Summary note for OGA interpretation of BOWLAND-12 3D seismic integrating drilling results from PNR1, PNR1Z and PNR2 wells

Project Background and Objectives

The Oil & Gas Authority (OGA) has received an application from Cuadrilla Bowland Resources to hydraulically fracture the PNR 1Z (LJ/06- 9Z) well as part of their proposed completion operations at the Preston New Road (PNR) Site, Lancashire.

As part a Completion Work Approval, where Hydraulic Fracturing operations are proposed, the OGA requires the operator to submit a Hydraulic Fracture Plan (HFP). OGA guidance sets out that a HFP must demonstrate how an operator will control and monitor the fracturing process, and mitigate the risk of induced seismicity by identifying and assessing the locations of existing faults to prevent hydraulic fracturing from taking place near to them.

Cuadrilla Bowland Resources submitted a final revised HFP for PNR 1Z to the OGA in July 2018, which included an assessment of local faulting and potential seismic discontinuities, and modelling to investigate fault reactivation vulnerability and slip tendency for identified faults.

In anticipation of this decision, and in recognition of our role to consider and mitigate the potential risks of induced seismicity from these proposed operations, in early 2017 we commissioned a study from the British Geological Survey (BGS Project GP17/01) to independently assess the faulting in the vicinity of the proposed Hydraulic Fracturing at Preston New Road, using the Bowland-12 3D seismic survey that was supplied by the operator.

This report was delivered to the OGA in July 2017, in which it concluded that the 3D survey was of good quality within the proposed site, and that the well targets an un-deformed fault block bound by major reverse faults to the North-West, the South, and the South-East. The assessment also identified several discontinuities in the data that extended within the operational boundary to the north of the well path, and which may be small faults.

The interpretation of these potential seismic discontinuities or small faults was included in the submitted HFP by operator, together with mapping the proximity to the wells, and modelling the potential for their reactivation.

Following the delivery of this BGS study in July 2017, Cuadrilla have since drilled several wells, including a pilot well called “PNR 1”, a deviated horizonal side track called “PNR 1Z”, and a horizontal well known as “PNR 2”.

Since the drilling of these wells, which completed in July 2018, provide a significant addition in both subsurface data and potential understanding of the geology in the area, the OGA commenced a further independent study in April 2018 to assess the faulting in the vicinity of the proposed area, and take into account existing and newly available data to confirm that the earlier evaluation by the BGS, and the operator is still valid.

This project was completed in July 2018, and following a peer review and technical workshop the BGS confirmed the methodology and findings of this study, which were in-line with the original evaluation from the BGS.

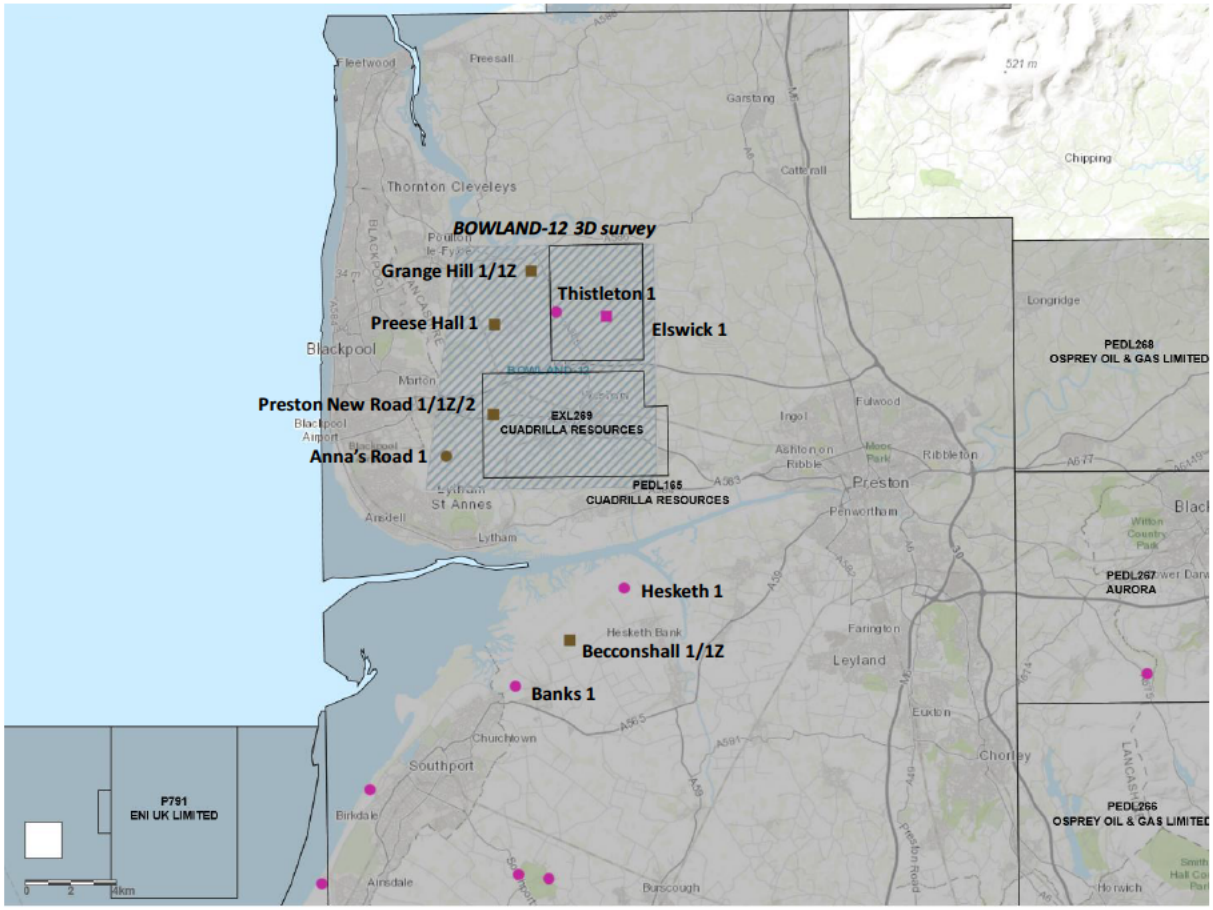
This technical note will summarise the findings of this independent study to support the consideration to grant approvals for Hydraulic Fracturing operations at Preston New Road.

