, and the cement, in the upper completion has not been compromised.

It is also worth noting that though it is standard to use production casing run to total depth and cemented in place, some US shales, such as the Barnett, now use horizontal wells with uncemented liners, to prevent frac initiation and screenout problems (Lohoefer *et al.*, 2010). The production casing provides zonal isolation between the producing zones and all other subsurface formations, for pumping hydraulic fluids from the surface into the producing formation without affecting any other geologic horizon. In cases where intermediate casing is used, cementing the production casing to the surface is not always necessary and it is usually recommended that good cement is at least 500ft above the highest formation where hydraulic fracturing is to be performed, to give required subsurface zonal isolation.

It should also be noted that the surface casing has, as a minimum, to be set below the underground sources of surface waters. (As noted earlier, the Environment Agency may require proportionate measures to protect other categories of groundwater.) As drilling operations progress, additional pipe is installed and cement sheaths installed. Therefore, in the final well the surface groundwater is actually protected by multiple layers of pipe and cement, the annular pressure of which is continually monitored and used to confirm “well integrity”.

6 CONCLUSIONS

The observed seismicity in April and May 2011 was induced by the hydraulic fracture treatments at Preese Hall. The events are located close to the point of injection and the timing clearly corresponds to the treatment schedule.

The similarity of seismic events suggests a highly repeatable source, i.e. a fault that failed repeatedly in a number of small earthquakes. It appears likely that fluid was able to flow into a fault adjacent to the well-bore through bedding planes in the reservoir, that opened during stimulation as a result of the high treating pressures. The character of the small events in stage 5 is similar to the earlier events from stages 2 and 4, which suggests that these also resulted from motion on the same fault and that fluid was injected directly into the fault during stage 5.

In two of the stages, the largest earthquakes occurred approximately ten hours after the start of injection, while the well was shut-in under high pressure. These events were preceded by smaller events, which started immediately after injection.

The numerical simulations of the seismicity fail to fully capture the magnitude distribution and temporal decay of the observations. Considerably fewer smaller events are observed, leading to a low B-value. This low B-value is unusual and is an interesting discrepancy that is not fully explained in the reports.

The lack of seismicity during stages 1 and 3, and the very weak seismicity during stage 5, demonstrates that the number and magnitude of any earthquake seismicity is related to the injected volume and also, to some extent, the implementation of flow back. This leads to the recommendation to use this as a mitigation strategy.

The maximum observed magnitude of coal-mining induced earthquakes in the UK provides a realistic upper limit for the maximum possible magnitude of events induced by similar hydraulic fracture treatments. This leads to a maximum magnitude of ~3.0 M_L. There have been no reports of structural damage from mining induced earthquakes of this magnitude in the UK, so an event induced by a hydraulic fracture treatment at a greater depth is unlikely to cause structural damage. There are, however, examples of mining induced earthquakes of similar magnitudes in the UK that caused superficial damage, for example, minor cracks in plaster, though these occurred at shallower depths. Such an event would be strongly felt by people within a few kilometres from the epicenter and could cause some alarm.

An effective mitigation strategy has to be based on effective monitoring, and we recommend that future HF operations in this area should be subject to an effective monitoring system that can provide automatic locations and magnitudes of any seismic events in near real-time. The sensitivity of this system should be sufficient to detect events at a magnitude of -1 M_L, allowing reliable monitoring of events in the magnitude range -1 to >1 M_L.

We agree with the recommendation for a traffic light system, but we consider that the threshold value of 1.7 M_L suggested by the consultants is unnecessarily high. In the present state of knowledge, it would be more prudent to adopt a lower threshold, which will reduce the likelihood of events perceptible to local residents, and offer a higher margin of safety against any possibility of damage to property. At least for the next few operations in this basin, we suggest that a threshold value of 0.5 M_L would be appropriate, and immediate flow back should be implemented if any events of that magnitude or above are detected. This threshold value can be adjusted over time, if appropriate, in the light of developing experience.

Advantage should be taken of the monitoring system recommended above, and the significance of any unusual seismic events, even if below the threshold value, should be assessed. If appropriate, operations should be suspended while this assessment is carried out.

We emphasise that the available base of information about the relevant characteristics of the basin remains limited and that, if further hydraulic fracture operations are permitted, these should be regarded as being exploratory in nature.

