Planning application no. LCC/2014/0096 by Cuadrilla Bowland Limited to drill at Preston New Road, Lancashire:

Objection on grounds of geology and hydrogeology

By

David K. Smythe

Emeritus Professor of Geophysics, University of Glasgow

La Fontenille

1, rue du Couchant

11120 Ventenac en Minervois

France

www.davidsmythe.org

September 2014

Version 1.3

NON-TECHNICAL EXECUTIVE SUMMARY

I have been asked by several local residents to write this **OBJECTION** to the development, based on geological and hydrogeological grounds.

This is the first site in the UK at which high-volume horizontal well fracking (now known as super-fracking) will be carried out. It is also novel because such a thick faulted shale layer as exists here has never been fracked before. A 3D seismic survey has been acquired across the licence area, but it seems to be somewhat inadequate for the required purpose of high-resolution imaging of layers and faults down to 1500 m depth. In addition, not enough data have been supplied for objective and independent scrutiny.

Geological faults are complex and unpredictable structures. In the absence of strong evidence to the contrary, faults at depth must be assumed to be leaky. Some of the natural oil and gas seeps at the surface of the Earth in Lancashire are directly linked to leaky faults. In the Bowland Basin it is therefore likely that some faults will leak fracking fluids and/or methane both to groundwater resources and to the biosphere. The hydrogeology of the area immediately east of the site shows that regional faults are transmissive. Gas seepages up faults and up through permeable cover rocks above a source can now even be imaged directly using modern geophysical techniques.

Cuadrilla has defined so-called 'regional' faults, which will be avoided by the fracking operations, and 'local' faults, through which drilling and fracking may take place. Its definitions are inconsistent and illogical. All faults should be avoided, whatever the scale; if this results in the Bowland Basin being unexploitable for shale gas, then so be it.

The history of relations between the Environment Agency and Cuadrilla over the Preese Hall-1 well shows that the Applicant is being evasive and non-transparent, but also that the EA is mishandling the legislation. In particular, there is a problem with the sealing and abandonment of the Preese Hall-1 well, a fact which the Applicant appears to be trying to keep secret.

The traffic light system of monitoring induced seismic tremors in real time, while it is to be welcomed, shows again that current legislation is inadequate, since there are no criteria specified for shutting down operations other than temporarily.

The cap rock above the fracking zone, the Manchester Marls, is completely inadequate to prevent possible upward migration of frack fluids and gases. The thick Sherwood Sandstone Group below the Fylde and overlying the Manchester Marls west of the Woodsfold Fault is highly saline and is not, therefore, a productive aquifer. But east of this fault, some 7 km from the proposed drillsite, the Sherwood is the main aquifer and water supply for NW England. I show, using the EA data on the recharge pattern of this aquifer, that the Woodsfold Fault is probably transmissive to fluids, and is not the barrier that the EA wrongly assumes it to be. Thus it is very possible that frack fluids and gas from the proposed site could eventually find their way into this important water resource. Such transport and resulting contamination may take years, but this is not a risk worth taking.

The crucial question of faulting was ignored by advisory committees in the UK, including the Royal Society. The reports from such committees have accepted uncritically the results of a US industry-funded study, based on confidential data, purporting to show that fracking is safe. I have shown by an extensive review of the four principal shale gas basins in the USA used by the American study that, in effect, there are no faults in these US basins that connect the fracked shale to the surface. But the density of faulting in the Weald, the Bowland Basin and the Midland Valley (Scotland) is 400 times greater, as measured by length of surface fault trace per unit area, than the average for the US shale gas and shale oil basins. No faulted basin like the Bowland has ever been fracked with horizontal shale wells; US experience does not apply to the UK. Therefore the Bowland Basin would be a guinea-pig for testing the safety or otherwise of such operations.

A large German study of the environmental risks of fracking advises that the method be banned from application in any area which is faulted. This supports my view that any application which is aimed at fracking should not be permitted in geological structures such as the Bowland Basin.

I make many recommendations for supply of further information and data by the Applicant, including new field and desk-based model studies which will cost less than the £3M p.a. that Applicant currently spends on PR. These proposals include drilling of the Woodsfold Fault to determine whether or not it is transmissive. A genuinely independent research group must be chosen to undertake this work to ensure transparency; unfortunately this safeguard eliminates many UK university groups from consideration.

TABLE OF CONTENTS

1 INTRODUCTION

1.1 Relevant personal details from my CV

I am Emeritus Professor of Geophysics in the University of Glasgow. Although I am now a French resident I remain a British citizen, and take an active interest in UK, French and foreign affairs, as well as in various facets of scientific research.

Prior to my taking up the Chair of Geophysics at the University of Glasgow in 1988 I was employed by the British Geological Survey (BGS) in Edinburgh, from 1973 to 1987. I was a research scientist, rising to the post of Principal Scientific Officer. My work in the BGS from 1973 to 1986 was funded by the UK Department of Energy as part of a Commissioned Research programme on the geology of the offshore UK region. I also gave geological advice to the Foreign & Commonwealth Office on matters pertaining to UK territorial claims offshore. This was during the exciting phase of early discoveries and development of the North Sea. I headed a team of seismic interpreters working mainly on the prospectivity of the western margins of the UK, using the industry seismic and well data supplied to the Department of Energy. As a result I became the UK's leading expert on the deep geology of the continental margin west of the British Isles. Although our interpretation groups in the BGS were never able to commission our own wildcat wells, we had many 'virtual successes', where our independent interpretations were confirmed by subsequent drilling, and where the industry operator was proved spectacularly off-course.

In the 1990s I was closely involved in the search for a UK underground nuclear waste repository. I served on the BNFL Geological Review Panel from 1990 to 1991. I served on this panel to support BNFL's case for a Sellafield site for a Potential Repository Zone (PRZ), at the time when Nirex was investigating both Dounreay and Sellafield. I resigned from the panel after the case for Sellafield had been successfully made.

I was closely involved with Nirex at this epoch, and conducted for Nirex an experimental 3D seismic reflection survey, which took place in 1994. The survey encompassed the volume of the proposed rock characterisation facility (RCF) – a deep underground laboratory planned as a precursor to actual waste disposal. This was a double world 'first' – the first ever 3D seismic survey of such a site, and the first academic group to use this method, which at the time was just emerging as an essential tool of the oil exploration industry.

Since my retirement from the university in 1998 I have carried out private research, acted as a consultant to the oil industry, and maintained an interest in the geological problems raised by nuclear waste disposal, shale gas exploration and coal-bed methane exploration. My tools for this work are up-to-date; I have my own licence for ProMAX 3D on a Linux workstation (seismic data processing), and currently hold on loan industry-owned licences for SMT Kingdom (seismic and well interpretation) and ModelVision (gravity/magnetic modelling including tensor fields).

1.2 Declaration of interest and non-liability

I have no conflicting interests to declare. This document was requested by several private individuals in Lancashire, and has been provided in exchange for a modest honorarium. I am not connected to, nor am I a member of any activist group, political party, or other organisation. I am solely responsible for its contents. It is supplied in good faith, but I can accept no liability resulting from any errors or omissions.

2 THE PROPOSED EXPLORATORY DRILLING AND FRACKING

2.1 Introduction

The application to drill at Preston New Road is the first of a series of four projects for test drilling by Cuadrilla Bowland Limited (hereinafter 'Cuadrilla' or 'the Applicant') within its EXL269 and PEDL 165 licences. It is therefore appropriate to consider the current application within this wider context.

2.2 Insufficient supporting data supplied

The current group of Bowland Basin drilling applications by Cuadrilla, of which this one is the first, comprises the first exploratory efforts in the UK in which high-volume fracking of horizontal wells (the process now re-named '*super-fracking*' by Turcotte *et al.* 2014) is to be employed. It is incumbent on the applicant to supply full justification. This has not been done.

The 3D seismic survey is a necessary and welcome background dataset to the application, as the main basis for its geological interpretation, but the information supplied in Appendix L, section L10.2.2, is inadequate. From the limited information made available, the 3D acquisition grid is based on a line geometry of 250 m square spacing, aligned to the National Grid. The receivers lie on E-W lines, and the sources on N-S lines. There are approximately 43 receiver lines and 28 source lines, this latter figure increasing progressively to about 43 in the SW corner of the survey. On Figure 37, which shows the grid at a poor resolution, the location of Preston New Road well is positioned too far to the west by 250 m.