Area overview

The proposed operations at Preston New Road, Lancashire are situated within Petroleum Licences EXL269 and PEDL165, both operated by Cuadrilla Resources Ltd.

In 2012, Cuadrilla acquired a 100 km^2 3D reflection seismic survey, named BOWLAND-12 across the region including coverage over the site at Preston New Road, which was granted planning permission for the drilling and hydraulic fracturing of up to 4 wells in 2014.

The Preston New Road site is located approximately 4 km south from the Preese Hall 1 well, which was drilled and hydraulically fractured by Cuadrilla in 2011. Two wellheads are sited within the compound, including the original pilot PNR 1, and the two horizontally deviated wells, PNR 1Z and PNR 2 which extend approximately 1 km west within the Bowland from their surface locations.



Map of Lancashire and Licence area (© UKOGL, 2018)

Database

The study focus area is bound by the BOWLAND-12 3D seismic survey, within which several wells have been drilled in the past.

SUMMARY OF WELLS

Thistleton 1

LJ/06- 1 was drilled in 1987 by British Gas to a total depth of 2116 m, and penetrated a section down to the Carboniferous. Following testing, no hydrocarbons were encountered and the well was plugged and abandoned.

Elswick 1

LJ/06- 3 was drilled by British Gas in 1990, and discovered the Permian-aged Elswick gas field. The well was drilled a total depth of 1588 m after reached the Carboniferous. Following a drill-stem test, the well was later put into production in 1996, and produced gas to until 2013.

Preese Hall 1

Cuadrilla Resources drilled the Preese Hall 1 (LJ/06- 5) well in 2010, to a total depth of 2714 m. This well is a key data point, as it was the first well to be drilled through the Carboniferous to log and evaluate the Lower Bowland Shales. A full series of wireline logs were acquired, and together with detailed biostratigraphic evaluations, this well provides a detailed log through the Bowland Basin. Together with VSP data from the well, this is a good quality calibration point for the BOWLAND-12 3D seismic survey.

After drilling the well, in 2011 Cuadrilla hydraulically fractured 5 stages of the well, but operations were halted after induced seismic events were associated with the stimulation activities.

Grange Hill 1Z

LJ/01- 1 and LJ/01- 1Z were drilled by Cuadrilla Resources Ltd in 2011 to a total depth of 3284.2 m, again targeting the Lower Bowland Shales. The original LJ/01- 1 was side tracked at approximately 1950 m due to operational issues. This is the northern-most well within the BOWLAND-12 3D survey.

Like the 2017 study by the BGS, this project used these existing wells to aid the interpretation of the seismic data, but in addition, the recently drilled PNR 1, PNR 1Z and PNR 2 wells and associated datasets have also been integrated into this subsurface assessment to give more certainty to this evaluation and the proposals by Cuadrilla Resources Ltd at Preston New Road.

Preston New Road 1

The LJ/06- 9 well was drilled in 2017 as a pilot hole to investigate and collect geological and geophysical information on the Bowland Shales, prior to the drilling of two horizontal wells which are intended to be hydraulically fractured. It was drilled vertically to a total depth of 2700 m, and included 3 cored sections within the Bowland Shales, wireline logging including a well deviation survey, and a vertical seismic profile survey.

