Objection to approval of Cuadrilla hydraulic fracture plan for PNR-2

David Smythe
12 November 2018

Summary

Cuadrilla Bowland Limited (hereinafter the Operator) still does not understand the geology at its wellsites, even after nine years of active exploration in the Fylde. Its geological interpretation of the pre-Permian at Preston New Road (PNR) has changed significantly between early 2015 and now. Some of the interpretations do not make structural sense, so are untenable even on their own internal evidence. A major error in the prior interpretations was discovered by the absence of the prognosed 300 m of Millstone Grit at Preston New Road-1, spudded on 16 September 2017 and completed on 11 January 2018. My access to the 3D Bowland-12 seismic survey, finally obtained on 6 November 2018, confirms that Cuadrilla's current interpretations are untenable. Major faults cutting the entire section, including the post-Hercynian Permian and Triassic sediments, have been omitted from Cuadrilla's example cross-sections. These were interpreted by myself based on the 2D seismic dataset, and have been confirmed by the 3D survey. I have resolved the paradox of the absent Millstone Grit, by interpreting major faults within the Carboniferous as reverse faults with a strong strike-slip component. This style of faulting is consistent with the earthquake fault plane solutions.

Cuadrilla should be required to re-interpret properly its 3D dataset in the light of PNR-1, before the HFP for PNR-2 is authorised by the OGA and the EA.

Cuadrilla's changing geological interpretations

It is normal for interpretations to be modified when new data, such as the results of drilling a well, become available. The biggest change in interpretation usually arrives with a 3D seismic survey replacing a network of 2D surveys. However, Cuadrilla has long had available the results of Preese Hall-1, drilled in 2011, and the Bowland-12 3D seismic survey shot in 2012. The only significant addition has been the drilling of PNR-1, completed in January 2018.

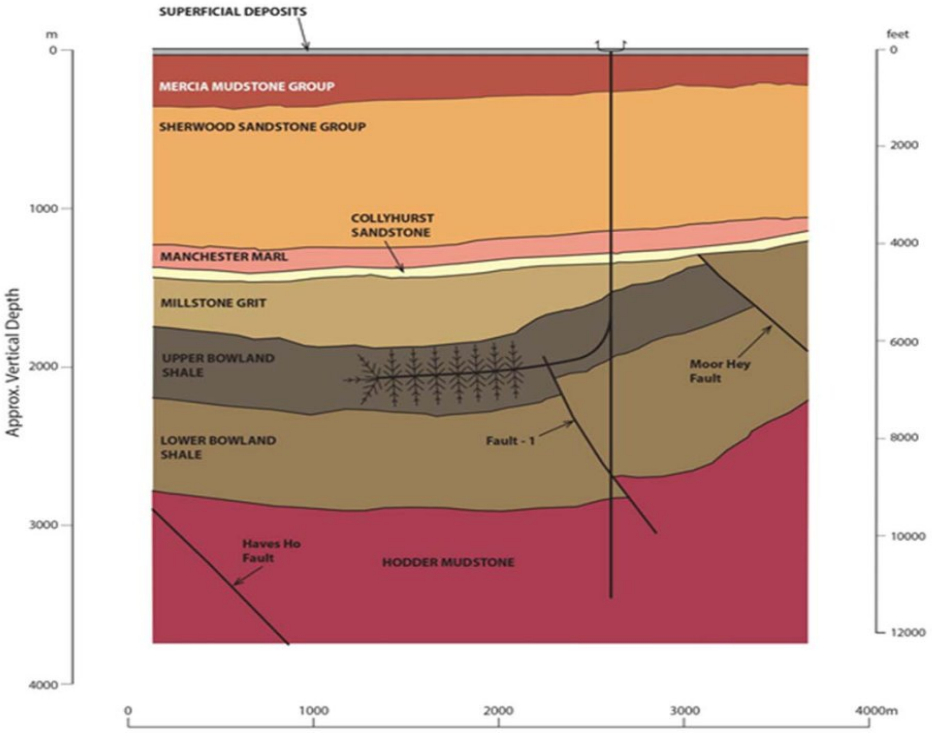


Fig. 1. E-W geological interpretation through PNR (2015).

Figure 3.2: Geological strata.

Figure 1 comes from the Environmental Statement, Vol. 1 (2015). It is an E-W section through the PNR site, as are all the succeeding cross-sections. This interpretation is dubious in its own right. No seismic reflection data were used to support it. I wrote in my Objection document to Lancashire County Council in 2015, questioning the geological soundness of the diagram:

> *" The 'local' fault, labelled Fault-1, through which it is proposed to drill the vertical pilot hole has a throw of 100 m down to the west at Base Upper Bowland level, increasing to about 150 m at Base Lower Bowland Shale. It has the geometry of a reverse fault, but it may have been a vertical normal fault at the time of deposition of the Bowland Shales, and only later tilted down towards the west. It is mapped by the Applicant as if it were a growth fault active during the deposition of the Upper Bowland Shale. But this is suspicious for two reasons:*
>
> *What other evidence is there of tectonic activity during this time? What is the flexure above the prolongation of the fault at the Top Upper Bowland shale horizon?*
>
> *The Applicant's interpretation is questionable, because it may be an attempt to minimise the possibility that faults such as this one post-date the Carboniferous, i.e. they are of Hercynian origin or re-activation, like most of the faults in this area, and therefore are likely to penetrate higher up than the Bowland Shale. It is more plausible that the fault cuts up through the Millstone Grit to the base of the Collyhurst Sandstone, just as does the Moor Hay fault lying 1 km to the east. In other words the little monoclinal flexure above the fault should be remapped as a fault offset. This interpretation is more likely in my view (unless evidence can be adduced that the Upper Bowland was a time of growth faulting) because it is geometrically implausible that a fault with a throw of 100 m can die out upwards within another 200 m, as Cuadrilla has interpreted.".*

In November 2017 the identical interpretation was used for the draft HFP for PNR-1z (Figure 2).

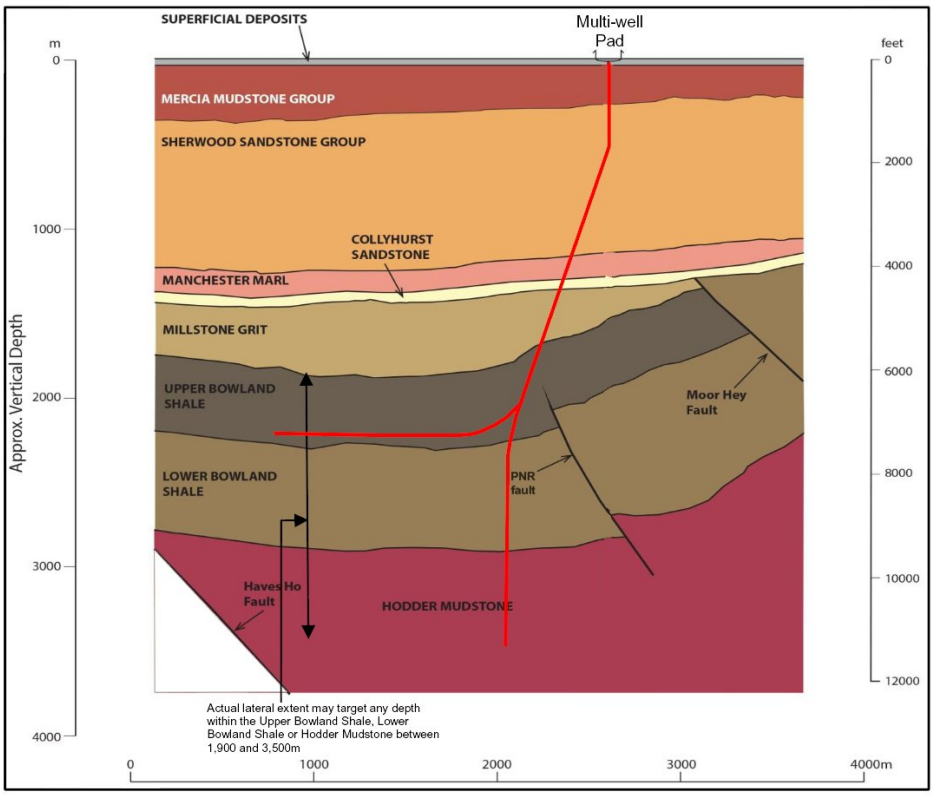


Fig. 2. HFP cross-section (November 2017) showing revised positioning of PNR-1 (vertical) and PNR-1z (horizontal).

The wellpath has been shifted to avoid Fault-1, now relabelled as the PNR Fault. The likelihood that this fault penetrates higher up, as I suggested in 2015, has been ignored. The horizontal to be fracked lies at about 2300 m depth, near the base of the Upper Bowland Shale.