It is impossible to comment in detail on the quality of the survey without more information. The seismic source was 91% explosive and 9% vibrator. A letter from Cuadrilla to LCC about the forthcoming 3D survey, dated 16 November 2011, states that:

> *"In areas of restricted access the energy source will be created by small explosive detonations known as 'shot firing'. It is expected that a shot pattern will comprise three individual holes drilled close together at 50m intervals, each being 10 centimetres in*

> *diameter, augered to an approximate depth no greater than 5 metres, and spaced 1- 2 metres apart."*

So the fundamental source interval of the 91% of the source points is 50 m. This is a typical interval. But it is likely that the fold of coverage, once the data has been binned into, say, 12.5 m bins, will be both low and irregular. My estimate is that at best it will be 60-fold, but this applies only over about half of the surface area due to the acquisition fringe, or apron, around the edge. The many data gaps will further reduce this figure.

There has been a trade-off in the processing (para. 381) between signal-to-noise ratio and resolution, with the former being favoured. This means that in the trade-off wider bins (lower spatial resolution), but at a higher fold (better signal-to-noise ratIo) have been chosen.

Overall, the 3D survey appears to be 'sparse' ; this is a standard term employed in 3D seismic acquisition parlance, meaning an economically-acquired survey covering the largest area possible with minimal effort, in order to achieve the desired goal. In the present case it appears to be insufficiently detailed to identify faults at a high enough resolution; therefore one of the chief goals of the survey has not been met by such an economy.

The applicant should supply for the seismic dataset and its interpretation:

1. The acquisition and the processing reports.
2. Numerous examples of seismic cross-sections through the 3D volume, in triplets comprising raw pre-stacked time, raw depth-converted and depth-converted with superimposed interpretation; around five E-W images and five N-S images should suffice, passing through existing wells.
3. These cross-sections should be accompanied by a graph above or below showing the fold (multiplicity) of coverage, as an indication of data quality.
4. Examples of well-tie to seismic *via* velocity and/or VSP logs should be shown, both for wells within the 3D area and, using 2D seismic, for other wells within the licence area.
5. The 'independent' interpretation review report carried out by Arup/DMT.

The local gaps in the survey grid are unavoidable, but in the case of the proposed drillsite they lead to a problem. There is no surface coverage SE of the proposed site, in the Little Plumpton and Westby areas. This means that imaging of the Moor Hay Fault may be inadequate.

2.3 Problems with data presented

Firstly, it should be noted that the diagrams provided are inadequate in that many of them are of too low a resolution to be studied properly, due to excessive lossy image compression. Secondly, there is a mixture of units; feet are used as the depth unit for maps, whereas cross-sections are sometimes given only in metres for the vertical scale. Thirdly, the structural maps presented are too localised around the proposed site. Fourthly, no actual data have been presented - only interpretations.

An overall structural map of the faults over the whole of the 3D area and beyond should be presented.

3 FAULTS

3.1 Summary of the general fault problem

Appendix A contains a detailed summary of current research on faults, with emphasis on their hydrogeological properties. Faults are near-planar surfaces cutting through rock layers. In Lancashire the fault plane attitudes vary from nearly vertical to dips (slopes measured down as an angle from the horizontal) of up to 45°, cutting through rock beds which usually not far from horizontal in attitude, but may locally be up to about 45°. The relevant key characteristics of faults include:

- Faults are complex and unpredictable in their hydrogeological behaviour.
- Faults have to be regarded as leaky (conduit for fluids) unless proven otherwise.
- Earthquakes occur on pre-existing faults.
- Pre-existing crustal stress and fracking-induced stress is concentrated along faults.
- Fracking activities can induce earthquakes.
- USA fracking history provides no guide for the UK geological environment.
- Leaks of released methane up faults, once started, may continue for decades.

3.2 Geophysical exploration technology

Special processing of offshore 3D seismic data can now image the migration of gas from hydrocarbon sources up fault planes or upwards through permeable overburden rocks. It is used as an exploration tool (Aminzadeh *et al*. 2013). But the quality of onshore 3D data is not yet of such a quality that the method can be applied onshore.

Microseismic monitoring is used in conjunction with fracking to control the progress of the latter. This will be used in the proposed Cuadrilla Lancashire drilling and fracking operations. But it has a major drawback, in that it cannot record the silent progress of fracking fluid up pre-existing fractures (also called 'stealth zones' - Pederson and Eaton 2013). This has been demonstrated in the USA (Pettitt *et al.* 2009, van der Baan *et al.* 2013).

3.3 Fault interpretation in the vicinity of the site

The ES section 12.6.2, pp. 345-348, summarises the geology around the site, with supporting information provided in Appendix L, section L6.3.

Cuadrilla's definition of regional fault is as follows:

> *"**Regional fault –** A regional fault is here defined as fault identified by the British Geological Survey and presented on their 1:50,000 scale mapping."* [Appendix L, p. L12]

This is unacceptable for two reasons:

1. It depends on the epoch at which the BGS mapped the terrain, and
2. It depends too much on the amount of superficial cover in any locality.

Thus in Figure 11.1 (Hydrogeology summary), as an example of the first dependency above; two parallel faults, one of which is labelled the Thistleton Fault, are shown on the published BGS solid geology maps as dying out in the centre of the picture about 2 km east of the site. But this is not because they actually die out, as Cuadrilla's own interpretation of its 3D results shows. The apparent termination of the faults at the western and southern edges of the Garstang 1:50,000 sheet 67 (published in 1990) is an inconsistency due to the fact that the three adjacent sheets were mapped at different epochs (Fig. 3.1). The intersection of the four sheets is 1.9 km ENE of the proposed drillsite. That is why the faults apparently die out to the south. In fact the newest mapping is of the Preston sheet 75 (published in 2012), which shows major faults, but these faults have not yet been added to the BGS digital database used by Cuadrilla.

The division of faults into 'regional' and 'local' by Cuadrilla is crucial, because Cuadrilla proposes drilling and fracking through so-called 'local' faults, but has decided to avoid penetrating regional faults horizontally. A more acceptable definition of a regional and local faults, for the present purpose, would be:

> **Regional**: faults which can be identified and correlated on the existing grid of 2D seismic data, and/or are mapped by the BGS. Such faults would have a vertical throw (offsetting beds on one side relative to the other) of the order of 25 m or more, or, in the case of

transcurrent faults (with no discernible vertical component of throw) recognisable in vertical seismic images by a zone of disturbance. The existing 2D data grid has a spacing of 1 to 2 km, with lines running both N-S and E-W.

Local: faults which *cannot* be mapped using the existing grid of 2D seismic data, but which can be recognised on a 3D survey. These will have thows of less than 25 m but greater than about 5 m, which is the limit of resolution of 3D data.

The definitions above are technology-based. But it should be remembered that faults occur on a continuum of all scales from micro-fractures invisible to the naked eye, up to tectonic plate boundary faults such as the San Andreas; therefore any two-fold subdivision is arbitrary.

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. This fault is discussed in more detail in section 5.6 below.

Doubts such as this about the validity of Cuadrilla's mapping, even when 3D seismic data has been used, make it crucial that examples of the 3D seismic data and its interpretation be provided for independent scrutiny.

4 REGULATORY INADEQUACIES

4.1 History of disclosure

There has been controversy about untreated naturally occurring radioactive material (NORM) from the Preese Hall-1 drilling operation being dumped in the Manchester Ship Canal. My understanding of this is as follows. After treatment at the Dayeyhulme water treatment plant, some 3850 cu. m of flowback water from the well was discharged into the canal. But it had not been treated for NORM. A further 81 cu. m remained behind in tanks at the drillsite. After about a year the EA permitted Cuadrilla to 'dispose' of this volume by sending it to test centres such as Remsol for 'testing'. It was radioactive to an average of 90 Bq/l, whereas the permitted level for disposal is 1 Bq/l. Was this ploy a means of bypassing regulations? A problem is that during the storage period the EA regulations changed.

This story illustrates that either Cuadrilla and/or the EA have acted in a non-transparent manner. It also exemplifies that UK regulations - touted as 'the best in the world' - are in a mess. A full explanation of this fiasco needs to be published.

The Preese Hall-1 well casing was deformed by the earthquake of 1 April 2011, but Cuadrilla did not inform DECC for six months. Minister of State Charles Hendry, MP, wrote to Lord Browne, Chairman of the Cuadrilla Board, on 11 May 2012, as follows:

> *"You will be aware that my Department is concerned that Cuadrilla failed to recognise the significance of the casing deformation experienced in the earth tremor triggered by tracking operations on 1 April 2011 . So much so, that the company did not report it to my officials in contemporary discussions as to the possible cause of the tremor and the possibility that it might be linked to the fracking. In the light of Cuadrilla's responses to the Department's subsequent inquiries, I have formed the view that this failure discloses weaknesses in Cuadrilla's performance as a licensee, which need to be addressed."*

DECC was rightly annoyed that the deformation of the well casing had been concealed from its officials. But Cuadrilla's response was:

> *"Cuadrilla was never required to report this issue as the casing deformation caused no actual or potential loss of well integrity and was neither a safety nor an environmental incident. No remedial action was needed to repair the well."*

Despite the alleged repair the well has since been closed down. Once again, this episode illustrates a lack of transparency and/or a failure of regulation.