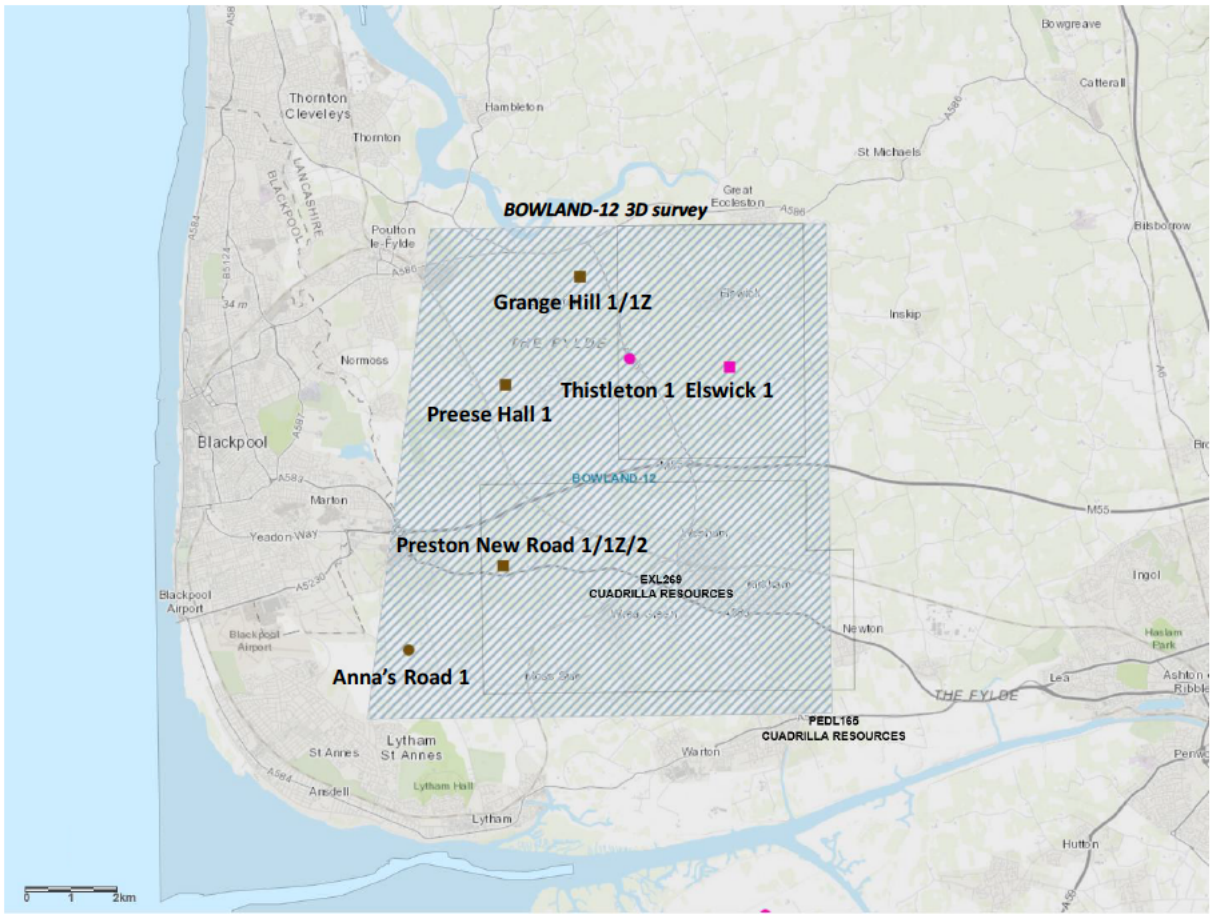
This new set of data is important to an investigation of the study area, as the measured time-depth relationship provides the most reliable tie to the existing BOWLAND-12 3D seismic survey, and well data such as well tops and formations. Detailed biostratigraphic analysis of the core and well cuttings give good confidence in the stratigraphy and formation picking from the well.

Preston New Road 1Z

LJ/06- 9Z was drilled in 2018 as a sidetrack to the Preston New Road 1 pilot hole, to an approximate depth of 2300 m, and is horizontally deviated along a 782m lateral section through the Lower Bowland Shales, intended for hydraulic fracturing. Data collected included wireline logs, and a well deviation survey.

Preston New Road 2

Cuadrilla Resources completed drilling the Preston New Road 2 (LJ/06- 8) well in July 2018. This well was also horizontally deviated for a 745 m lateral section within the Bowland Shales, also to be hydraulically fractured. Deviation data for this well was also supplied by Cuadrilla for this project.