In June 2018 the diagram was altered to take account of the fact that no Millstone Grit was encountered in drilling PNR-1 (Fig. 3). The post-Hercynian geology remains identical. The locations of the Moor Hey Fault and the Haves Ho Fault are unchanged, as is the base of the Lower Bowland Shale.

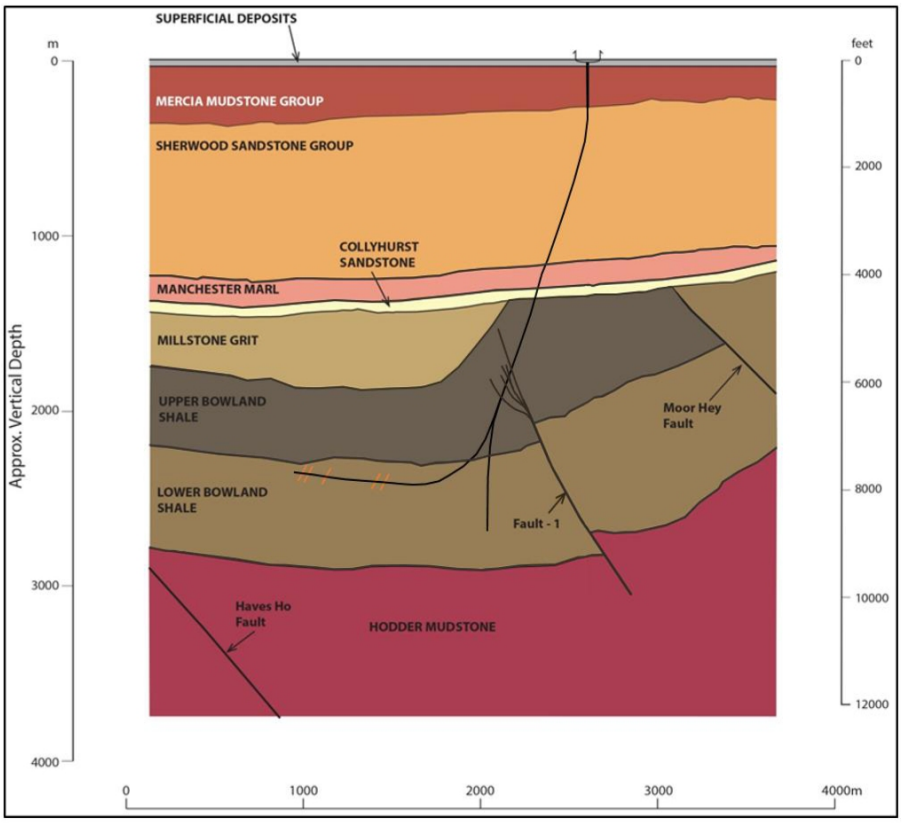


Fig. 3. June 2018 interpretation (HFP for PNR-1z).

The PNR Fault (now re-named back to Fault-1 again) is shown cutting the Upper Bowland Shale, together with a number of splays. Presumably there was some evidence for faulting encountered in the drilling. Note that a reverse fault like this would result in repetition of log data and of lithologies. The base of the Millstone Grit has been folded upwards to avoid having the layer intersecting the wellbore. This is intrinsically unsound, since it leaves the Upper Bowland abruptly thickening to the east. It might have been more logical to have extended Fault-1 up to the sub-Permian unconformity (Base Collyhurst Sandstone), while re-drafting the base of the Millstone Grit to avoid intersecting the well.

The latest version of the geology is in the current version of the HFP awaiting final approval (Fig. 4). This time the thickness increase of the Upper Bowland has been 'solved' by making its base turn upwards to a dip of about 60°, parallel to the top of the layer west of the wellbores. The base of the Lower Bowland has been similarly upturned in the vicinity of the Moor Hey Fault to an unlikely dip of about 80°. The post-Carboniferous succession remains unchanged from 2015.

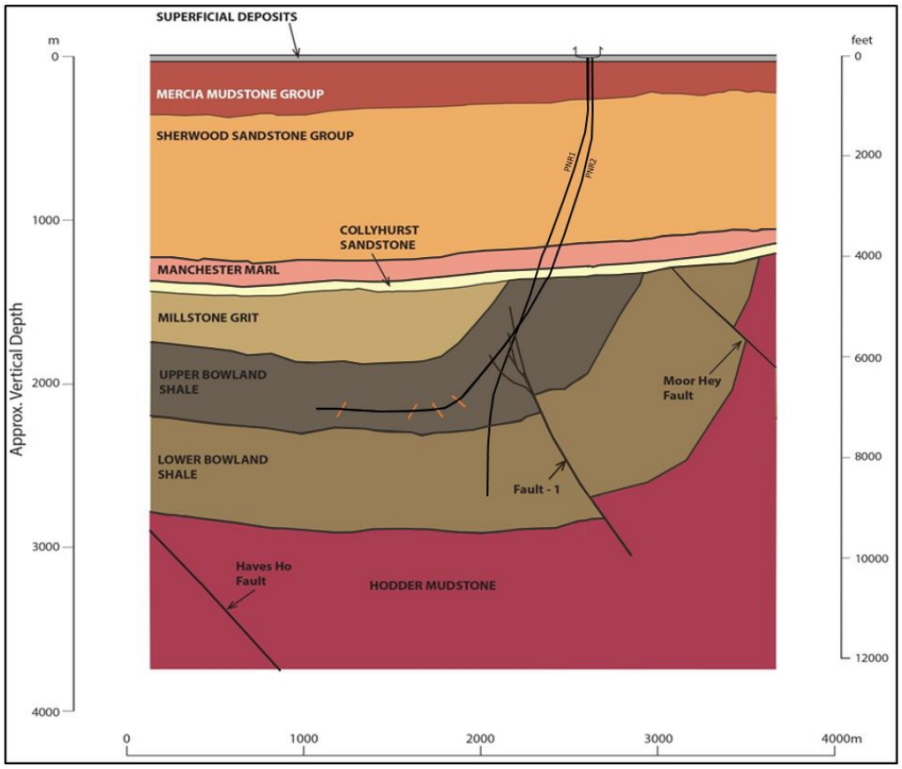


Fig. 4. Current version of the HFP for PNR-2 (November 2018).

Evidence from the 3D seismic survey

The three versions of HFP geological interpretations (Figures 2-4 above) have been accompanied by E-W vertical seismic displays in depth, not two-way time. These are shown in Figures 5-7 below, respectively.

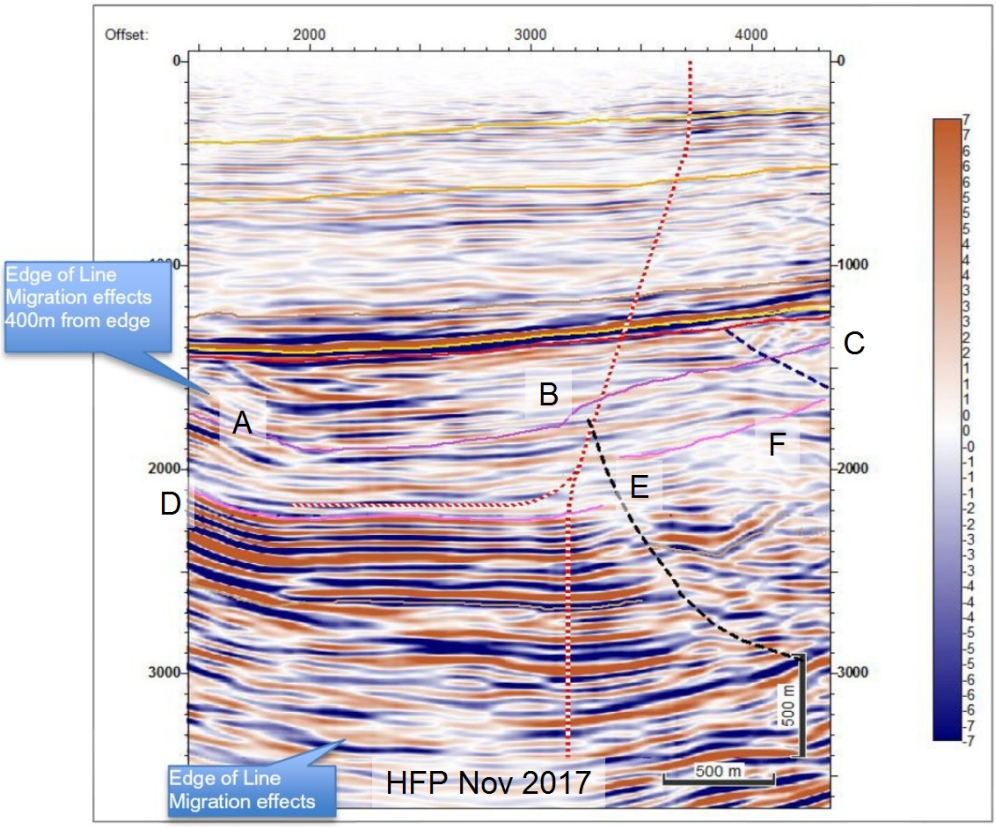


Fig. 5. Vertical seismic display (November 2017).