Local inhabitants and well-placed experts know that there are ongoing problems at Preese Hall-1. The Cuadrilla website reports that:

> *"We have an application to extend the current planning permission to allow time to seal the well and return the site to its former condition. Any waste generated during the plugging and abandonment of the well will be managed in accordance with the requirements of the Environmental Permitting Regulations 2010 (as amended).*
> *The site will continue to be monitored for a period, and at a frequency, to be agreed with the Department for Energy and Climate Change and the other regulatory bodies. Monitoring to date confirms that there have been no leaks to the environment, nor is it believed that there is any prospect of such leaks."*

This statement appears to be at variance with the shut-down of the well that Cuadrilla had completed in 2011. It does not take three or four years to plug and abandon a well. A report for Cuadrilla by Ground Gas Solutions Limited, dated February 2014 states:

> *"No evidence of shale gas, hydraulic fracturing fluid or formation waters, originating from the Preese Hall exploration well, were detected within any of the monitoring wells during the monitoring programme.*
> *Overall, there was no evidence to suggest that Cuadrilla's activities have caused any pollution at the Preese Hall, Weeton exploration site during the monitoring period."*

The monitoring period ran continuously from 2011 to 2014. Only traces of biogenic methane were observed.

A possible solution to this apparent inconsistency is that the Cuadrilla 'Weeton' web page is simply nine months or more out of date. But that does not explain the recent activity reported at the wellhead. Once again, there seems to be an environmental problem here, which is not being treated in a transparent manner.

Comments have been made about Cuadrilla's purchase in 2010 of the Elswick gas field, producing gas from the Elswick-1 well. Such a purchase does not lie within the company's core strategy. It has been commented that the field, which is small and inoffensive to the locals, was bought so that it could be associated in a positive way with the Cuadrilla, even though the latter had no hand in its development. In other words, by including Elswick-1 in its portfolio Cuadrilla is making a cynical attempt to soften up its image as a shale-fracking company.

In conclusion, the Applicant needs to be much more open and transparent regarding disclosure of relevant information. Even though the current regulation framework is evidently inadequate and, furthermore, is apparently changing by the month, Cuadrilla should be pro-active about discussing any problems for which it is responsible. I refer specifically to the current activity at the Preese Hall-1 well.

4.2 Earthquake mitigation

The 'traffic-light' system of control on fracking progress is to be welcomed in principle, but questions remain. I have few concerns about the ground shaking caused by any tremors triggered by fracking. These will have a low upper magnitude limit which is unlikely to damage any property at the surface. I am more concerned about the risk of transmission of fluids up pre-existing faults as a results of fracking.

The reasonable assumption is initially made that all faults are critically stressed (Appendix L, para. 397). This is a worst-case assumption, and a rule-of-thumb is then devised:

> *"the approach to hydraulic fracturing would ensure that the offset distance from the location of a hydraulic fracture stage and a regional fault will be two times the anticipated fracture length"* [para. 398].

But 'fracture length' is nowhere defined. A hydraulic fracture is typically a vertically-orientated surface, which is much longer in the horizontal direction than the vertical. Perhaps it is assumed to be the distance from the perforated tubing of the frack stage and the furthest-away microseismic events which are viewed in real time. But such an operational or heuristic definition omits the fact that fracture fluid may progress along 'stealth zones', that is, silently. When this occurs it means that fluid has therefore *already* percolated into a pre-existing fault or fracture where it was not supposed to go, before such an escape can be inferred either by loss of hydraulic pressure and/or by a step-change in the location of the cloud of microseisms.

The offset distance defined above also refers to 'regional faults' which, as I have pointed out in section 3.3 above, have been defined by Cuadrilla in an inconsistent and far too lax manner. The entire procedure is designed to avoid the fact, recognised internationally, that faults and fault zones must be avoided altogether when fracking (see the Appendix for a more detailed discussion). **It is unacceptable even to contemplate drilling through faults, whatever the size.**

The ES Appendix L acknowledges that 'small scale' faults will be encountered (para. 409), but the monitoring process is designed only to try to prevent a possible tremor. It says nothing about fluid transmission *per se*. Under the traffic light system, if a red range level of tremor (magnitude $M_L > 0.5$) occurs then hydraulic injection is stopped. After assessment of the events:

> *"Cuadrilla will commence discussions with DECC regarding methodology for continuation or termination of hydraulic fracturing operations."* [para. 433].

What this is saying is that *<u>there is no substantive mechanism already in place</u>* for abandonment or resumption of fracking; this is yet another gap in legislation. What should be in place are clear quantitative criteria, defined beforehand, for the compulsory abandonment of fracking. For example, the distance within which any new fracking stages would be banned could be based on a relationship to the location and magnitude of the largest earthquake triggered. This would be simple and transparent; in contrast, the concept of '*discussions with DECC*' is not what I would call transparency.

5 IMPLICATIONS FOR ENVIRONMENTAL CONTAMINATION

5.1 Migration up faults and natural fractures

The US fracking experience tells us that faults at the fracking level are to be avoided if possible, because they reduce the effectiveness of the fracking treatment and can divert stresses away from desired trends. According to Baker Hughes (2013, a major oil service company like Halliburton), **re-activated faults are usually conduits to fluid flow**. The problem of environmental contamination by fugitive methane and/or fracking fluids reaching the surface never arises in the USA because there are practically no faults in the shale basins studied which extend from the fracking level up to the surface.

Controversy over contamination in the USA due to fracking operations has therefore concentrated on the problem of faulty well casings, leading to fugitive methane emissions. There is no question that in some localities, for example at Dimock (PA), there have been severe problems. In the scientific literature there are well-funded (industry-sponsored) papers purporting to show that methane emissions are natural (i.e. pre-dating the advent of drilling and/or negligible). One example of this is a paper purporting to prove low methane emissions – but the test sites, which remain confidential, were pre-selected by the industry. The most telling paper to date is by Jackson *et al*. (2013), who analysed 141 drinking water wells in Pennsylvania. Their study shows that elevated and often dangerous methane levels correlate with nearness to well sites, at a probability level of well under 1% (i.e. the chances of this correlation being by random chance) *and* they prove by its characteristic signature that the methane comes from the Marcellus Shale, and is not a shallow biogenic product.

In the area studied by Jackson *et al*. there are no faults. Even if the source of the methane leak is due to faulty drilling completion, the interesting fact remains that the fugitive methane is not found just at the wellbore, but up to several kilometres away. This suggests that the cover rocks above the fracked Marcellus Shale, which here is at depths of 1500 to 2100 m, do not make a perfect seal. The Department of Environmental Protection of the State of Pennsylvania, which is where the Marcellus Shale is mainly being exploited, has recently released data showing that fracking has polluted shallow groundwater resources and wells in around 250 cases.

Modern imaging techniques applied to 3D seismic datasets are now even capable of imaging gas seepages up faults and through permeable overburden (cover rock) above a hydrocarbon source (Aminzadeh *et al.* 2013). In fact this visual evidence of seepage and upward escape is being used by the oil exploration industry as a new exploration tool.

5.2 Are the rock layers above the fracking levels in Lancashire an adequate seal?

The geology of the area in question has all three ingredients for a successful conventional hydrocarbon play:

- Source - Bowland Shales
- Reservoir - Sherwood Sandstone Group
- Seal - Mercia Mudstone Group.

The Fylde lies within the East Irish Sea Basin, where oil exploration has been more successful than in the Central Irish Sea basin further south. This is attributed by Duncan *et al.* (1998) to the presence of ductile impermeable halites within the Mercia Mudstone Group (MMG) re-establishing seal integrity after inversion uplift, during which these shales were taken into the brittle tensional strength field.

How much rock is required above a fracked zone to seal it? In the Central Irish Sea Basin it is reported that at least 600 m of MMG is required for it to be an effective hydrocarbon seal there, due to the inversion uplift (Duncan *et al.* 1998), and in the absence of the ductile and sealing halites that are present in the East Irish Sea basin.

In the Fylde there are only 200 to 300 m of MMG, and halites are absent in the target area, although they were once present, as proven by collapse breccias and pseudomorphs after halites. Halites are, of course, present further west near Blackpool, where there is the Preesall Salt Field (Aitkenhead *et al.* 1992). Therefore the MMG, if depleted of its original halite layers, is proven by the Central Irish Sea exploration history to be completely inadequate as a seal to prevent upward migration of liquids and gas.