Map of Project Area and Well Database (© UKOGL, 2018)

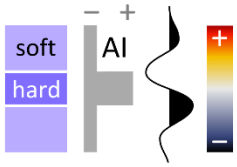
SUMMARY OF SEISMIC DATA

BOWLAND-12 3D seismic survey

In 2012, Cuadrilla Resources acquired a proprietary 3D reflection seismic survey across the their PEDL165 licence. The survey covered an area of approximately 100 km^2, within which it incorporates the existing wells used in this project, and in addition the recently drilled wells at the Preston New Road site.

The operator provided the survey to the OGA in post-stack time migration (PSTM) form. The survey was acquired on a 25 m x 25 m grid spacing, and uses European waveform polarity convention, but

with a colour scheme showing an increase in acoustic impedance as a red peak and respectively, a decrease as a blue trough to match those seismic images presented by Cuadrilla Resources in their Hydraulic Fracture Plan, and is consistent with the approach used by the British Geological Survey in their own study.



Methodology

Well data

The key well used for interpretation in the project area is the Preston New Road 1 (LJ/06- 9) pilot hole. Cuadrilla Resources supplied a deviation survey and the vertical seismic profile acquired for this well, these were both used as the primary tie for the well to the BOWLAND-12 3D seismic survey.

Interpreted well tops were also provided to aid seismic interpretation and in addition, the three coring points from the well were used as tops to identify potential horizons of interest within the Bowland Shales.

On completion of drilling, the deviation data and well tops were also supplied for Preston New Road 1Z, and the Preston New Road 2 horizontal wells.

Seismic data

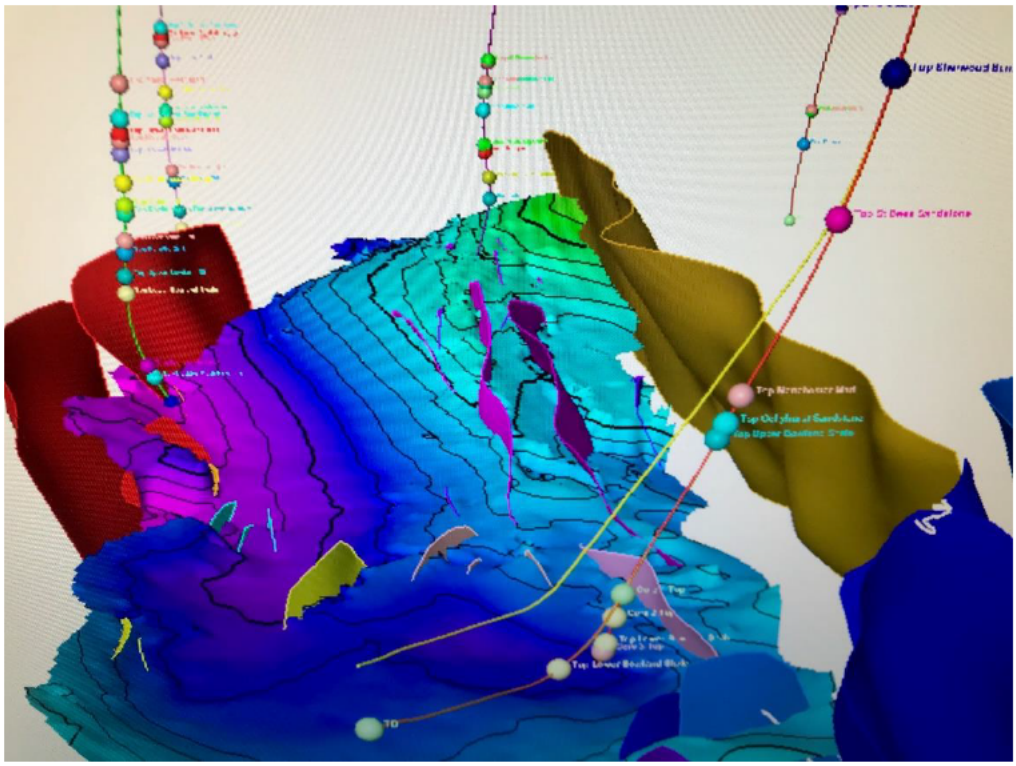
The PSTM data from the Bowland-12 survey was used in the seismic interpretation, rather than any later proprietary depth-migrated volumes, as these are depth-constrained based upon data from Preese Hall 1, and the confidence in the depth conversion is likely to be limited further south towards the area of interest, and it is less likely to suffer from any artefacts introduced from the depth migration. The recently acquired VSP survey from Preston New Road 1 provides a more reliable time-depth tie for this project.

Horizon Interpretation

Seismic data quality is good within the proposed area of hydraulic fracturing operations, and also within other fault blocks where there is limited structural deformation, but the quality is significantly degraded in areas adjacent to regional-scale faults. The zones of poorly resolved seismic signature can in themselves be used to interpret these regional-scale faults. The Lower Bowland Shale is well imaged within the area of interest, as reflected by the moderate to high levels of confidence for the interpreted horizons.