The seismic display covers the same E-W extent as the geological interpretation which it accompanies (Fig. 2). The diagram correctly points to the migration artefacts (blue labels) coming in from the western edge of the survey. There are three yellow markers visible in the upper part of the section indicating (presumably) Top Sherwood Sandstone, Top St Bees Sandstone and the main Top Carboniferous unconformity. Less visible are two other brown markers. All these horizons have the appearance of having been picked automatically, by an algorithm that searches through the data volume from a seed point. This method is suitable as a first pass interpretation tool in simple layering. There are minor errors which should have been manually corrected, but presumably the Operator is not interested in the accuracy of mapping that does not bear directly on the target rocks.

I have added labels A-F to the diagram. At A, the Base Millstone Grit is shown bending upwards, following the possible migration artefacts. This may or may not be correct, but it is inconsistent with the geological diagram (Fig. 2). At B the horizon takes a dog-leg (monocline) to avoid the tip of Fault-1 (aka the PNR Fault); however, the tip of the fault is now shown cutting the planned wellbore - again, inconsistent with Figure 2. At C the Base Millstone Grit is shown cutting through the Moor Hey Fault at significantly greater depth than shown in Figure 2. The lack of offset across the fault implies that the Operator must regard the fault is having a purely strike-slip component. At E the PNR Fault offsets the Top Lower Bowland by about 200 m. The track of the fault through reflector offsets looks reasonable. But at F the Top Lower Bowland cuts across reflectors; this is unreasonable, and gives the impression of careless or hurried mapping.

Figure 6 accompanies the June 2018 version of the HFP for PNR-1z. The E-W extent of the image has been truncated relative to the geological section (Fig. 3), so that the only point of reference is the wellhead.

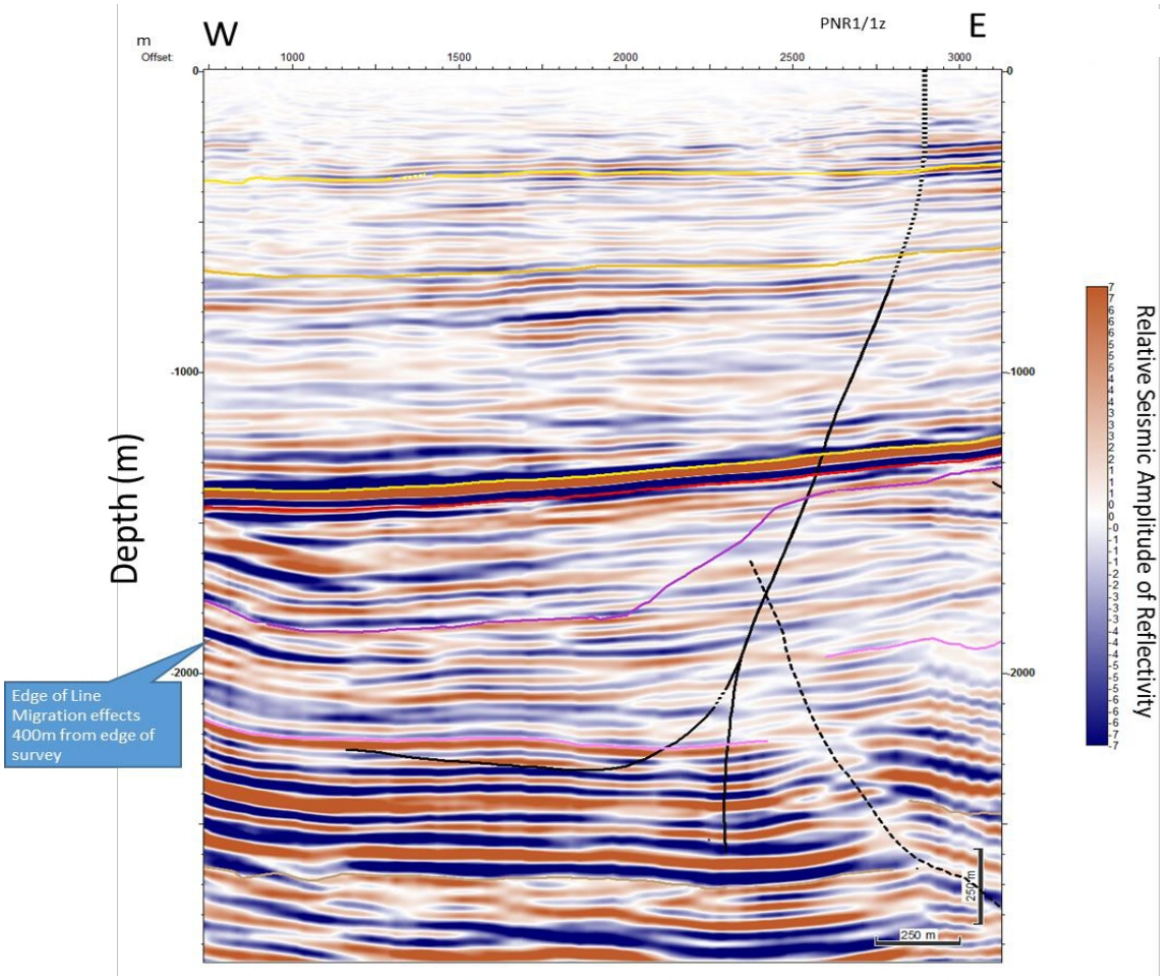


Figure 6. Seismic display for PNR-1z HFP (June 2018).

Here we see the Base Millstone Grit thinning in a wedge just west of the wellbore, and cutting across reflectors at and angle of about 40°. It then continues east, implying that there is about 50 m of Millstone Grit at the well. Again, this is careless and inconsistent mapping. Below it, Fault-1 is mapped as intersecting the wellbore, cutting across continuous reflectors at 1600-1800 m depth.

Lastly, Figure 7 shows the vertical seismic display to accompany the current geological cross-section shown in Figure 4 above.