Equally, the lack of identification of the causative fault, and the generally poor understanding of the fault systems in the basin, has implications for the hazard from induced earthquakes during future operations. There may be many small faults at reservoir depths throughout the basin, given the tectonic history of this area. Although a comprehensive 3-D seismic reflection survey might improve understanding of the nature and orientation of fault systems in the basin, we do not think it is essential for the continuation of operations during the evaluation phase. Previous experience, mainly in the US, suggests that 3D surveys can be of limited value in predicting faults that can be affected during hydraulic fracture creation, whereas microseismic can be effective for this, as well as calibrating 3D data (Warpinski *et al.*, 2009).

7 RECOMMENDATIONS FOR MITIGATION OF HAZARDS

We recommend the following specific measures to mitigate risk, prior to the resumption of hydraulic fracturing operations in the Bowland Basin. Additional to these recommendations we also outline some general “best practice” operational guidelines for onshore hydraulic fracture operations, in Appendix B. Providing these precautions are effectively implemented, we see no reason why the risk of induced seismicity should prevent further hydraulic fracture operations in this area.

Hydraulic fracture growth in the reservoir was poorly constrained by the available data from the treatments in April and May 2011. To better understand the nature and extent of possible fracture growth in the Bowland shale reservoir and the hazards associated with this, we recommend that detailed analysis of microseismic activity is used to monitor fracture growth in the next hydraulic fracture treatment in the Bowland shale. Hydraulic-fracture induced micro-seismicity is widely used in the oil and gas industry to image fracture networks. Microseismic data should be recorded using either a dense array of near-surface sensors, or an array of borehole sensors.

The induced seismic protocol mitigation system proposed for future treatments in the Bowland shale is based on work from extensive EGS experience of similar activities (Majer *et al.*, 2008) and may be considered as “industry best practice”. We believe that a suitable traffic light system linked to real-time monitoring of seismic activity is an essential mitigation strategy. However, this requires the definition of acceptable limits for the cessation and recommencement of operations. The initial threshold for cessation of operations proposed was 1.7 M_L. This was based on the critical magnitude 2.6 M_L and a maximum post-injection magnitude increase of 0.9 M_L. However, we note that, based on this limit, no action would have been taken before the magnitude 2.3 M_L event on 1 April 2011. We recommend a threshold of 0.5 M_L for cessation of operations, to minimise the probability of further felt earthquakes. We also suggest that a more detailed analysis of seismic activity is required, rather than application of a simple upper limit, so that numbers, magnitudes and mechanisms of any induced earthquakes are considered. We also recommend that these values are refined as more experience and data is acquired, to better understand the behaviour of any induced seismicity. Even with real time monitoring there may be a time delay between injection, monitoring and remedial action, and we feel that the lower traffic light threshold will minimise such control risks.

Any traffic light system crucially depends on the ability to monitor seismic activity effectively in real time. This requires a suitable number of seismometers either buried at surface in quiet locations near the injection well, or in boreholes at greater depths. These may be a part of the microseismic system, which we recommend for fracture monitoring, or a separate auxiliary system. Given the high levels of cultural noise in the area, shallow boreholes are preferred, but we recognise that this may not easily be possible. Data from the sensors must be transmitted in near real-time to a central processing site, where a reliable automatic algorithm for detection and location of seismic events can provide real-time estimates of times, locations and magnitudes of events during the fracture treatments. The recommended detection threshold for this system should be at a magnitude of -1, allowing reliable monitoring of events in the range -1 to >1.

Since the number of fluid injection induced earthquakes above a given magnitude will increase approximately proportionally to the injected fluid volume, reducing volumes and implementing flow back, where appropriate, should reduce the probability of significant earthquakes. This is clear from the observations of the induced seismicity at Preese Hall. We therefore recommend that future fracture treatments should initially be modified to reduce the probability of future induced earthquakes, by both reducing the injected fluid volume and also by initiating immediate flow back post-frac.

More generally, to better understand the hazard of induced earthquakes associated with future shale gas operations in the UK, we recommend that seismic hazards should be assessed prior to proceeding with these operations. This should include:

1) Appropriate baseline seismic monitoring to establish background seismicity in the area of interest.
2) Characterisation of any possible active faults in the region using all available geological and geophysical data.
3) Application of suitable ground motion prediction models to assess the potential impact of any induced earthquakes.