In total 13 seismic horizons were interpreted within the project area of interest, 5 horizons to represent the overburden, and 8 horizons within the Bowland Shale.

Well tops from the Preston New Road 1 pilot hole were used to guide the interpretation of the main formation tops, whilst within the Bowland Shale, well tops, core points and significant seismic reflectors were used in the interpretation.



Well tops tied within the BOWLAND-12 3D seismic volume

A high-density grid of inlines, crosslines, and arbitrary NW-SE and SW-NE oriented lines were interpreted for the Carboniferous-aged horizons, especially where pre-Permian aged faulting increased the structural complexity of the area.

Prior to the generation of grids, each interpreted horizon was 3D auto-tracked using a high (>80%) correlation quality threshold to extend the coverage in areas of high confidence.

System	Series	Formation Top / Horizon		QC / Confidence
Overburden				
Triassic	Lower	Top Sherwood Sandstone		Moderate
		Top St. Bees Sandstone		Moderate-Low
Permian	Upper	Top Manchester Marl		High
	Lower	Top Collyhurst Sandstone		High
		Permian Unconformity		High
Intra- Bowland Shale				
Carboniferous	Pennsylvanian	-	-	-
	Mississippian	Core point 1		High
		Inter Core point 1 to Core point 2		Moderate
		Core point 2		Low
		Below Core point 2		Low
		Top Lower Bowland Shale		Moderate-High
		Sub- Top Lower Bowland Shale		Moderate-High
		Mid Lower Bowland Shale		Moderate-High
		Early Lower Bowland Shale		Moderate-High

Fault Interpretation

Several interpretation techniques were used for the detailed mapping of faulting within the 3D seismic volume, especially in areas where conventional fault picking was hindered by the poor seismic data quality associated with many of these regional-scale faults.

To mitigate the limitations of the seismic quality in fault zones, and to increase confidence in the presence, trend and dip of faults, a detailed 3D volume of "fault sticks" was generated by interpreting individual inlines and crosslines. This volume could then be interpreted to identify individual faults, trends and fault relationships across the seismic survey.

To increase the interpretation confidence of regional-scale faults where the seismic character was poor, time-slices from the 3D seismic volume were used to better define the fault blocks with coherent seismic character from the disrupted, uncertain character of the faulted zones.

A variance attribute cube was generated from the existing seismic volume, which was then extracted using the interpreted horizons to identify smaller scale potential fault trends. Further structural analysis of the surfaces using edge detection and dip angle tools were used to aid this interpretation, and was particularly effective at identifying small scale structural features that were close to the limits of the seismic resolution.

The final fault interpretation was integrated using a Structural Framework into a 3D Fault Model, which constrained the geometry of faults, and the relationship between faults to a set of structural and geological rules.

Depth conversion

A 1D velocity model was generated used the Preston New Road 1 VSP data to depth convert the key horizons and faults within the project, which could then be used to evaluate the proximity and geometry of any mapped faults to the proposed operations with a higher degree of confidence compared to using post-stack depth migrated seismic data or depth converted data using only the Preese Hall 1 checkshot data.

Interpretation

Regional structural setting

The Carboniferous-aged Bowland Basin extends across the north-west of England, including much of Lancashire. Situated in PEDL165 / EXL269, the Preston New Road site lies within the western part of the Bowland Basin.

The proposed operations target a north-east trending Carboniferous fault block, which is bound to the north-west by the reverse Haves Ho fault, and to the south-east by the reverse Moor Hey fault. These regional high angle reverse faults both trend south-west to north-east, and dip east-south-east. The reverse Anna's Road fault constrains the fault block to the south-south-east, and extends to join the Moor Hey fault.

These regional scale faults are pre-Permian in age, and as indicated by the Carboniferous-aged sedimentary fill would have developed with an extensional nature, and have later been inverted through the Variscan orogeny. They are often associated with a characteristic zone of poor seismic

quality within the BOWLAND-12 3D survey, but which clearly constraint a fault block with limited structural deformation and a continuous coherent seismic character.

Local structural setting

Within the mapped fault block, the Preston New Road 1Z and 2 wells are deviated westwards to target a coherent and undeformed gentle structural depression in the southern part of the block. The seismic character within this area is generally continuous, especially within the Lower Bowland Shale, where strong parallel reflectors are characteristic within this section.

The undeformed northern part of this fault block is more elongate towards the north-east, and is cut by a ridge-like feature that extends to the north-east, trending parallel to the east-bounding Moor Hey fault.

Throughout this fault block the Permian Unconformity truncates both the Upper Carboniferous and Bowland Shale sections, in addition to the mapped intra-Carboniferous faults. drilling results from PNR 1 confirm this, with the previously anticipated Millstone Grit Formation missing in this location.