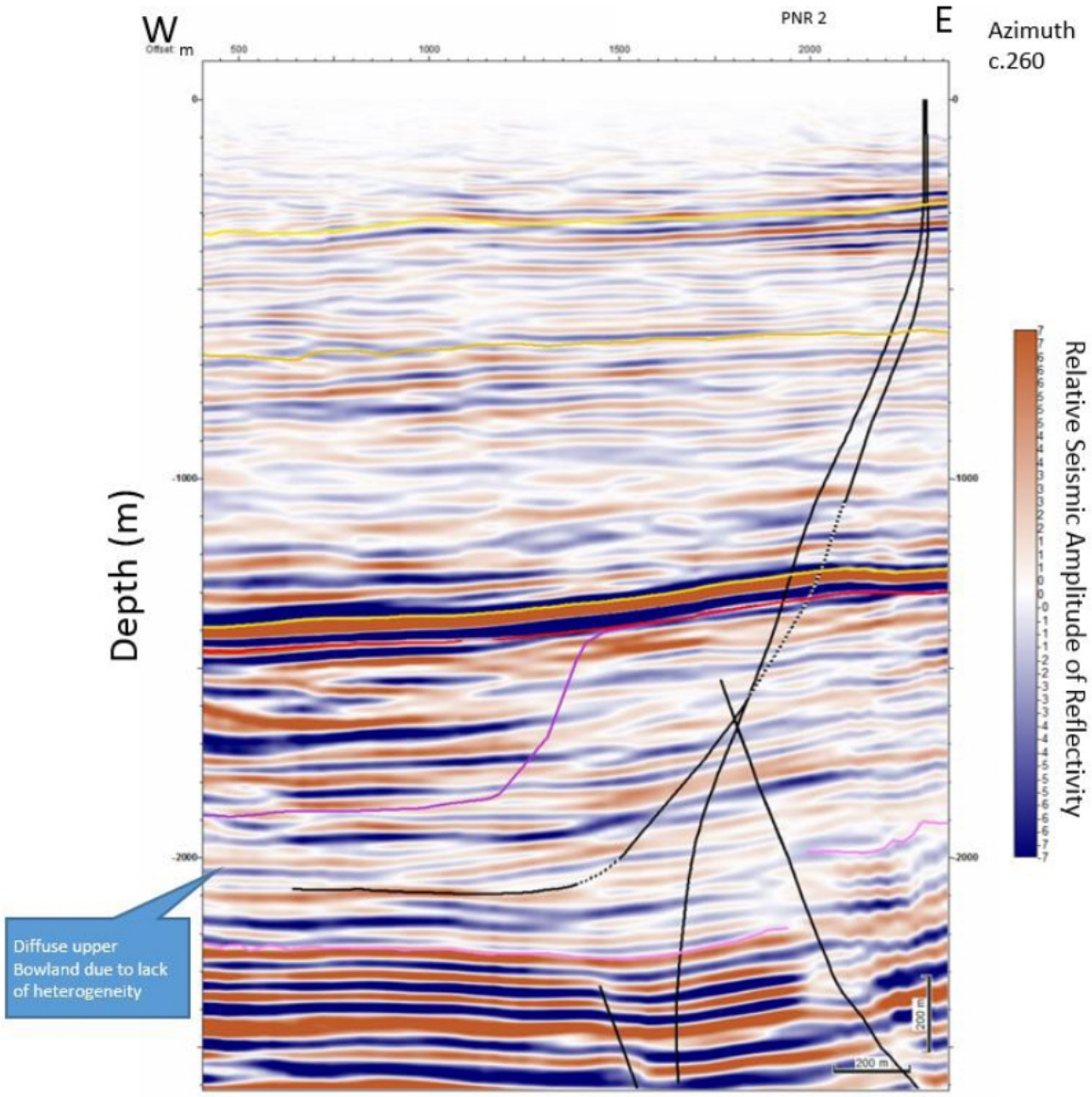


Figure 7. Seismic display for PNR-2 HFP (November 2018).

Once again there is no map on which to locate the display, which is now stated to be at an azimuth of about 260° (presumably parallel to the horizontal section of PNR-2). The display is even more truncated than earlier versions. The Base Millstone Grit is now shown wedging out abruptly over about 250 m, cutting across strong reflectors. There is now no thickness of Millstone Grit shown at the wellbores. Fault-1 similarly cuts unrealistically through strong reflectors around its intersection with the wellbores.

Preliminary evidence from the 3D seismic survey

The available version of the 3D dataset is the original migration (UKOGL suffix _OM). No other documentation has been supplied, such as the acquisition and processing reports. The Inline and Xline numbering have been taken from the trace headers; their names seem possibly swapped over, because I understand that in the acquisition the shot lines were N-S, and these are conventionally called the Inlines. Herein, for the avoidance of doubt, the Inlines are oriented E-W. Also, for the avoidance of doubt, the results discussed below from my independent mapping are based on just a few hours' work, and may well be subject to revision.

Some of the Operator's seismic displays appear to have been based on a revised pre-stack migration, with vertical scale in depth. It is unclear whether the processing involved pre-stack time migration with subsequent depth conversion, or pre-stack depth migration. In either case, the additional processing available to the operator will make no significant difference to the discussion herein.

Wakepark Fault

Using the 2D seismic database only, in 2017 I mapped a new fault at the west of the 3D survey area which I named the Wakepark Fault (see Appendix A). It had been independently mapped at Top Permian level by British Gas and by Eukan Energy, former licensees, in 1991 and 1994. I remapped this fault and showed that it extends up to near-outcrop (Figure 8). It is a normal fault, extending in a NNE-SSW azimuth, with its outcrop approximately from the vicinity of from Anna's Road-1 to near Preese Hall-1, passing by the artificial Wakepark water sports lake some 1500 m NW of the PNR pad.

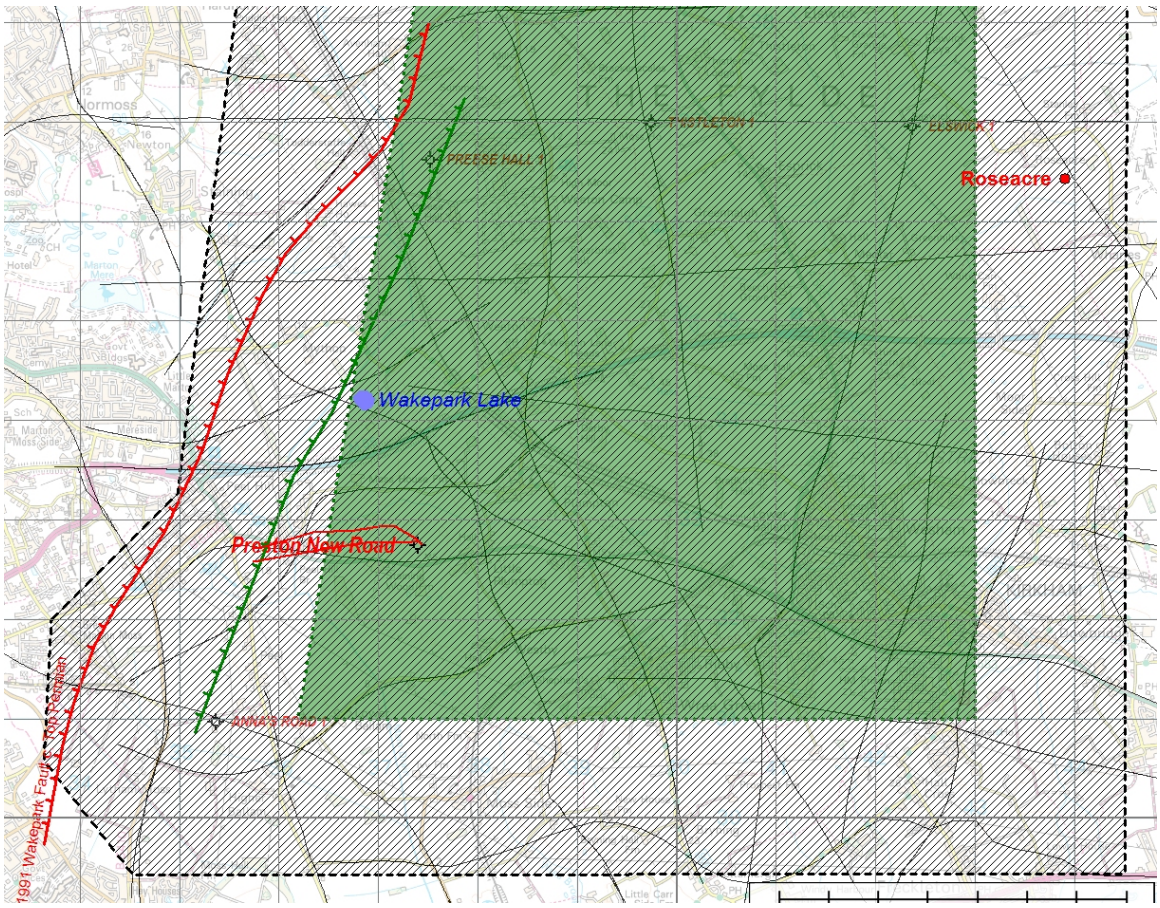


Figure 8. Wakepark Fault at outcrop (green) and at Top Permian level (red), based on 2D seismic data (thin black lines). The surface extent of the 3D survey is shown by the hatched area, within which the green polygon indicates the full-fold coverage.

The outcrop lies over the toes of PNR-1z and PNR-2, and at the depth of these two wells it is over 1 km to the west. I have confirmed the existence and accuracy of this mapping now that the 3D dataset is available. The 2D-mapped fault lies within one or two 3D bins (25-50 m) of its more accurate placement using the 3D data. However, it can be seen from Figure 8 that the fault lies mainly in the outer fringe of the 3D volume, where fold diminishes progressively from 100% to zero. Thus a combination of the 2D data and the 3D volume is needed to map the fault.

The importance of this fault is that it might be a feeder for the four freshwater springs that replenish the Wakepark lake. If so, then the source of the water might be fresh water in the upper Sherwood Sandstone at 300 m depth. This is discussed further below.

There is no mention or depiction of the Wakepark Fault in any of the Operator's documentation.

Absence of Millstone Grit

I have concentrated on the western portion of the 3D data volume, to determine why the Millstone Grit is present at Preese Hall-1 but proved to be absent at PNR-1. I illustrate my findings with a timeslice at 996 ms, Xline 2144 and Inline 5285. The timeslice is shown in Figure 9.