REFERENCES

Arthur D.J. and Cornue D.B., "*Environmental Best Practices for Shale Gas Development*", presentation to Independent Oil and Gas Association, July 2009

Baisch, S. and Voros, R. "*Geomechanical Study of Blackpool Seismicity*", Q-Con report for Cuadrilla (2011)

Barree R., Barree V. and Craig D., **SPE 107877** "*Holistic Fracture Diagnostics*" (2007)

Bishop I., Styles P. and Allen M. "*Mining Induced Seismicity in the Nottinghamshire Coalfield*", Quarterly Journal of Engineering Geology, 2**6** (4), 253-279 (1994).

Bommer J.J., Stafford P.J., Alarcon J.E. and Akkar S. "*The Influence of Magnitude Range on Empirical Ground-Motion Prediction*", Bulletin of the Seismological Society of America, 97, 6, 2152-2170 (2007)

Cipolla C.L., Lolon E.P., Erdle J.C. and Tathed V. **SPE 125532** "*Modelling Well Peformance in Shale Gas Reservoirs*". (2009)

Daneshy A.A. **SPE 6088** "*Hydraulic Fracture Propagation in Layered Formations*" (1978)

de Pater H. and Pellicer M. "*Geomechanical Study of Bowland Shale Seismicity – Fracture Geometry and Injection Mechanism*", StrataGen report for Cuadrilla (2011)

de Pater, H. & Baisch, S. "*Geomechanical Study of Bowland Shale Seismicity*", Synthesis Report (2011)

Dorbath, L. "*Seismic response of the fractured and faulted granite of Soultz-sous-Forêts (France) to 5 km deep massive water injections*", Geophysical Journal International, 177,2, 653-675 (2009)

Eisner L., Janska E and Matousek P. "*Seismic Analysis of the events in the vicinity of the Preese Hall well*", Seismik report for Cuadrilla Resources (2011).

Fisher K. and Warpinksi N.R., **SPE 145949** "*Hydraulic Fracture Growth: Real Data*" (2011)

Frohlich, C., Hayward C., Stump B. and Potter E. "*The Dallas–Fort Worth Earthquake Sequence: October 2008 through May 2009*", Bulletin of the Seismological Society of America, **101**, 1, 327–340 (2011).

Green C.A., Barree R.D. and Miskimins J.L., **SPE 106270-PA** "*Hydraulic Fracture Model Sensitivity Analyses of a Massively Stacked, Lenticular, Tight Gas Reservoir*" (2007)

Gutenberg, B. and Richter, C.F. Frequency of earthquakes in California, Bulletin of the Seismological Society of America, **34**, 4, 185-188 (1944).

Harper T. "*Geomechanical Analysis of the Worston Shale Microseismicity*", Geosphere report for Cuadrilla (2011)

Holland, A. "*Examination of Possibly Induced Seismicity from Hydraulic Fracturing in the Eola Field, Garvin County, Oklahoma*", Oklahoma Geological Survey Open-File Report OF1-2011 (2011).

Hubbert M.K. and Rubey W.W., "*Role of fluid pressure in mechanics of overthrust faulting: parts I and II*", Geol. Soc. Am. Bull., 70, 115-205 (1959)

Ketter A.A, Daniels J.L., Heinze J.R. and Waters G., **SPE 103232-PA** "*A Field Study in Optimising Strategies for Fracture Initiation in Barnett Shale Horizontal Wells*" (2008)

Lohoefer D., Snyder D.J., Seale R. and Themig D., **SPE 135386** "*Comparative Study of Cemented versus Uncemented Multistage Fractured Wells in the Barnett Shale*" (2010)

Main I., Irving D., Musson R. and Reading A. "*Constraints on the frequency–magnitude relation and maximum magnitudes in the UK from observed seismicity and glacio-isostatic recovery rates*", Geophysical Journal International, 137, 2, 535-550 (1999)

Majer E.L., Baria R, Stark M, Oates S., Bommer J., Smith B. and Asanuma H., "*Induced seismicity associated with Enhanced Geothermal Systems*", Geothermics, **36**, 3, 185-222 (2007)