Cuadrilla claims, on the other hand, that the Permian Manchester Marls underlying the Sherwood Sandstone Group will provide the required seal. But this layer is only 160 m thick in the area of the well (ES vol. 1, table 3.1). Cuadrilla states:

> *"The Manchester Marl locally forms a seal to underlying hydrocarbon bearing geological units. The Collyhurst Sandstone is the gas reservoir at Elswick gas field in central Fylde, where it immediately underlies the Manchester Marl."* [ES section 3.3.1]

This statement is misleading because it implies that the sandstone is a conventional gas reservoir requiring a top-seal. The Collyhurst Sandstone is a low permeability, low porosity sandstone. It was described by the developer which took it over from the BGC-BP consortium, Eukan Energy Limited (1994), as "*a low grade reservoir rock. the porosity and permeability readings being very low.*" The Sherritt relinquishment report of 2009 shows a photo of Collyhurst Sandstone core from the Elswick-1 borehole, where it is described as:

> *"Very-fine-grained well-rounded quartz arenite with quartz and calcite cement. Porosity = 2 – 12 %, Permiability* [sic] *= 0.01 – 8 mD (DTI well file)."*

The sandstone required fracking to produce the gas (although it should be noted that conventional fracking of this vertical conventional well has little in common with high-volume horizontal fracking of shale). Therefore its modest success as a gas producer owes little or nothing to the overlying Manchester Marls being a seal.

The Collyhurst Sandstone varies considerably in thickness, from over 500 m in the Elswick-1 well to zero in the Thistleton-1 borehole. At the application site it is 160 m thick.

Cuadrilla uses the BGS lexicon (British Geological Survey 2014) to describe the Manchester Marls, as:

> *"a red marl (calcareous mudstone and siltstone) with thin beds of fossiliferous marine limestone and dolomite; locally green; sandy in places especially in top part; local breccias and pebbly beds".*

The thickening of the Manchester Marls in the Garstang sheet 67 area across faults is attributed to syndepositional movement on the faults (Aitkenhead *et al.* 1992). Such thickness changes are not seen in the documents produced by Cuadrilla for the present application, but are clear further east, in the neighbourhood of the proposed Roseacre Wood well.

The Manchester Marls have a similar lithology (and a similar desert salt-flats or sabkha origin) to the Mercia Mudstone Group. Therefore their mechanical and hydrogeological characteristics will also be similar, and it is unlikely that they will provide an adequate seal to prevent upward fluid migration. In addition, they layer is cut by numerous faults, many presumed to be syndepositional in nature. Such faults zones will comprise breccias and crush rock, and so are unlikely to be good fluid seals; on the contrary, they will be transmissive.

The Health and Safety Executive report (Watson *et al.* 2008) investigating releases from potential UK underground gas storage facilities stated, regarding the Elswick gas field:

> *"The Collyhurst Sandstone forms the reservoir formation for the currently operating Elswick gas field. Porosity averages 5.6% and the permeability of the formation is <1mD. Evans (2007) does not give the initial pressure in the gas reservoir. The hydrocarbon trap appears to be a graben. Some of the faults that cut the crest of the graben extend to the surface but are expected to be sealing over at least part of their length."*

Here we have further confirmation of the hydrogeological properties of the Collyhurst Sandstone (incidentally, the authors have confused *horst* with *graben*). But note that the faults are expected to be sealing only "*over at least part of their length*".

In conclusion, the Collyhurst Sandstone and overlying Manchester Marls are not a reliable seal for upwardly escaping fluids.

5.3 Evidence of seeps

Selley (1992) has described and tabulated 173 occurrences of surface petroleum seepages and impregnations in the UK. One of the best known localities is at Formby, some 25 km south of the current application site. Surface oil seeps led to the development of the now-abandoned

Formby oil field in 1939. It lies within PEDL164, operated by Aurora Exploration Limited. Aurora (2011) states, regarding the numerous surface seeps:

> *"The oil is sourced from deeply buried Carboniferous-age, organic-rich shales and migrates to the surface through the largely sand-prone overburden and via numerous faults."* [my underlining].

This is evidence that the faults in the Formby area are leaky.

Selley (2012) discusses in more detail the migration of gas up pre-existing faults elsewhere in the UK, in relation to shale gas basins:

> *"In Upper Palaeozoic rocks gas seeps in Carboniferous coal mines are too numerous and commonplace to mention. There are though two noteworthy surface gas seeps. One, near Wigan in Lancashire, is colloquially referred to as 'Camden's cooker' ... In view of the immediate subsurface geology it is unclear whether that Camden's cooker results from gas seeping from underlying beds of Carboniferous coal and/or shale. The proximity of this seep to Cuadrilla's shale gas well is noteworthy.*
>
> *A second seep has been reported not far away at Storeton on the Wirral peninsula. ... In the 1920s quarrying in Triassic sandstone liberated quantities of gas. In view of the date and occurrence it is not feasible that this was 'garbage gas' from a landfill. It is more probable that it was derived from Carboniferous Coal Measures or deeper Lower Carboniferous shales."*

At the international level, hydrocarbon seepage is now proven as an exploration tool, and the upward migration of gas can even be directly imaged using high-quality (usually 3D) seismic reflection data combined with clever computer visualisation methods. Aminzadeh *et al.* (2013) provide an up-to-date review of developments. The most important lesson to be learned from their wide-ranging review is that faults are crucially important in providing migration pathways. The next most important lesson is that cap rocks are rarely 100% effective. Petroleum systems with continuous leakage upwards, balanced by continuous replenishment from a source below, are commonplace. The new imaging methods show that gas migration can be diffuse, and is not necessarily confined just to identified faults. The Earth is far from perfect at keeping hydrocarbons trapped underground.

5.4 Groundwater data

The Environmental Statement (ES), Chapter 11, Appendix K, discusses the aquifers. At outcrop below the site area there is the Mercia Mudstone Group (MMG), which is classed as a Secondary B aquifer. Below the MMG lies the Sherwood Sandstone Group (SSG), which is a Principal Aquifer. The SSG is one of England's main sources of drinking water, after the Chalk.

In the study region the SSG is considered to have different hydrochemical properties east and west of the Woodsfold Fault. East of the fault it is a Principal Aquifer. There is one sample, taken from the EA observation borehole at Kirkham, which shows that the Sherwood Sandstone Group is highly saline at that location. The two samples taken had 63 and 91 mg/l of chloride, which is 2-3 times that of seawater (35 mg/l).

Sage and Lloyd (1978) stated, regarding the SSG aquifer:

> *"... a groundwater gradient of 1:3000 is indicated across the coastal area. This apparent head drop, however, does not take into account the density effects of saline waters which are found locally at depth in the aquifer and may have a fairly extensive distribution in this area. The composition of the saline waters where sampled is of interest in that iodide levels of up to 400 µg/l occur, suggesting a long residence time in the aquifer and not modern seawater contamination. In the northern part of the area, therefore, the chemistry infers that the thick drift deposits form a reasonably effective confining layer and the suggestion is that little groundwater flow, if any, occurs across coastal areas."*

The Garstang sheet 67 Memoir (Aitkenhead *et al.* 1992) notes that recharge of the freshwater content of the SSG east of the Woodsfold Fault occurs by groundwater held in Millstone Grit (Namurian) sandstones brought into direct contact with the SSG along the Bilsbarrow Fault. Thus this fault is regarded as transmissive. The Memoir also states, quoting Sage and Lloyd (1978) that:

> *"bodies of sand or sand and gravel, although irregular in shape and laterally impersistent, probably do provide an important route for surface wate to pass through the drift to recharge the aquifer".*

The piezometric gradient is gently down to the west from the Bowland Fells, but because the SSG west of the Woodsfold Fault is deeply buried, the groundwater in it is not being recharged. It may be of ancient origin. There is controversy about whether its salinity is from marine incursion or from solution from rock due to its long residence time. These issues are not, however, germane to the present problem of fluid flow resulting from fracking.

The BGS Memoir states that overpumping of the abstraction boreholes (east of the Woodsfold Fault and/or north of the MMG outcrop) has to be carefully monitored, because over-abstraction could reverse the prevailing westward flow and cause saline water to contaminate the boreholes. This is an illustration of the delicacy required in managing water reources.

Most of these facts are depicted in a schematic geological cross-section prepared by the Environment Agency (2006), to which I have added red arrows and labels (Fig. 5.1) and will discuss below.