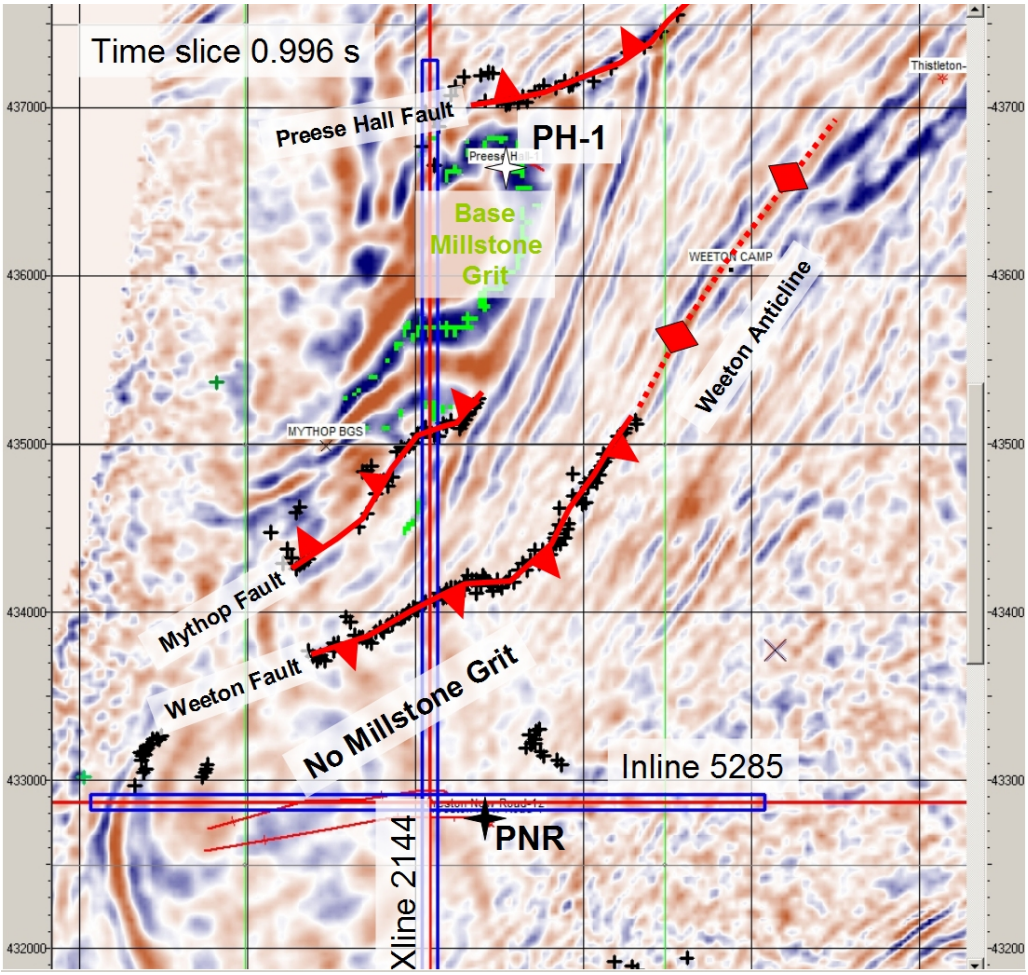


Figure 9. Timeslice at 996 ms showing structure at near base Millstone Grit. Green picks of the Base Millstone Grit are shown on the dark blue (positive amplitude) seismic data.

My main finding is that there is a complex steep reverse fault below the pre-Permian unconformity, called the Weeton Fault. It bounds a block to the NW where the Millstone Grit is present, as proved at PH-1, from the area to the south including PNR where the Millstone Grit is absent. The Weeton Fault changes character running north-eastwards, becoming a sharply pointed (chevron) anticline

with a fault bifircating the axis. This style of faulting is consistent with the earthquake fault plane solutions.

Figure 10 shows a preliminary contour map of the Base Millstone Grit, in units of TWT.

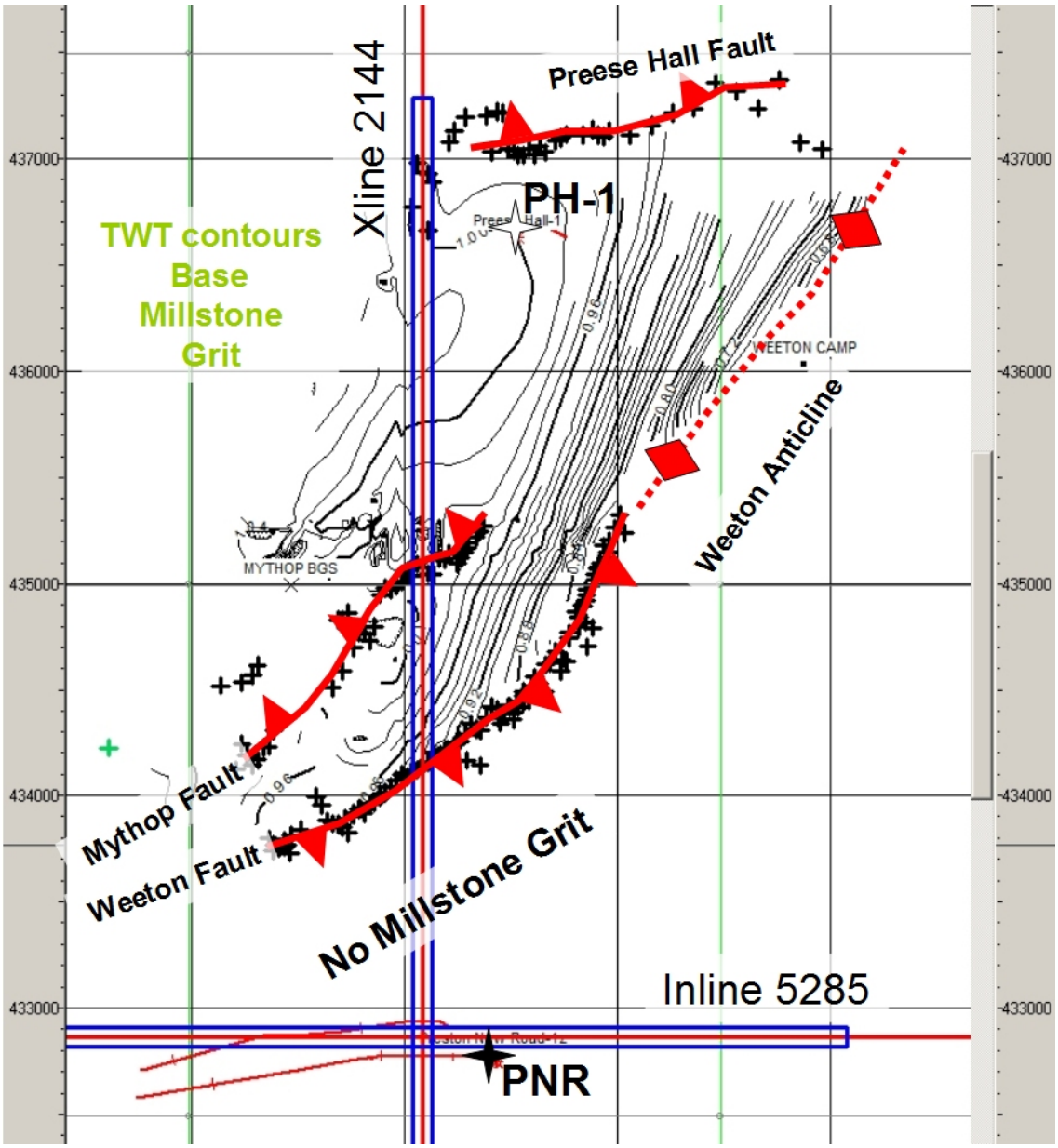


Figure 10. Contour map of Base Millstone Grit.

The Preese Hall Fault is a south-verging high-angle reverse fault with a classic horse structure. However it is not shown on sample line Xline 2144 (Figure 11). Xline 2144 runs from 500 m west of PH-1 south through the heels of the PNR wells. The Weeton and Mythop Faults, both reverse faults, have opposite senses of vergence, but the former is the principal fault. It may be argued that the Base Millstone Grit (light green pick) must continue on the south side of the Weeton Fault, because of the small vertical offset of the Lower Bowland Shale beneath; but this is not the case. Once it is recognised that these high-angle reverse faults probably have a considerable component of strike-slip displacement, the lack of significant vertical offset is understood, and explains the thickening of the Upper Bowland Shale to the south. The mismatch of dips in the Upper Bowland Shale across the Weeton Fault - dipping NW on the NW side, and flat-lying to gently south-dipping on the south - is also explained by invoking lateral slip. Two-dimensional sections cross the fault zones do not balance; this fact requires that lateral displacement be invoked.