Majer E., Baria R. and Stark M. "*Protocol for induced seismicity associated with enhanced geothermal systems*". Report produced in Task D, Annex I (9 April 2008), International Energy Agency-Geothermal Implementing Agreement (2008)

Maxwell S.C., Waltmann C.K., Warpinski N.R., Mayerhofer M.J. and Boroumand N. **SPE 102801** "*Imaging Seismic Deformation Induced by Hydraulic Fracture Complexity*", (2006)

Miskimins J.L. and Barree R.D., **SPE 80935** "*Modelling of Hydraulic Fracture Containment in Laminated Sand and Shale Sequences*" (2003)

Oil and Gas UK (UKOAA) Guidelines,: http://www.oilandgasuk.co.uk/publications/publications.cfm

Ottemoller L., Nielsen H.H., Atakan K., Braunmiller J. and Havskov J. "*The 7 May 2001 induced seismic event in the Ekofisk oil field, North Sea*", Journal of Geophysical Research,**110**, B10301 (2005).

Pearson, C. "*The Relationship Between Microseismicity and High Pore Pressures During Hydraulic Stimulation Experiments in Low Permeability Granitic Rocks*", Journal of Geophysical Research, **86**, B9, 7855-7864. (1981)

Redmayne D.W. "*Mining-induced seismicit in UK coaldfields identified on the BGS National Seismograph Network*", in Engineering Geology of Underground Movements, Geological Society Engineering Geology Special Publication, **5**, 405-413 (1988)

Redmayne D.W., Richards J.A. and Wild P.W. "*Mining-induced earthquakes monitored during pit closure in the Midlothian Coalfield*", Quarterly Journal of Engineering Geology, **31**, 21-36 (1998)

Rutledge, J.T. and Phillips, W.S., "*Hydraulic stimulation of natural fractures as revealed by induced microearthquakes, Carthage Cotton Valley Gas Field, East Texas*", Geophysics, **68**, 2, 441-452 (2003)

Shapiro, S.A., Dinske C., Langenbruch C. and Wenzel F. "*Seismogenic index and magnitude probability of earthquakes induced during reservoir fluid stimulations*", The Leading Edge, **29**, 304–309 (2010)

Shapiro S.A., Patzig R. and Rothert E. "*Triggering or seismicity by pore pressure perturbations: permeability related signatures of the phenomenon*", Pure Appl Gephys, **122**, 947-965 (2003)

Suckale, J. "*Moderate-to-large seismicity induced by hydrocarbon production*", The Leading Edge, **29**, 310–314 (2010)

Townend J. & Zoback M.D. "*How faulting keeps the crust strong*", Geology, **28**, 5, 399-402.

Veatch, R.W. Overview of Current Hydraulic Fracturing Design and Treatment Technology--Part 1, Journal of Petroleum Technology, 35, 4, 677-687 (1983)

Warpinksi N.R., Schmidt R.A. and Northrop D.A., **SPE 8932** "*In-situ Stresses: The predominant Influence on Hydraulic Fracture Containment*" (1982)

Warpinski N.R., Waltman C.K., Du J. and Ma Q. **SPE 124208** "*Anisotropy Affects in Microseimic Monitoring"* (2009)

"*Wellbore Failure Analysis and Geomechanical Modelling in the Bowland Shales",* Blackpool, GMI report for Cuadrilla(2011)

Westbrook, G.K., Kusznir, N.J., Browitt, C.W.A. and Holdsworth, B.K. "*Seismicity induced by coal mining in Stoke-on-Trent (U.K.)*", Engineering Geology, **16**, 225-241 (1980)

API Standards

API 51R – Environmental Protection for Onshore Oil and Gas Production Operation and Leases. July 2005
API 65 - Isolating Potential Flow Zones During Well Construction (Dec 2010)
API Guidance Documents for Hydraulic Fracturing
API HF1 - Hydraulic Fracturing Operations – Well Construction and Integrity Guidelines (Oct 2009)
API HF2 – Water Management Associated with Hydraulic Fracturing (June 2010)
API HF3 – Practices for Mitigating Surface Impacts Associated with Hydraulic Fracturing (Jan 2010)

APPENDIX A

Additional figures from SPE paper 145949.