Faulting

The naming convention used in this study for identified fault is consistent with those presented by Cuadrilla Resources in their hydraulic fracture plan where interpretations are similar.

PNR-1 Fault

The PNR-1 fault is a reverse fault, dipping towards the south-east. The feature extends for approximately 2 km, from the Anna's Road fault system and trending SSW-NNE towards where Fault-2 develops. The fault is also mapped by Cuadrilla, located immediately west of the Preston New Road site, and the well paths for PNR1, 1Z and 2 are all deviated to avoid intersecting this fault, and to land the Pilot well, and both laterals within the Bowland Shales westwards of it. The heel of PNR 1, and therefore the nearest hydraulic fracturing stage is approximately 550 m from this fault.

Fault-2

The Fault-2 feature identified in the HFP is closely associated with the ridge-like feature that trends north-west through the northern half of the fault block. Whilst only this single fault is presented in the HFP, it is likely to be part of a complex series of features associated with, and running parallel to the Moor Hey fault. A pair of faults can be mapped with a reverse nature bounding the ridge feature, and antithetic faults associated with the trend are common. The feature extends for at least 6 km towards the Thistleton 1 well, and run beyond the northern extent of the BOWLAND-12 survey.

The nearest injection point at PNR 1Z lies approximately 1 km to the south of the southerly limit of the feature, and beyond the southern tip of Fault-2 some small-scale associated faulting can be mapped, which is discussed within the seismic discontinuities section.