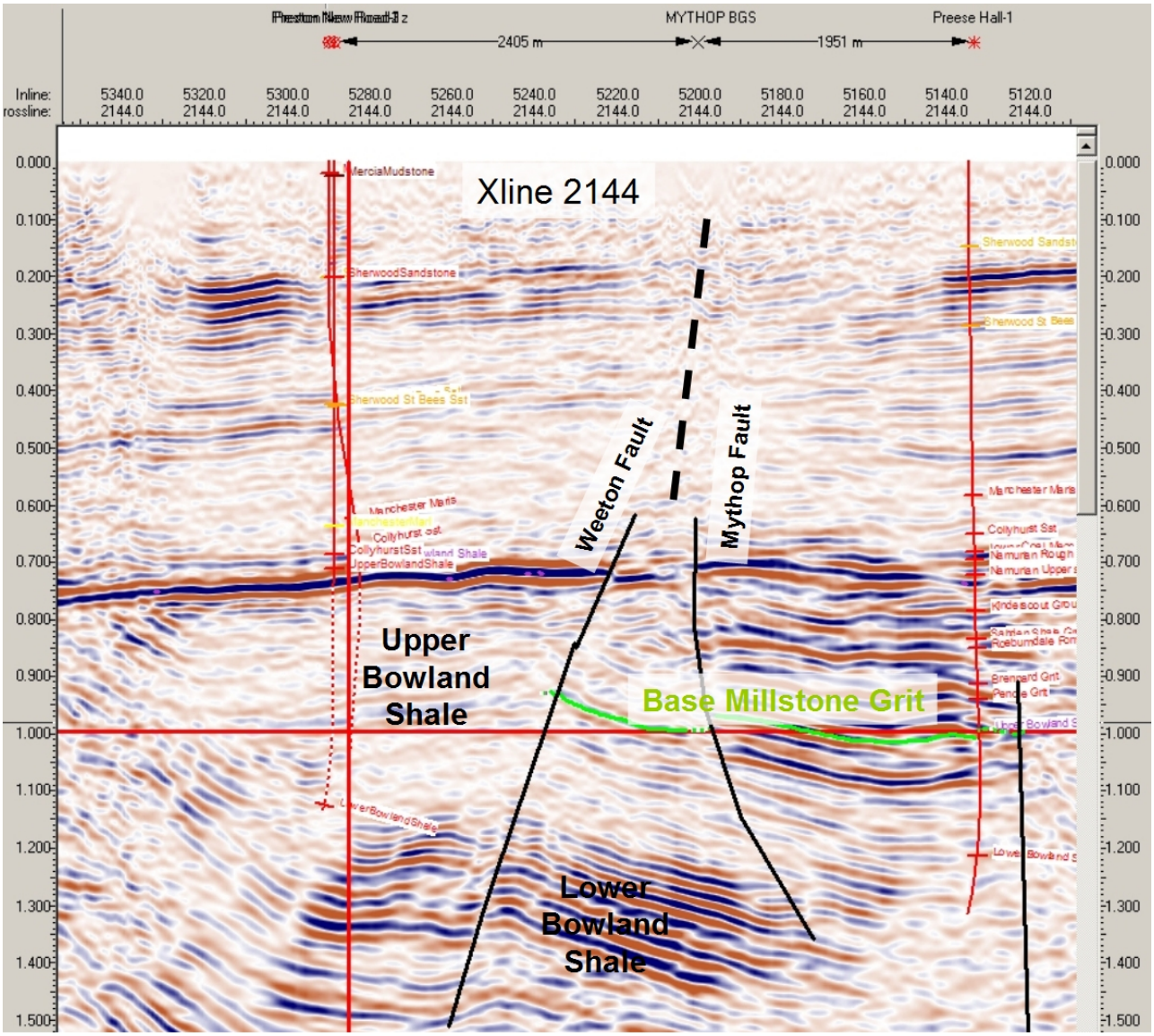


Figure 11. Xline 2144, illustrating the reverse faults 1-2 km north of the heel localities of PNR-1z and PNR-2.

The Weeton Fault and the Mythop Fault both displace the sub-Permian unconformity, the Collyhurst Sandstone and the Manchester Marls in a vertical component of displacement (in addition to presumed but non-measurable strike-slip displacement). This shows that the Manchester Marls cannot act as the supposed cap rock to prevent possible upward migration of fluids from the frack zone situated some 1200 m to the south. Indeed, further west, the horizontal distance from the Weeton Fault to the horizontal section of PNR-2 is about 1 km.

Another significant feature of the two reverse faults is that they converge upwards into a fuzzy seismic reflection zone within the Sherwood Sandstone Group. This is shown by the heavy dashed black line in Figure 11. There is a vertical offset of the Top Sherwood Sandstone of around 50 ms. This shows that the major strike-slip fault zone extends up into the Mercia Mudstone, practically up to outcrop.

None of this information appears to be known to the Operator, unless the Operator knows it but is withholding it from disclosure.

Figure 12 shows the E-W vertical display of Inline 5285, running along the horizontal legs of PNR-1z and PNR-2. The former is shown by the solid red line, the latter by the dashed red line above. The well tops confirm the absence of Millstone Grit, with Upper Bowland Shale directly underlying the pre-Permian unconformity. The reverse fault shown by the solid black line corresponds to the Operator's Fault-1 (aka the PNR Fault). To the east, where the strong lower Bowland Shale reflectors die out rather abruptly, there is a zone of very poor reflection quality. This zone is also apparent in the SE corner of the timeslice shown in Figure 9 above.

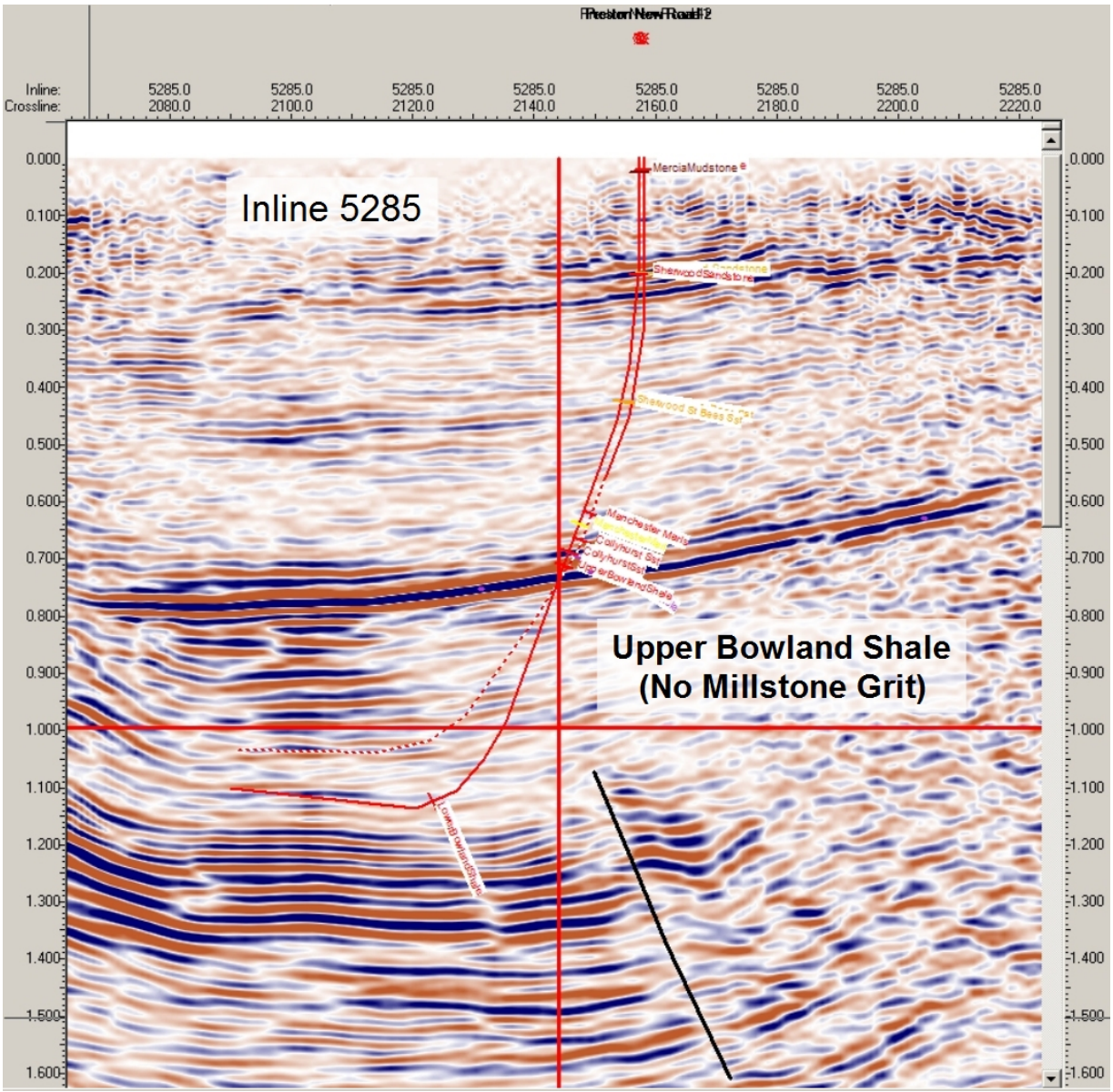


Figure 12. Inline 5285 running along the PNR wells.