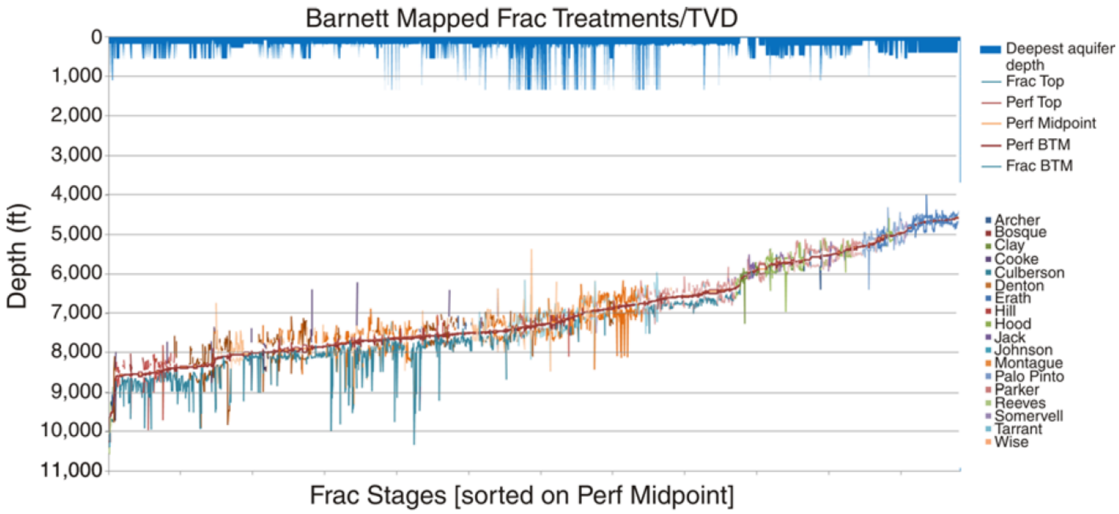


Figure 4: Barnett shale measured fracture heights compared to aquifer depths (copyright SPE)

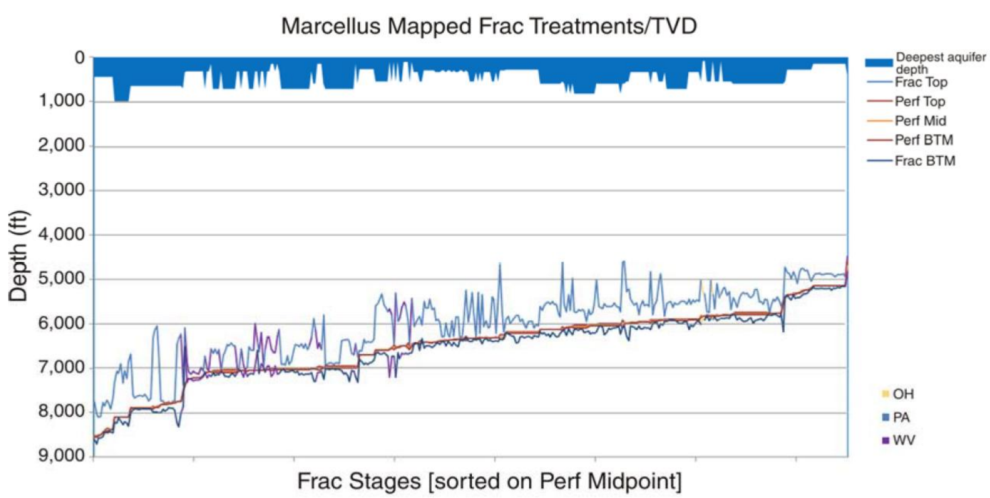


Figure 5: Marcellus shale measured fracture heights compared to aquifer depths (copyright SPE)