5.5 The current EA view

The most succinct summary of what I presume to be the current EA view is contained in a response dated 27 February 2014 by the Rt. Hon. Michael Fallon, MP, former DECC Minister of State, to a question put by the local MP, Mark Menzies, on behalf of a Fylde constituent, Mr Gary Liggett. Below I reproduce an extract of part of the response (italics), with my own comments interposed in upright font within square brackets:

> *"The sandstone to the west of the Woodsfold Fault is buried under approximately 200m of Mercia Mudstone."* [correct] *"The Mercia Mudstone is impermeable, so no water moves downward through the formation or upwards from the sandstone beneath."* [oversimplified - the MMG is poorly permeable, and is a Secondary B aquifer; therefore it cannot be impermeable] "*The Woodsfold fault prevents water movement into or out of the sandstone along the eastern boundary."* [there is no justification for this; the faults further

> east are transmissive, so why would this fault be different?] *"This sandstone west of the Woodsfold fault has no outcrop at the surface, rainwater cannot enter the rocks, water cannot discharge from them, and this means that the water in these rocks has no flow."* [correct] "*Due to the depth of burial and the lack of flow, the water already held in the rock has had a long time to dissolve minerals from the sandstone and become highly saline. This is an expected and common feature of deep buried water bearing rocks around the country."* [correct but incomplete, it omits the chloride source from the halites in the overlying MMG].
>
> *"By contrast the sandstone to the east of the Woodsfold Fault outcrops at the surface, so rainwater can enter the rocks and groundwater is discharged via rivers and abstraction points. This throughflow means that the residence time of the water in the rock is short and the salinity/mineral content of the water well within the recommended concentrations for raw drinking water supplies."* [correct].

The main flaw in the EA picture summarised above, although it is, by and large, reasonable, lies in:

- The assumption that the Woodsfold Fault is non-transmissive, even when SSG is juxtaposed on either side, and
- That this non-transmissivity accounts for the saline water within the SSG to the west.

In fact the deep burial of the SSG by downthrow on the Woodsfold Fault is sufficient of its own accord to render the groundwater saline over a long period, because of lack of recharge other than a very slow influx of highly saline water moving down and dissolving out the halite beds from the MMG above. The MMG, although poorly permeable, is not 100% impermeable.

5.6 Discussion of potential groundwater contamination paths

We can now synthesize the information of the two preceding sections. Figure 5.1 is a schematic cross-section (Environment Agency 2006) of the area east of the current application site. I have added labels, and arrows to indicate water flow. Recharge of the important SSG aquifer (orange in the centre of the cross-section) occurs both by downward filtration through the Quaternary sand and gravel, and also through the Millstone Grit Series of the Bowland Fells across the Bilsborrow Fault. The red arrows show fresh water transport directions.

To the west of the Woodsfold Fault the SSG is overlain by the Mercia Mudstone Group (MMG). Dissolution of halites from the MMG has rendered the underlying SSG highly saline. There are no nearby surface recharge points by which fresh water could be introduced to this body of rock.

The Woodsfold Fault is very likely to be transmissive, just as the EA (2006) states is the case for the Bilsborrow Fault. But the two bodies of water (fresh and potable to the east, and briny to the west) are kept largely separate, because the latter body is both more deeply buried, and the brine is denser than fresh water.

We now turn to the E-W geological cross-section presented by Cuadrilla, passing through the proposed drillsite. It is reproduced in the left-hand side of Figure 5.2. The right-hand side of the figure shows an outline of the geological structure within the blue rectangle on the left. I have altered the geometry of the so-called 'local' Fault-1 by extending it upwards with a similar magnitude of throw (displacement) of around 100 m as Cuadrilla has interpreted it at the base of the Upper Bowland Shale, based on my discussion in section 3.3. above. This alteration is at point A in the diagram. I also extend it up to the unconformity (point B) at the base of the Permian Collyhurst Sandstone (the thin yellow layer in Fig. 5.2). This is justifiable because the fault can then be presumed to be Hercynian in age (post-Carboniferous, pre-Permian) just like the Moor Hay Fault, shown on the right of the Cuadrilla diagram.

The right-hand side of Figure 5.2 shows the possible flow paths from the Upper Bowland fracked shale, labelled as follows (numbers within red rectangles):

1. Directly upwards from the Upper Bowland Shale into the permeable Millstone Grit Group.
2. Up the transmissive fracture zone of Fault-1.
3. Along the highly permeable Collyhurst Sandstone, generally up-dip to the east, and only partially confined by the Manchester Marls.

4. Directly upwards from all the preceding sources through the Permian and superficial deposits to the surface.

None of these plausible, and even probable, migration pathways are shown in the Cuadrilla scenario (ES Chapter 11 fig. 11.5). I do not discuss here the other, man-made, migration pathways induced by drilling.

The cap-rock, or sealing overburden, above the shales to be fracked is simply inadequate, as discussed in section 5.2 above. The gross thickness of the capping mudrocks (Manchester Marls and MMG) is around 500 m, which is insufficient, given the experience of the MMG (without halites) as a cap-rock in the East Irish Sea Basin - of which the Fylde, geologically, is a part. The direct paths 1 and 4 to the surface in the vicinity of the drillsite (say within 5 km horizontally of the fracked zone below) will lead to potential contamination of the minor groundwater sources within the Quaternary, as well as of rivers and streams.

More crucially, the Manchester Marls, at only 160 m thick, will not provide a viable cap-rock. In any case, flow paths 1 and 2 (Fig. 5.2) permit rapid migration along the highly permeable Collyhurst Sandstone below. The drillsite is 7 km from the Woodsfold Fault, which, I have argued, will be transmissive. It is therefore feasible that flowback and/or produced water and gas from the fracking of the Upper Bowland Shale at Preston New Road will pass into the SSG, the important Principal Aquifer, lying to the east side of this major fault.

The potential contamination process along the pathways discussed above will be aided by the fact that the contaminated water, whether or not it holds methane in solution, is less dense than the brine in the SSG west of the fault. Being more buoyant, it will therefore have a propensity to flow upwards and displace the brine downwards.

Given the crucial importance of the Woodsfold Fault as either a boundary or else as a transmissive zone between the saline SSG to the west and a vitally important Principal Aquifer to the east, Cuadrilla should be required to undertake an exploratory borehole through the Fault. In addition, two other boreholes should be drilled at a short distance on each side. All three boreholes should be drilled to a depth of 1 km or so. The central borehole must be cored so that the properties of the fault zone may be studied; the two ancillary boreholes will enable sampling of the groundwater and permit cross-flow tests to be run. This research programme will take around a year and will cost less than the £3M p.a. that Cuadrilla is reportedly spending on its PR contract with Bell Pottinger.

Free gas such as methane will, of course, migrate very rapidly. The effects of liquid contaminated groundwater migration may take months, possibly may years, to make themselves felt.

In view of the complexity and number of potential migration pathways it is essential that a full 3D hydrogeological model of this part of the Bowland Basin be constructed by an independent research organisation, but funded by Cuadrilla. The choice of research group should be made by the County Council in consultation with independent experts such as myself. It would be unacceptable for any UK university research group that has existing industrial links to undertake this work, since it is crucial that it is seen to be independent. For example, the universities of Edinburgh (Scotland) or Duke (North Carolina) have the requisite international expertise and high standing, and are clear of suspicion of any industrial links which might be presumed to call into question their independence. In contrast, UK university earth science research groups such as those at Leeds, Manchester, Durham, Newcastle, Strathclyde, Glasgow, Heriot-Watt, Oxford, Keele and Bristol, to name a few, are not. Cambridge is 'clean', but may not have the expertise (or the desire) to undertake this kind of industrial applied research.

Such a desk study can be started in parallel with the recommended drilling of the Woodsfold Fault, and the results from the latter project can be fed into the 3D hydrogeological model. Such a study will take around a year and cost of the order of one year's Cuadrilla PR fees; there is, therefore, no reason why both these studies should not be completed before any more drilling is contemplated.

6 DISCUSSION AND CONCLUSIONS

6.1 Implications of the faulted geology for environmental contamination

Fracking technology is not only 'unconventional'; it has never been tested to any degree in a highly faulted shale basin such as the Bowland Basin. Faults are complex features, and difficult to understand. In the USA faults at the frack level, if any, are avoided because they reduce the efficiency of the fracking process. In addition, no faults within any fracking province of the USA extend all the way to the surface, so the problem that the UK has simply does not arise there.

In NW Germany, a thorough study of fracking risks has been carried out by neutral academic experts (although, it must be noted, funded by ExxonMobil), which includes the question of fracking through faulted zones (Borchardt *et al*. 2012). I have not completed translating this report, which is in German and runs to some 140 pages; however, there is an English-language summary (Ewen *et al*. 2012), one of the main conclusions of which is that fracking in fault zones should be banned. It states:

> *"The following hydrofracking fluid transport barriers are crucial:*
>
> - *The presence of massive sealing clay strata and other strata.*
> - *The barriers resulting from the fact that salt fractures close up naturally.*
> - *The absence of faults or fault zones, i.e. underground areas that are more porous owing to fractures in geological materials."*

The Bowland Basin has none of these crucial barriers. The presence of oil and gas seepages in the Formby area, 25 km south of the proposed site, is more evidence that faults in the Bowland Basin cannot be assumed to be barriers to migration.