I believe that this poor-seismic quality zone is not due to acquisition problems, as is claimed, but is due to very complex low-angle thrust faulting below the Moor Hey reverse fault (shown in Figures 1-4 by the Operator; not marked in Figure 12). This will require meticulous study to unravel.

Discussion

It is apparent that the Operator still misunderstands the rather complex geology of the western Fylde. The prognosed presence of Millstone Grit at PNR is perhaps understandable, but was based on the false assumption that the many mappable faults in the licence area have only vertical displacement, whether in the normal or the reverse sense. The Operator's geologists seem to have underestimated the importance of strike-slip faulting. In fact the 3D survey provides many instances of classic strike-slip geology.

The omission of the Wakepark Fault from the Operator's submissions and publications is a severe error. The breach of the supposed Manchester Marls seal by faulting appears to have been withheld from scrutiny by the regulators - it is difficult to accept that the Operator is unaware that some faults cut the Permian.

The margin of error between prognosed geological layer depths and subsequent results from drilling is typically a few metres up or down. The absence of an entire formation some 300 m thick constitutes a major error in interpretation, which cannot simply be patched up by minor changes.

The many errors, together with the minimal cosmetic changes to the geology made by the Operator late in the day, imply that the Operator is seeking to do the absolute minimum of work in order to satisfy the regulators. This is unacceptable.

Approval of the HFP by the EA

The current version of the HFP for PNR-2 has serious and fundamental shortcomings. It would be unacceptable for the regulators to approve it. Nevertheless, the EA appears to ready to issue its permit, based on the incomplete, erroneous, and at times mendacious data supplied by the Operator in its HFP. A recent leaflet issued by the EA (6 November 2018) states, under the heading 'What is the risk to groundwater or drinking water?':

> "*The EA has fully assessed the risk of operations at Preston New Road before deciding to issue a permit. There is no plausible risk to people's drinking water from the hydraulic fracturing operation. The layer of rock that is being fractured is more than 2 kilometres beneath the surface, and several layers of impermeable rock lie between it and the shallow water table.*
>
> *We have assessed that there is no groundwater in the shale and we do not expect fractures to enter the layer of Millstone Grit above. If fractures were to go beyond the underground permitted boundary (set at the upper boundary of the shale rock) the impact is likely to be materially insignificant. The environmental permit does not allow for any chemicals that are hazardous to groundwater to be used in hydraulic fracturing fluid.*"

Clearly the mention of "*Millstone Grit above*" is untenable, because there is no Millstone Grit either at the well or above the fracking zone.

A recent FOI request to the EA (CL101888HR) states:

> *"Question: Given that they had misinterpreted the section of the vertical well before drilling, what level of confidence do you have in their assertion that 'the seismic shows' that the MG is actually present above the lateral well ?*
>
> *Response: The seismic cross section data at the Preston New Road site originally showed the millstone grit at the vertical part of the well. However, as you say, this was not identified in*

the borehole itself, and the Environment Agency requested a modification to the Hydraulic Fracture Plan (HFP) to take account of this new information. The operator still believes this formation to be present, from the interpretation elsewhere. As a result they have retained the original interpreted level of the top bowland shale where it is above the lateral to be hydraulically fractured. This interpretation has been the subject of discussion between the Oil and Gas Authority (OGA), ourselves, and the British Geological Survey.

We have accepted the interpretation in the HFP on the basis that the alternative is that the top bowland shale horizon corresponds to a higher reflection event, and as this horizon defines the upper permit boundary, the current interpretation of a lower horizon is a safe one."

So the EA accepts the scanty diagrams and explanation given in the current HFP, based on vague assurances ("*the operator still believes* ...") that it has also discussed the matter with other agencies (OGA and BGS). This complacent attitude is inconsistent with sound regulation.

The same FOI request yields the following exchange:

[Query 4] "Have you helped with all these interpretations or have Cuadrilla taken extra advice maybe ? What confidence do you have in their understanding of the seismic survey ?

Response: We request enough information about the 3D seismic results to understand the quality, reliability and fault resolution capability of the cross-sections extracted, and challenge these aspects if appropriate. At this site, the final data quality was not the best, due to site factors. We do not assist in the original interpretation or re-interpret the operator's data volume, but in this case the 3D dataset has been reviewed by the OGA. Please note that a complete reinterpretation of such a 3D seismic data volume could potentially take weeks, and may involve an element of re-processing."

The response above shows that the EA seems to be more concerned about saving the Operator some time and money, than about actual regulation. The Operator has had some nine months since the results of PNR-1 came in, and therefore should have had ample time to fully re-interpret the 3D survey. Instead, the Operator seems to have relied on superficial tinkering with a couple of horizons in the vicinity of the PNR wells. As shown above, these re-interpretations are contradicted by the seismic data.

Lastly, the EA has responded to the FOI query about the multiple changes to the geology around the Moor Hey Fault (see Figures 2-4 above):

"Question: Given that Well 2 does not go anywhere near the Moor Heys fault, how /why have Cuadrilla changed the interpretation?

Response: As the area around the Moor Hey fault is not relevant to the hydraulic fracturing of PNR1z and PNR2 laterals, we have not challenged the interpretation of this area as part of the HFP assessment."

This demonstrates again that the EA is taking a very narrow view of its regulatory remit. It is unacceptable that major changes in the geology within one or two kilometres of the well are deemed to be "*not relevant*".

The EA has written off all the groundwater in the Sherwood Sandstone Group below the Fylde west of the Woodsfold Fault as being saline, static, and therefore not of concern should it be contaminated by drilling and fracking activities. I published a detailed discussion of the groundwater in the western Fylde, in the context of a critique of the late Professor Paul Younger's expertise in hydrogeology. I attach extracts from this article as Appendix A below.

The principal points I made were:

- The EA is wrong to assume that the Woodsfold Fault is a non-transmissive boundary. It cites the modelling studies of 1997 and 2009, in which the fault was *defined* as a boundary, *a priori*. Therefore it cannot then take the modelling results as proof that the fault is a barrier to flow.

- The Kirkham borehole, which encountered hypersaline water, penetrated salt horizons within the Mercia Mudstone Group. Use of this anomalous result cannot then be applied to the whole of the western Fylde. The same applies to the recent deep borehole drilled by the BGS near Roseacre Wood.

- The EA is unaware of the implications of two old boreholes which penetrated to the Sherwood Sandstone, and which presumably drew fresh water.

- The EA has never sampled, nor considered the implications of, the water in the Wakepark lake.

- The Wakepark Fault, if acting as a conduit for upward flow from the confined Sherwood Sandstone aquifer, completes discharge end of the cycle of recharge-discharge, which was missing from the EA's investigations and used as an argument for no flow.

Conclusions

The concerns that I have raised above need to be addressed as a matter of urgency by the OGA and the EA.

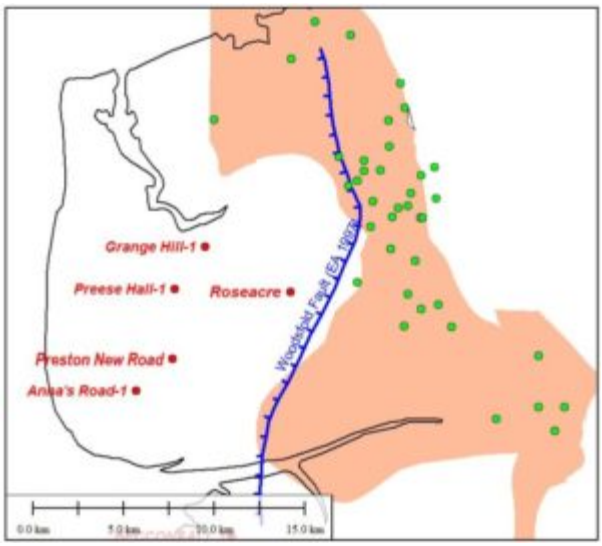
There exist pathways from the neighbourhood of the frack zone upwards to the Millstone Grit and Sherwood Sandstone Group, and even *via* faults through the Mercia Mudstone Group to the surface. It is the primary responsibility of the EA to see that these secondary and primary aquifers are protected. The EA cannot and should not rely on the incomplete and sub-standard information supplied by the Operator.