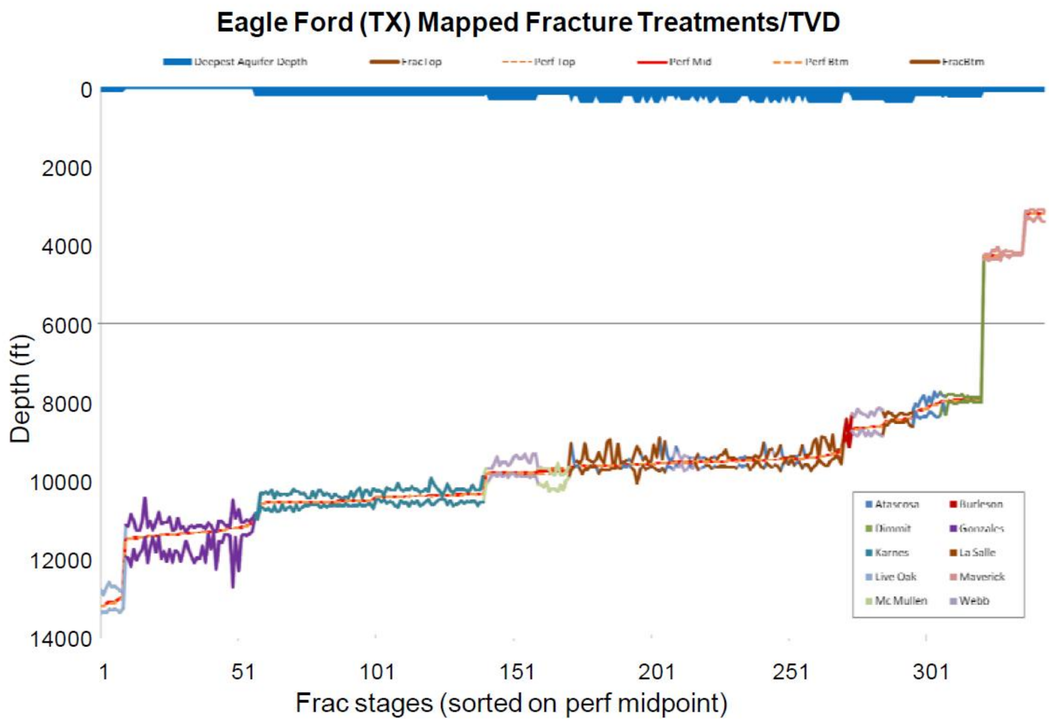


Figure 6: Eagle Ford shale measured fracture heights compared to aquifer depths (copyright SPE)

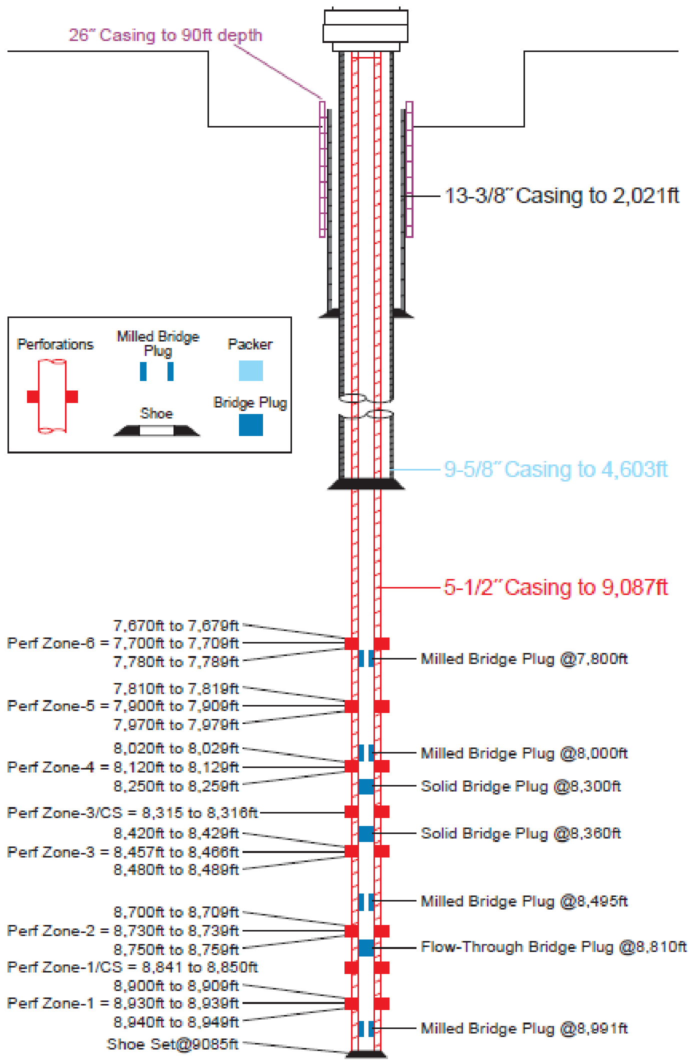


Figure 7: Cuadrilla completion schematic (Figure 11 Synthesis Report)