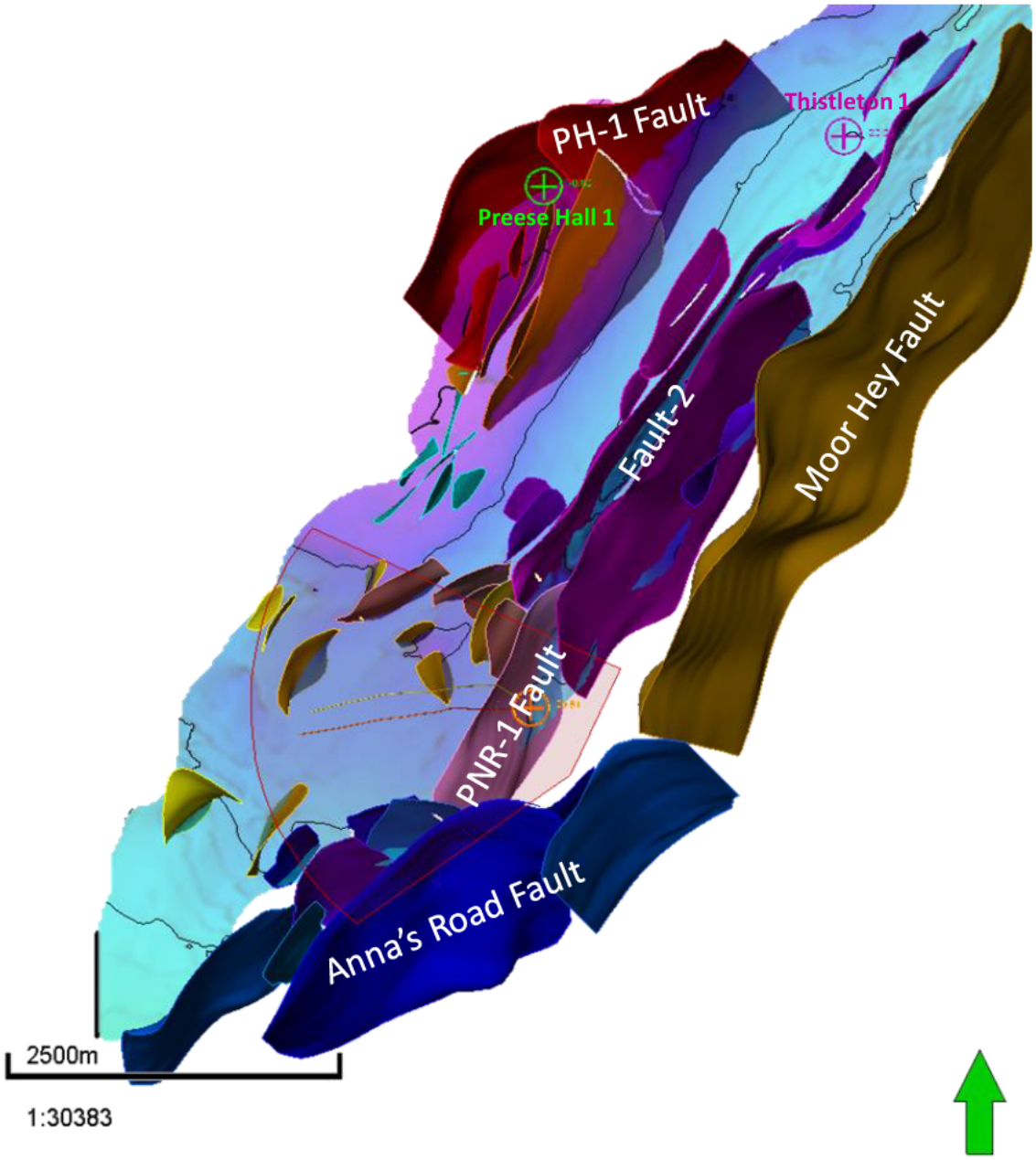
PH-1 Fault

The PH-1 Fault is a feature consisting of a series of predominantly reverse SW-NE trending faults adjacent to the Preese Hall 1 well. It follows the same trend as the Haves Ho Fault, and is likely to be associated with this regional fault.

The well path of Preese Hall 1 potentially intersects, or lies close to this faulted feature within the Lower Bowland Shale, and it is therefore a strong likelihood that the associated induced seismicity during the hydraulic fracturing of Preese Hall 1 in 2011 was due to the reactivation of this, or a nearby fault.

The features are mappable for a length of approximately 3 km within the BOWLAND-12 survey, but may extend further beyond the data coverage.

The nearest injection points at Preston New Road are located over 3 km from the PH-1 Fault feature.



Map of the interpreted faults within the BOWLAND-12 3D seismic volume

Seismic Discontinuities

Within the southerly area of the regional fault block, a number of small structural features have been identified within the seismic for the Lower Bowland Shale. These have been described as “seismic discontinuities” within the HFP, and whilst it is possible these could be seismic artefacts, they may represent small-scale faults at, or near to the minimum resolvable limit of the seismic.

SD1

The SD1 feature (mapped by the BGS as Fault PNR-2) shows some minor reverse offset in the seismic, and can be mapped for 800 m SSW-NNE where it appears to link to the Fault-2 feature. The discontinuity lies approximately 350 m north-east from the nearest stage in PNR 1Z, but also only offsets the lowermost beds in the Lower Bowland Shale, and does not appear to propagate upwards to the layers where the proposed fracs could occur.

Associated with the Fault-2 feature, there may also be other minor seismic discontinuities that form a linkage and transfer zone from the southerly tip of Fault-2, these are poorly defined in the seismic, but have been mapped within my project interpretation.

SD2

A discontinuity can be mapped for approximately 870 m in length, in a south-west to north-west trending direction, but the limited seismic offset of the feature is inconsistent within the Lower Bowland Shale. SD2 has a reverse nature, and may be associated with a fault transfer zone that extends south-west from Fault-2. It is 830 m from the nearest injection point in PNR 1Z.

SD3

The SD3 discontinuity is the closest mappable feature to PNR 1Z, located 200 m north from the nearest injection point, at the heel of the lateral, and is 400 m in length, trending SSE to NNW . Whilst normal faulted offset can be seen in the seismic, the feature is 100 m deeper and does not extend upwards into the horizon to be hydraulically fractured. Offset can only be seen within the Lower Bowland Shale, and does not extend upwards into the target horizon.