The Operator should be required to undertake a wholesale remapping and submit a revised HFP before approval is granted to proceed with fracking of PNR-2. I would expect the new plan to include many more samples of interpreted seismic data. It must also encompass a wider area than just the narrow zone above the horizontal wells. Structure contour maps of various horizons need to be included, including the Permian and Triassic horizons.

Appendix A
Extracts from Frackland blog:
'The expertise of Professor Paul Younger – Part 3. Hydrogeology of fracking (Part B)'
published by David Smythe on 3 February 2017

Introduction

... The scientific issue here is whether or not the Sherwood Sandstone Group aquifer below the salt-bearing Mercia Mudstone Group in the Fylde west of the Woodsfold Fault (where Cuadrilla's drilling and fracking activities are focussed) is saline or not.



Citation of previous research

... Fig. 1. Hydrogeology of the Fylde. The tan colour is the major Sherwood Sandstone aquifer at the surface. All the available hydrogeology studies concern the aquifer east of the major Woodsfold Fault (blue toothed line), where the water boreholes that were studied are situated (green dots). None of these studies have any bearing on the hydrogeology of the western Fylde, where Cuadrilla has drilled and proposes to drill (red dots).

But all nine of the citations that Professor Younger accuses me of neglecting are either irrelevant and/or outdated. None of the cited work has any bearing on the hydrogeology of the western Fylde, west of the Woodsfold Fault - the area of interest where Cuadrilla wishes to frack (Fig. 1). They all concern the major aquifer at outcrop (i.e. at the surface), some 10-20 km to the east.

... I have disputed the EA's claim that groundwater here is saline, and that it is therefore is not of concern if it were to be contaminated by fracking. ...

Western Fylde borehole evidence

Kirkham borehole (type E)

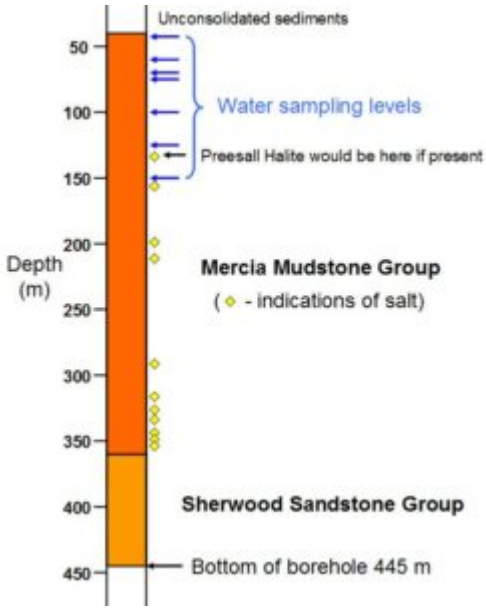


Fig. 6. Simplified geological log of the Kirkham borehole, western Fylde. Groundwater sampling levels measured by the EA are shown by blue arrows. Evidence of halite is shown by yellow diamonds. If the Preesall Halite, found further NW, were present, it would be at the level shown by the black arrow.

This borehole was drilled in 1970 as a test for underground gas storage, but has since then been used as an observation borehole. It penetrated the Sherwood at 366 m and went on down to 445 m.

The only evidence that the EA seems to consider, in dismissing the groundwater potential of the entire western Fylde, is the hypersalinity of the water samples observed in this borehole. I pointed out that this evidence

is invalid because two of the three hypersaline samples were taken from levels within the Mercia Mudstones, where the observed hypersalinity, some two or three times more salty than seawater, can be explained by perched (hydrogeologically isolated) relict halites known to exist within the Mercia Mudstones.

Rowe's Model Dairies, Inskip (type E)

Fig. 7. Rowes Model Dairies, Inskip, c. 1950, where a 161 m deep borehole penetrated the Sherwood Sandstone aquifer at 124 m. Photo credit: Francis Frith Collection.

This borehole was drilled in 1940-41. It lies 6 km NNE of the Kirkham borehole, and, like it, is just west of the Woodsfold Fault. It is 2.7 km NE of Cuadrilla's Roseacre Wood site. It supplied a dairy and cheese factory untill the mid 1960s. Would Professor Younger have us believe that saline water was used here?

Phoenix Mill, Wesham (type E)

This borehole was drilled to a depth of 445 m in the nineteenth century. It lies 1.7 km west of the Kirkham borehole and 4.2 km east of Cuadrilla's Preston New Road site. No geological details are available, but this depth appears to be through the Mercia Mudstone Group and well into the Sherwood.

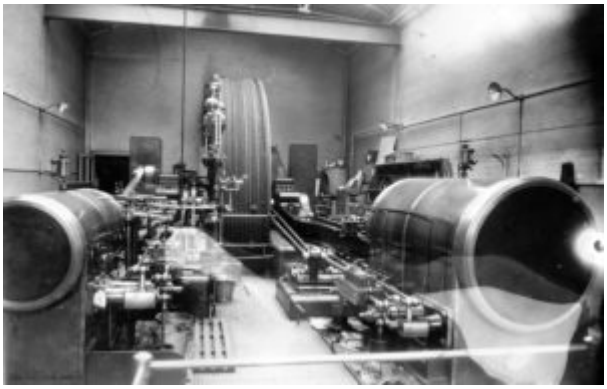


Fig. 8. Compound steam engine of the type used at Phoenix Mill in the nineteenth century. Consumption of water, which would necessarily have been fresh, was about 40,000 l per day, of which most could be recycled.

The water would have been required chiefly for the compound steam engine to run the weaving looms. The water would have re-used in a closed cycle, with a reservoir on-site. The existence of the reservoir has been confirmed from a 1911 map. Mr John Phillp of the Northern Mill Engine Society says that such an engine would require about 40,000 litres per day, but that most of this would be recycled. However, it is unlikely that a source of salty water would have been countenanced, because it would lead to precipitation and corrosion in the boiler, with resulting inefficiency.

Fylde discussion

The boreholes described above are part of a group which I examined, comprising some 39 relevant wells west of the Woodsfold Fault, of depth greater than 30 m, which are available on the BGS borehole mapper website. About five of these borehole records are confidential, and/or there is no information. In addition, I studied the water composition records of 56 boreholes, which I obtained from the EA.

I think it is reasonable to conclude that it is unlikely that hypersaline or even saline (undrinkable) water was used either for the cheesemaking at the dairy or for powering the looms at the mill.

The EA believes, based on no solid evidence, that the flow across the Woodsfold Fault will be low. Next, it assumes that there will be little or no vertical flow – but this assumption ignores the presence of faults cutting the Mercia Mudstones. These could be transmissive pathways, particularly when one considers the stress regime in the uppermost 300 m below ground level.

The EA cannot find a discharge for the flow, if present, but this again ignores the presence of faults. Lastly, since the Woodsfold Fault is *defined* as a no-flow boundary, the lack of westward flow in the model cannot be used as an argument to prove that there is no westward flow.

Since I published the paper in January 2016, and taken account the ensuing commentaries on it, I have done a little more research on the possible flow pattern of the groundwater under the western Fylde. I have obtained the 2D seismic data for the area shown in Figure 7, and mapped a newly-recognised fault, which I call the Wakepark Fault, running (coincidentally) from the Cuadrilla wells Preese Hall-1 to Anna's Road-1. In fact the fault has been previously recognised at depth, both independently by an oil company in 1994 and more recently by the BGS, but has not previously traced up through the Mercia Mudstones to the surface. It does not appear on the current BGS paper or digital geology maps.

Figure 9. Blackpool Wakepark recreational lake is fed by four pure freshwater springs. These could originate in the postglacial sandy deposits in the top 30 m of the subsurface (unlikely) or else could be fed by flow up the Wakepark Fault (red toothed line). Use of copyright OS digital data acknowledged. Photo credit: Ream Hills Holiday Park.

The Blackpool Wakepark Lake is an artificial lake created from boggy ground (Figure 9), and replenished by four springs. Now, it is possible that the springs supplying this lake are recharged from the unconsolidated sandy post-glacial deposits in the top 30 m of the subsurface, but the volume of flow from such a source would seem to be far too small. The more likely alternative, in my view, is that they are fed by upflow along the Wakepark Fault from the Sherwood. This newly identified discharge is the missing link in the flow cycle, originating as recharge in the Bowland Fells, that the EA failed to find.

A spokesperson at the Ream Hills Holiday Park told me that the lake water is tested annually, and is of such good quality that it could be bottled and sold as spring water. So this is not a resource that should be lightly written off, as the EA and Professor Younger conclude.

Conclusions

My concern that the EA has written off a past and future potential groundwater resource in the Fylde is justified. Before any unconventional exploitation begins it would be prudent for the EA and/or the BGS to sample the water at SSG levels.

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