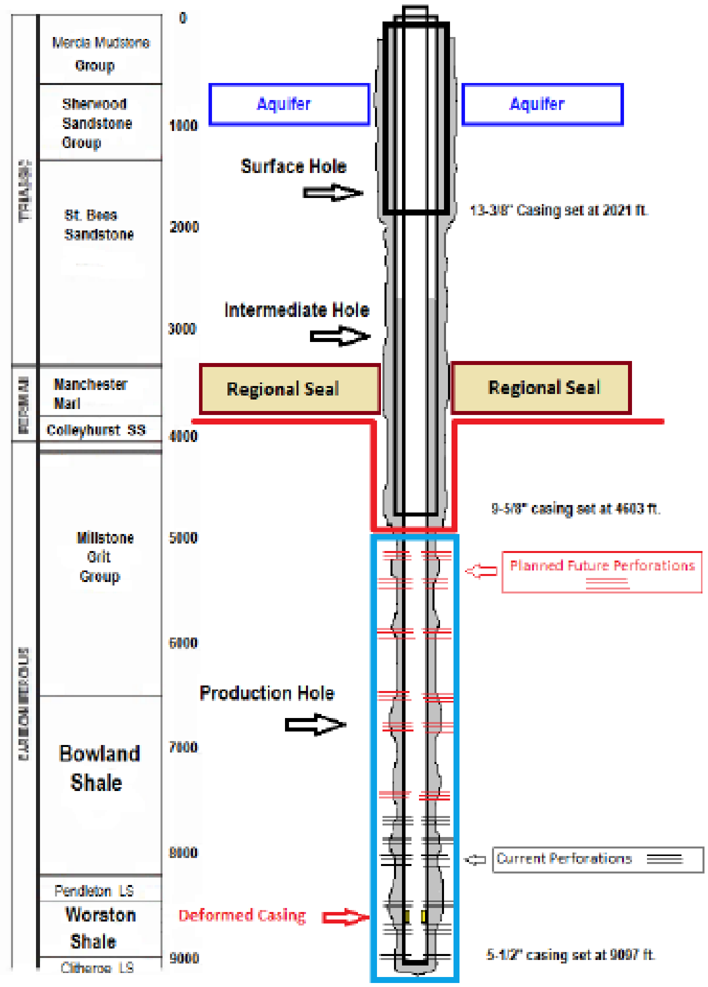


Figure 8: Casing deformation with respect to well integrity (Figure 35 Synthesis Report)