SD4

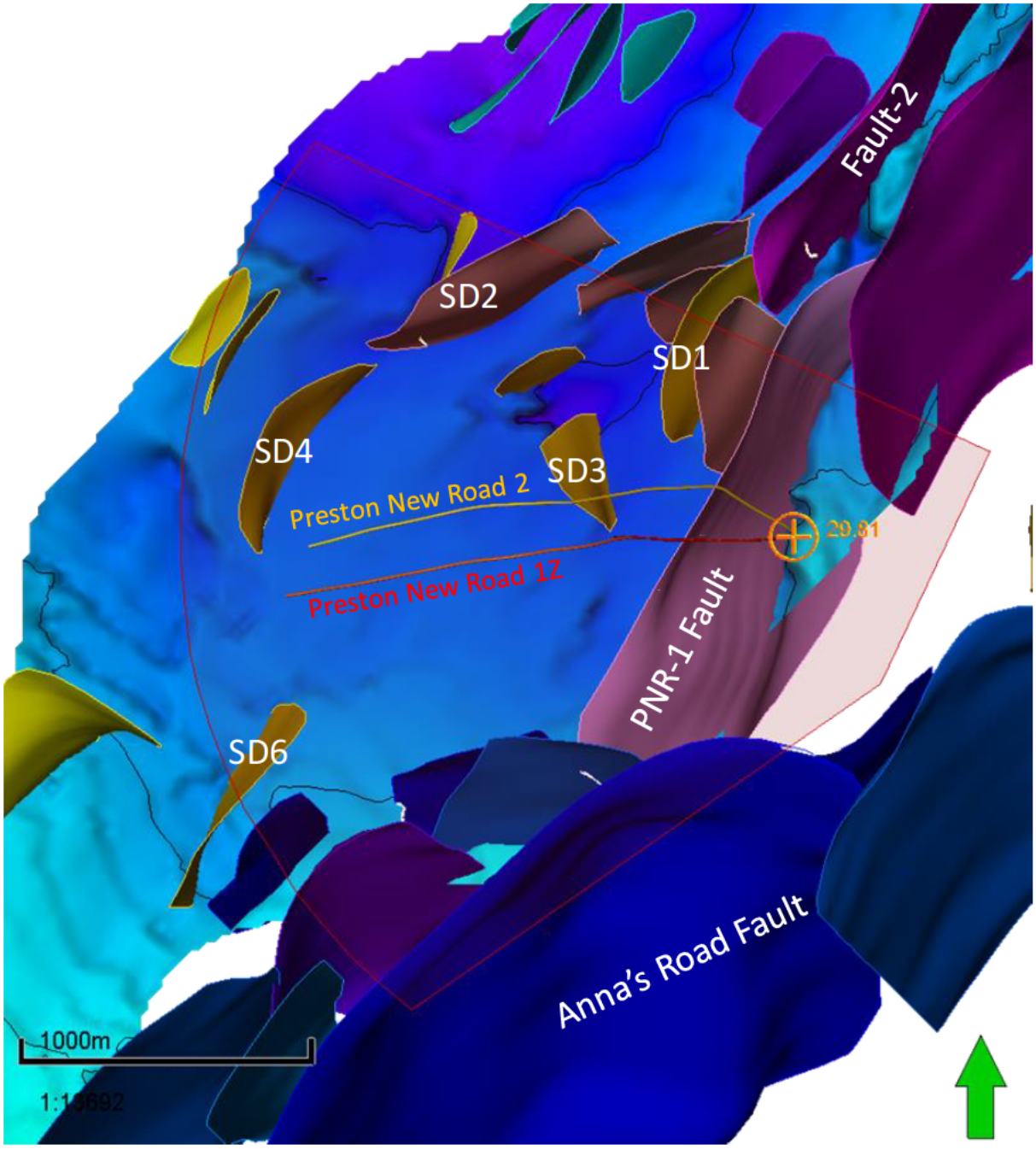
This discontinuity appears to be a continuation of the structural trend from SD2, extending to the south-west for 730 m. The feature is approximately 400 m from the toe of PNR 1Z, but the consistency of offset in the seismic is poor, and is a subtle discontinuity at best.

SD5

The SD5 feature was presented within the HFP from Cuadrilla, and had been mapped to be adjacent to the toe of the PNR 1Z. It was not possible to identify this feature in the seismic from my own mapping.

SD6

A poorly defined discontinuity may be located approximately 400 m south from the toe of PNR 1Z, trending in a SSW-NNE direction. It has a maximum length of 800 m, but the seismic offset is inconsistent, and has a highly variable dip. It this is a true discontinuity, it may be an antithetic feature associated with the Anna's Road fault.



Map of the interpreted faults and seismic discontinuities within the Preston New Road Area

Conclusions

The primary objective of this project was to integrate the newly available drilling data from the PNR 1, PNR 1Z and PNR 2 wells into the 3D seismic interpretation, and to evaluate whether this new information required changing any of the interpretation, or the conclusions made within the original BGS study, which could change the risk of frac-induced seismicity. It was also important to compare this work, and the BGS interpretation with that submitted by Cuadrilla within the Hydraulic Fracture Plan.

This project interpretation at Preston New Road closely matches that of the BGS study. Some differences include a more detailed interpretation of the faulting and fault relationships, in particular for minor faults. With the supplied deviation surveys for the lateral wells, a direct tie could be made to interpret the horizons that are being proposed to be hydraulically fractured in PNR 1Z and PNR 2.

Both reports do independently conclude that the proposed locations for hydraulic fracturing at Preston New Road do not intersect any major mappable faults, therefore confirming the lower risk of induced seismicity than that seen at Preese Hall in 2011.

Discontinuities have been identified within the seismic data, which may represent small faults. There is a higher level of uncertainty in these features, but the PNR 1Z lateral wellbore does not directly intersect these features, and by implementing a real-time traffic light system during hydraulic fracturing operations, the risk of causing disturbance through seismicity by reactivating these, or any other unmapped faults may be managed.

The interpretation in this project and that of the BGS generally agrees with the mapping of faults and discontinuities presented by Cuadrilla in their Hydraulic Fracture Plan.

In conclusion, integration of the 3D seismic with new well data for Preston New Road provided by Cuadrilla does demonstrate that the company has adequately assessed the risk of induced seismicity through the mapping and identification of faults, and taken appropriate measures to avoid hydraulically fracturing into any known faults. The new well data has increased the confidence in the 3D seismic interpretation and has not changed the risk of frac-induced seismicity.

September 2018