6.2 Baseline surveys

The Royal Society and others have called for baseline surveys to be conducted before any fracking operation. This means establishing what the environmental state is before any work is undertaken that might alter this state. The surveys that it would be appropriate for Cuadrilla to undertake before the drilling envisaged in the present application include monitoring of groundwater and possible natural leakages of methane.

6.3 Conclusions

Lancashire's geology is intrinsically unsuitable for fracking. No similar geology been fracked before. The USA experience is completely irrelevant. Fracking poses a direct threat to groundwater resources, and there is the possibility that fugitive methane may even reach the surface.

The Council should consider the following questions when determing this application:

- What benefits to the community arise (if any) from the present application?
- Will any of these benefits (if they exist) outweigh the clear inconvenience to the community?
- Why should parts of Lancashire be put at potentially grave environmental risk, when the main beneficiaries will be the Applicant and the Exchequer?
- Would the financial benefits of any putative Community Benefit Scheme based on a share of royalties outweigh the costs of possible accidents, leakage and other deleterious effects on the environment?
- What do the constituents wish?
- Why have countries such as France and Bulgaria banned fracking outright, while Germany and several US states have moratoria until the environmental and health impacts have been assessed?

If the Council is minded not to refuse the application outright, the Council should request further information from the Applicant. I have listed what, in my opinion, is required, in, respectively, sections 2.2 (geophysical and geological data), 2.3 (improved quality of diagrams and maps), 4.1 (disclosure of current Preese Hall-1 problems), 5.6 (boreholes to investigate the Woodsfold Fault; 3D hydrogeological model), and 6.2 (baseline surveys).

Notwithstanding my recommendations for further work to de done and information to be supplied, I conclude that on the technical and environmental safety grounds discussed above, **the application should be refused.**

REFERENCES

Aitkenhead, N. *et al.* 1992. Geology of the country around Garstang. Memoir for 1:50 000 geological sheet 67. HMSO.

Aminzadeh, F. *et al.* 2013. *Hydrocarbon seepage: from source to surface.* Geophysical Developments Series no. 16, Society of Exploration Geophysicists and American Association of Petroleum Geologists, Tulsa, OK, 244 pp.

Aurora Exploration (UK) Limited 2011. *Application to drill boreholes to evaluate the redevelopment potential of the abandoned Formby oilfield.* Lancashire County Council Planning Application no. 08/11/0210.

Baker Hughes 2013. Fault Seal Analysis: Improve reservoir understanding with fault seal analysis. Web page available at: http://www.bakerhughes.com/products-and-services/reservoir-development-services/consulting-services/geomechanics/fault-seal-analysis

British Geological Survey (BGS), 2014. Lexicon of named rock units [Online]. Available from: http://www.bgs.ac.uk/Lexicon//

Davies, R.J. *et al*. 2012. Hydraulic fractures: how far can they go? *Mar. Petrol. Geol.* **37**, 1-6.

Duncan, W.I., Green, P.F and Duddy, I.R. 1998. Source rock burial history and seal effectiveness: key facets to understanding hydrocarbon exploration potential in the East and Central Irish Sea Basins. *Am. Ass. Petrol. Geologists Bull*. **82**, 1401-1415.

Borchardt, D. *et al*. 2012. *Abschätzung der Auswirkungen von Fracking-Maßnahmen auf das oberflächennahe Grundwasser- Generische Charakterisierung und Modellierung* (Assessment of the impact of fracking operations on the near-surface groundwater - Generic characterisation and modelling).[full report, in German, available at www.dialog-erdgasundfrac.de].

Environment Agency 2006. *The Wyre catchment abstraction management strategy.*

Eukan Energy Limited 1994. *Proposed Gas Production / ElectricaJ Power Generation Site near Elswick, The Fylde, Lancashire, Planning Application Supporting Statement.*

Ewen, C. *et al*. 2012. *Hydrofracking Risk Assessment Executive Summary* [English summary version of Borchardt *et al*. 2012, available at www.dialog-erdgasundfrac.de].

Fisher, K. and Warpinski, N. 2012. Hydraulic-fracture-height growth: real data. Society of Petroleum Engineers Annual Conference Paper SPE 145949, Denver 2011. *SPE Production & Operations*, February 2012, pp 8-19.

Green, C.A. *et al*. 2012. *Preese hall shale gas fracturing review & recommendations for induced seismic mitigation*. Report to DECC.

Jackson, R.B. *et al.* 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. Proc. Nat. Acad. Sci. *PNAS Early Edition*, available at: www.pnas.org/cgi/doi/10.1073/pnas.1221635110.

Lunn, R.J., Shipton, Z. K. and Bright A. M. 2008. How can we improve estimates of bulk fault zone hydraulic properties? *Geol. Soc. London, Spec. Publ.* **299**; 231-237.

Pederson, P. K. and Eaton, D. W. 2013. Reservoir heterogeneity and 'stealth' zones in microseismic: role of rock fabric. CSEG Recorder, **38** no. 3.

Pettit, W. *et al*. 2009. Using continuous microseismic records for hydrofracture diagnostics and mechanics. *Soc. Explor. Geophys. Ann. Meeting Expanded Abstracts.*

Royal Society and Royal Academy of Engineering 2012. *Shale gas extraction in the UK: a review of hydraulic fracturing.* DES2597. Available online: www.royalsociety.org/policy/projects/shale-gas-extraction

Sage, R. C. and Lloyd, J. W. 1978. Drift deposit influences on the Triassic Sandstone aquifer of NW Lancashire as inferred by hydrochemistry. *Quart. J. Eng. Geol. Hydrogeol.* **11**, 209-218.

Selley, R.C. 1992. Petroleum seepages and impregnations in Great Britain. *Mar. Petrol. Geol.* **9**, 226-244.

Selley, R.C. 2012. UK shale gas: the story so far. *Mar. Petrol. Geol.* **31**, 100-109.

Sen, M.A. and Abbott, M.A.W. 1991. Hydrogeological investigation of a fault in clay. *Quart. J. Eng. Geol. Hydrogeol.* **24**, 413-425.

Sherritt International Oil and Gas Limited 2009. *Relinquishment report License P1549 Block 110-05.* DECC.

Tellam, J.H. and Lloyd, J.W. 1981. A review of the hydrogeology of British onshore non-carbonate mudrocks. *Quarterly Journal of Engineering Geology and Hydrogeology*, **14**, 347-355.

Turcotte, D.L., *et al.* 2014. Super fracking. *Phys. Today*, August 2014.

van der Baan, M. et al. 2013. *Microseismic monitoring developments in hydraulic fracture stimulation.* Intech open-file e-book Effective and sustainable hydraulic fracturing, chapter 21.

Watson, S. *et al.* 2008. *Scoping calculations for releases from potential UK underground gas storage facilities*. Health and Safety Executive RR606.