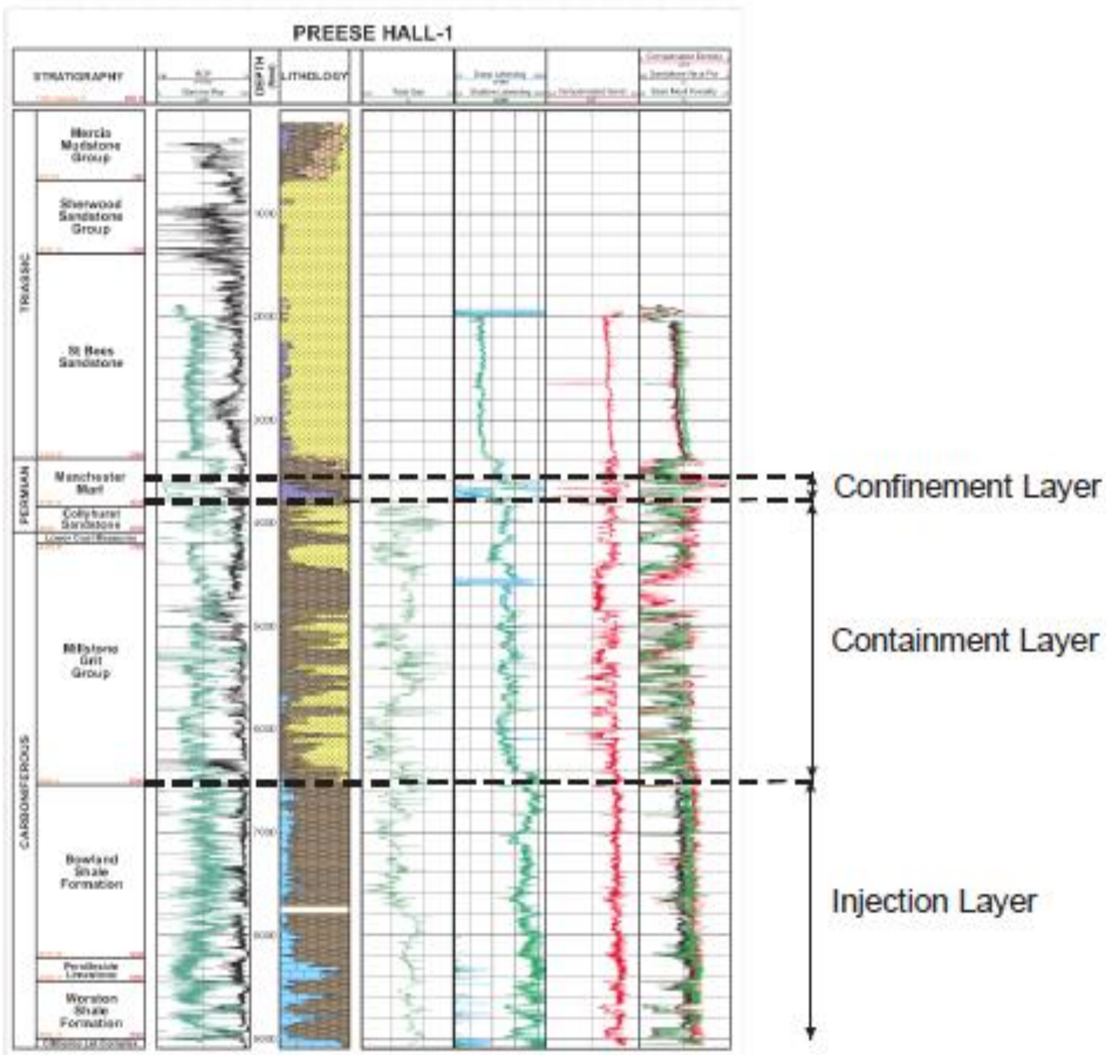


Figure 9: Stratigraphy summary with confinement and containment layers highlighted (Figure 37 Synthesis Report)

APPENDIX B

In addition to the review report there is a general need to identify what should be done for future hydraulic fracture operations and general onshore drilling operations to be executed satisfactorily. Offshore operations have a well developed best practice regime but as there has been less onshore development, there is less in the way of protocols developed by bodies such as Oil and Gas UK. Best management practices (Arthur, 2009) are increasingly becoming important in order to develop technologies and procedures that avoid, reduce or mitigate environmental and community impacts associated with oil and gas, not least shale gas activities. Some degree of impact may be necessary in order to produce any resource, but correctly adopted general procedures can minimize their effects.

Based on experience in the US, the following best practice outline is recommended for any hydraulic fracture developments:

1. **Formal risk assessment of potential well drilling and completion operation impacts, prior to spudding the well**
2. **Geophysical logging, to delineate the base of freshwater aquifers and determine reservoir parameters**
3. **Surface casing and packers/cement deep enough to protect freshwater aquifers**
4. **Production completion (casing/cement packers) designed to prevent upward migration of reservoir and injected fluids (e.g. intermediate string inclusion, if necessary)**
5. **Cement bond logging and pressure testing of each completion string to ensure good seals**
6. **Drilling and frac fluid storage in tanks and offsite burial of drill cuttings**
7. Fracture diagnostics, especially microseismic and tiltmeter monitoring of hydraulic fracture growth
8. Avoidance of fracturing near faults/subsurface structures
9. Reuse of frac fluid to reduce freshwater resource impacts and potential disposal issues
10. Water sampling before and after drilling/HF operations to ensure no aquifer contamination.
11. Regular updates and frequent engagement with stakeholders, about ongoing operations.

The above list is a general guide for shale play development, but 1-6 are what we would consider good general practice for hydraulically fractured wells, and would be recommended for any new well drilled onshore.