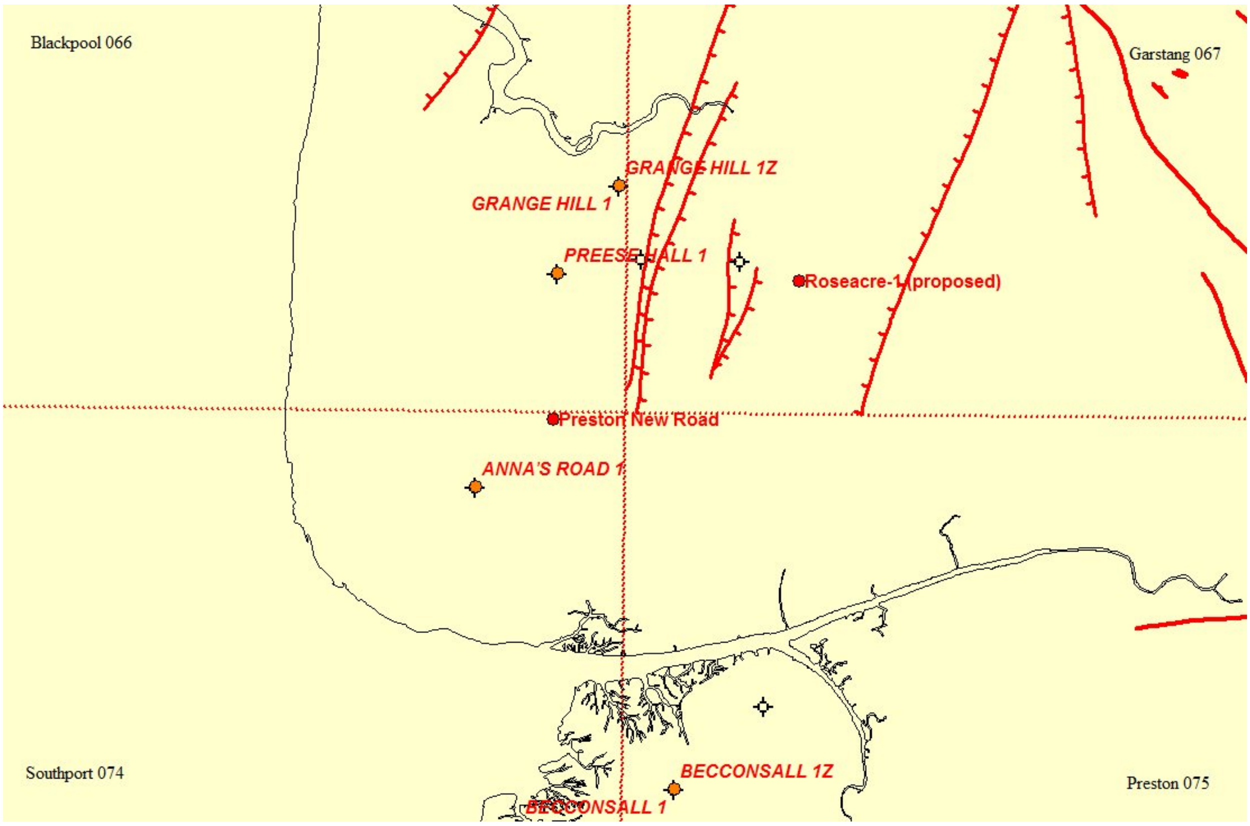

Fig. 3.1. Intersection of four BGS solid geology sheets (red dotted cross) showing that the apparent dying-out of faults (red tooth-marked lines) is an artefact of the geological surveys having being done at different epochs. Cuadrilla drilled wells are shown by an orange disc, Cuadrilla proposed wells by a red disc.

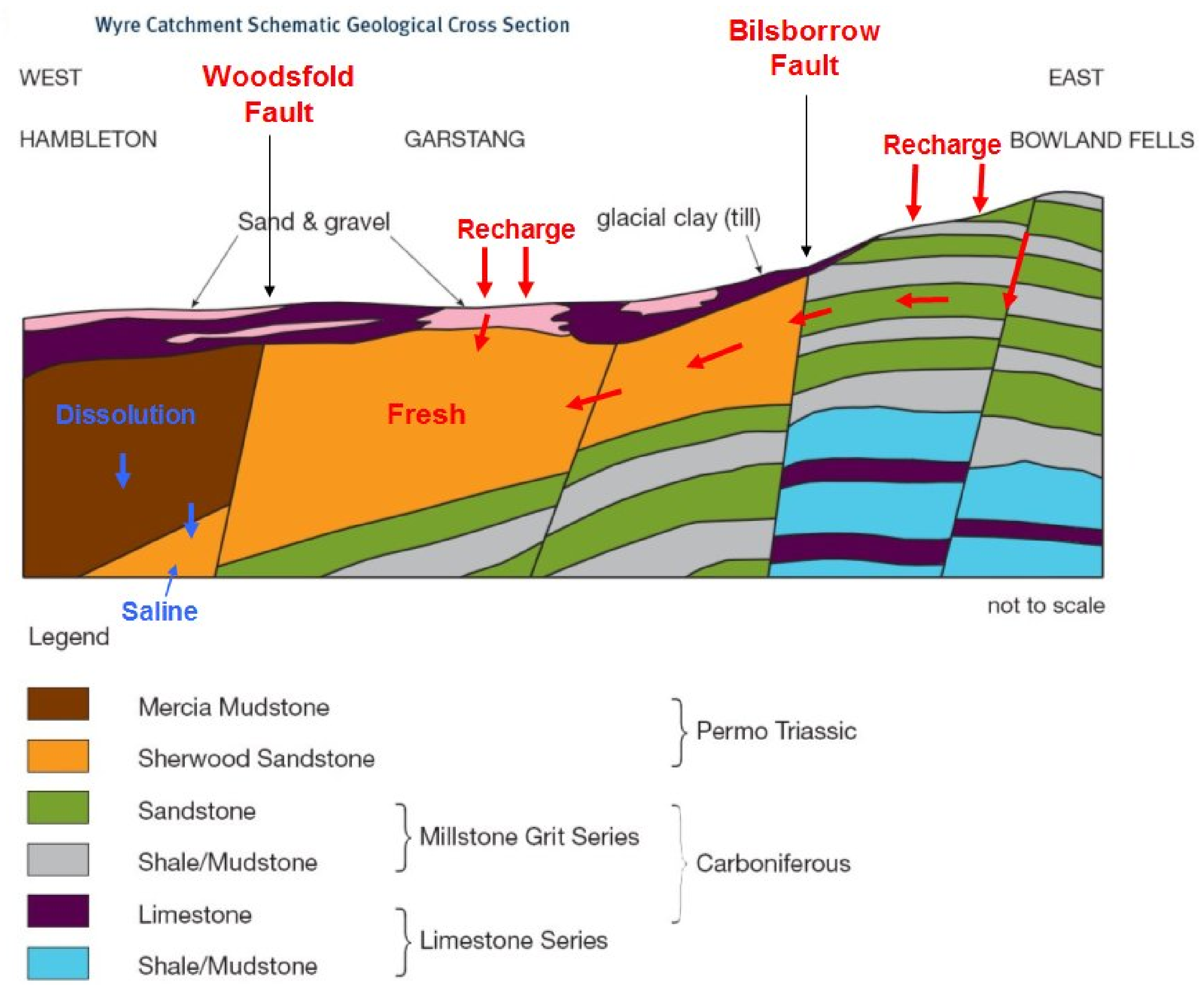

Fig. 5.1. Schematic geological cross-section (Environment Agency 2006), to which labels and arrows in red and blue have been added, showing hydrogeological characteristics across the Woodsfold Fault. Red indicates fresh water, blue saline.

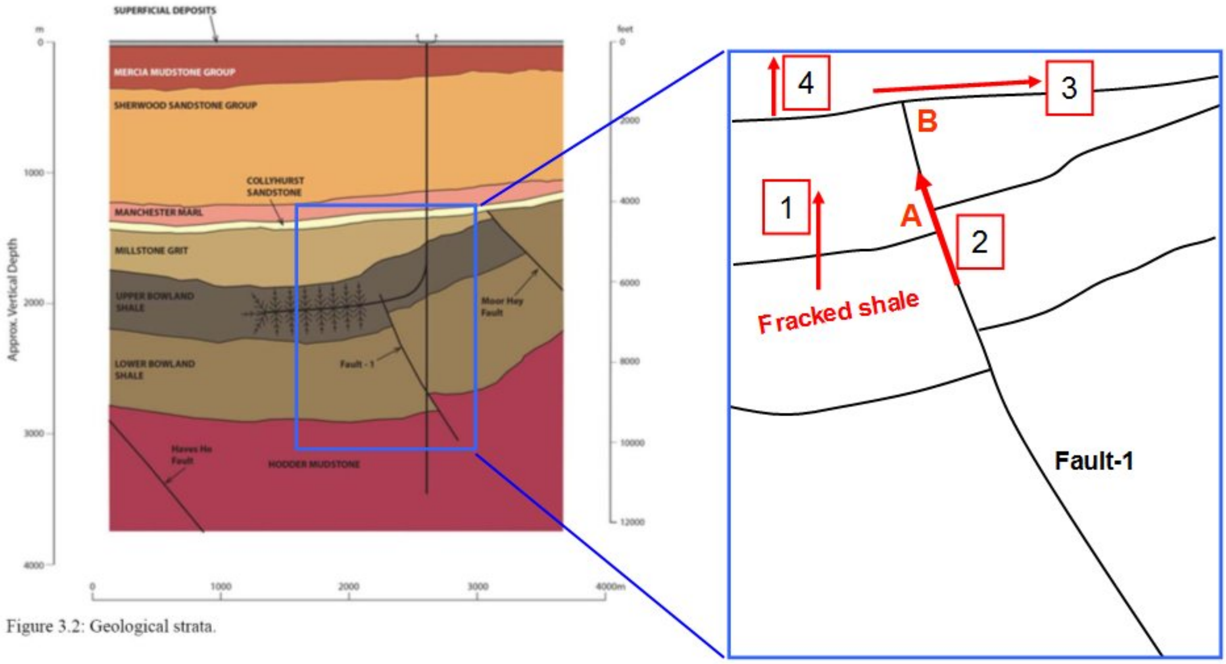

Fig. 5.2. Cuadrilla geological cross-section through the proposed well (left) with extract of the blue rectangle (right). Cuadrilla's interpretation of Fault-1 is geologically improbable; therefore it is re-interpreted on the right at point A (monoclinal flexure made into a fault) and B (continuation of the fault up to the sub-Permian unconformity. Numbers in red rectangles beside each arrow refer to likely fluid flow paths:

1. Directly upwards from the Upper Bowland Shale into the permeable Millstone Grit Group.
2. Up the transmissive fracture zone of Fault-1.
3. Along the highly permeable Collyhurst Sandstone, generally up-dip to the east, and only partially confined by the Manchester Marls.
4. Directly upwards from all the preceding sources through the Permian and superficial deposits to the surface.

APPENDIX A

FAULTS

A.1 Introduction

The Royal Society and the Royal Academy of Engineering issued a combined report into the risks of fracking in the UK (Royal Society and Royal Academy of Engineering 2012). Much of the report concentrated on the risk of induced seismicity. The problem of pre-existing faults was barely discussed at all, even though it was introduced as a subject for concern by a submission to the expert committee by the Geological Society of London.

Instead, the Royal Society report accepted uncritically the Halliburton study (Fisher and Warpinski 2012) discussed above, as did Green *et al*. (2012) in their report commissioned by the Department of Energy and Climate Change (DECC).

This uncritical attitude towards an industry publication is surprising and somewhat naïve, given that:

- Halliburton has not published its database, which remains confidential.
- Wells are only located to county level.
- Individual wells cannot be identified on the four main graphs presented.
- We do not know whether inconvenient results have been omitted.
- We do not know how complete is the database.
- There are essentially no wells in areas of complex geology (faults or tight folds) extending to the surface.

There are some surprising facets to the database; for example Cleveland County (OK) has just one fracked well, but is listed in the graph for the Woodford Shale, whereas several other counties in the Anadarko/Arkoma basin of Oklahoma, with dozens of wells apiece, have been omitted. The answer may simply be that Halliburton did not have contracts for the operators in these counties, but the problem remains that we simply cannot know.

Even if we accept Halliburton's main thesis at face value – that creation of new fractures by fracking has a natural upward limit above the horizontal wellbore of around 500 m, perhaps 1000 m at the most – the account is erroneous at several places:

1. Plotting fractures by microseismic monitoring is incomplete. Pettitt *et al*. (2009) show that a sequence of microseismic events can jump 'silently' up a fault plane to another level, in their example about 100 m higher. Therefore **microseismic activity does not record the passage of fracking fluid up a fault.**
2. Such **leakage up faults could be a slow process**, not necessarily occurring at the time of fracking.
3. The authors argue that, in effect, **if faults were conduits they would have leaked all the gas away by now. This is clearly false**; the whole point of fracking is to release gas which is trapped and therefore unable to migrate.

In conclusion the Halliburton study is severely flawed, even when considered on its own terrain of US geology. It is certainly inapplicable to the UK.

In the UK some publicity was given to the paper by Davies *et al*. (2012) of Durham University, in which natural hydraulic fracture pipes were studied and shown to have a limiting upward extent of about 1100 m. The paper appears to give support to the idea that fracking is safe. But the study is a side issue, because the principal concern regarding fracking safety, not addressed hitherto, is the effects of natural faults, not natural pipes. The latter are a freak phenomenon, geologically speaking, and of no real importance.

A.2 Identification of faults

Faults are mapped at outcrop by field geologists. Identification at depth requires geophysical methods, of which imaging by the seismic reflection method is by far the best. Two-dimensional seismic profiles can image faults having a vertical displacement of one side relative to the other (if the fault cuts near horizontal layers) of 30 m or greater. So the 'resolution'- the finest detail that can be seen - is at least 30 m in length. Strictly speaking, it is this offset of layers one side with respect to the other across a fault which is usually seen, and not the fault itself. With the 3D seismic technique the resolution is brought down to the order of 4-5 m (i.e. improved).

Faults are often missed even when a vertical well is drilled. This is because the drilling process grinds up the rock, which is identified only by the cuttings coming back up with the returning drilling fluid. So it is not surprising that a fault, which is characterised in detail by ground-up, crushed and fractured rock, often cannot be seen. This is what probably happened with Cuadrilla's Balcombe-2 well in West Sussex; The vertical section of that well will have cut through the Paddockhurst Park Fault without being recognised, and Cuadrilla was (luckily) then able to drill horizontally to the along the limestone layer without encountering another fault.

Even if a well is cored, which involves the taking of a solid intact cylinder of rock from the inner zone of the drilling, faults can be difficult to recognise with certainty. In oil exploration coring is only done over a few limited intervals of a vertical well, because of the extra costs.

A.3 Permeability, hydraulic conductivity and vertical flow in faults

<u>Permeability</u> is a general term applied to fluids (liquids and gases); it is a measure of how easily the fluid can flow through the medium. <u>Hydraulic conductivity</u> is a more restricted term referring to specifically to water flow, and more frequently used by civil engineers; however it measures the same thing as permeability, but using different units. I frequently find that civil engineers speak of permeability when the parameter they speak of is really hydraulic conductivity. The units used are the key to spotting the difference.

The literature on the fluid sealing or conducting properties of faults in sediments is large and confusing. Research is driven by the need to understand sealing of hydrocarbon reservoirs at depths of 2-3 km on the one hand, and engineering properties of faults in the near-surface (down to a few hundred metres), especially in unconsolidated sediments. In addition, the subset of research into the effects of faulting in pelitic rocks (e.g. mudstones) is very limited.

There are dozens of academic research groups and oil-industry service companies working on the problem of whether faults act as *conduits* or as *barriers* to fluid flow. The default position in the hydrocarbon industry is the conservative one, that <u>faults do not act as seals</u>; in other words, they are leaky unless proved otherwise. In oil or gas exploration, if a fault is wrongly judged to be a seal when in fact it is permeable, no damage is done, other than to the bank balances and share prices of companies and individuals. However, in the case of shale gas exploitation, the consequences of over-optimistically assuming that faults act as seals may be extremely damaging to the environment.

My brief and necessarily incomplete review of this large field of research and development (R&D) leads me to the following impressions and tentative conclusions:

1. There are field measurements of faults at outcrop and at shallow depth; it is realised that small-scale structures associated with faults dominate the bulk hydrogeological properties. These are characteristically fractures sub-parallel to the master fault plane, which are collectively termed the 'damage zone'. Such zones can be several metres to tens of metres in horizontal width, and are often the locus of fluid flow up or downwards, rather than across the master fault plane. This is illustrated in diagrammatic form in Figure A.1.
2. In an unconsolidated mixed sand/clay stratigraphy, the conductivity in the damage zone can be enhanced by several orders of magnitude, but clay smearing along the core fault plane reduces the bulk conductivity.
3. Iron oxide re-precipitation in the core fault, due to the enhanced flow in the damage zone, is another mechanism which can reduce the core conductivity.
4. The relative hydraulic conductivity of a fault cutting indurated low-conductivity clays is neutral; i.e. the conductivity of the fault zone remains within the same order of magnitude as the unfaulted clay. An example is the set of measurements across the Down Ampney fault, made by the BGS, in which Oxford Clay is juxtaposed against Oxford Clay or Forest Marble Clay (Sen and Abbott 1991).
5. However, the same dataset shows that the conductivity of the fault zone as a whole is enhanced by one or two orders of magnitude, because the succession includes limestones and sandstones as well as the aforementioned clays.
6. Smectite in shear zones can be dehydrated to anhydrous illite minerals as a shear fabric develops; this in turn can account for overpressure build-up. This mechanism accounts for high hydraulic conductivity observed in accretionary wedges, but contradicts laboratory experimental studies suggesting that sheared clays in fault zones represent aquitards.
7. Laboratory measurements of permeability or hydraulic conductivity usually give results

> that are an order of magnitude lower than *in situ* measurements. Tellam and Lloyd (1981) studied the hydraulic conductivity of British mudrocks. The laboratory measurements gave values 2 to 3 orders of magnitude lower than the *in situ* values.

Lunn *et al.* (2008) have modelled the fluid flow pathways across models derived from detailed outcrop observations. Starting with their summary that:

> "*Faults can be barriers to flow, conduits, or combinations of the two, and their hydraulic properties vary considerably over both space and time*".

They conclude from their study that the *micro* properties as opposed to the *average* hydraulic properties in a fault zone are crucial, but that these properties are *unmeasurable at depth*. A multi-variate stochastic approach is the only way forward, they say, which:

> "*implies that a very large database of fault architecture is needed to accurately characterize fault permeability distributions. This can only be achieved by pooling a large number of field datasets. This would require an international consensus on the recording of the gross parameters (e.g., lithology, offset, stress history) and the architectural detail at each site*."
> [NB authors' emphasis on *very large*].

From Lunn *et al.*'s observation (which was already widely known across the hydrocarbon exploration industry) that "*faults can be barriers to flow, conduits, or combinations of the two*", one can construct a cartoon of how normal faults cutting sediments will affect flow direction (Figure A.1). I have indicated in this cartoon the general flow parallel to sedimentary bedding, in this case down-dip. But when the flow encounters a fault zone it will be redirected upwards; this fact is irrespective of whether the fault is acting as a barrier or as a conduit to fluid flow.

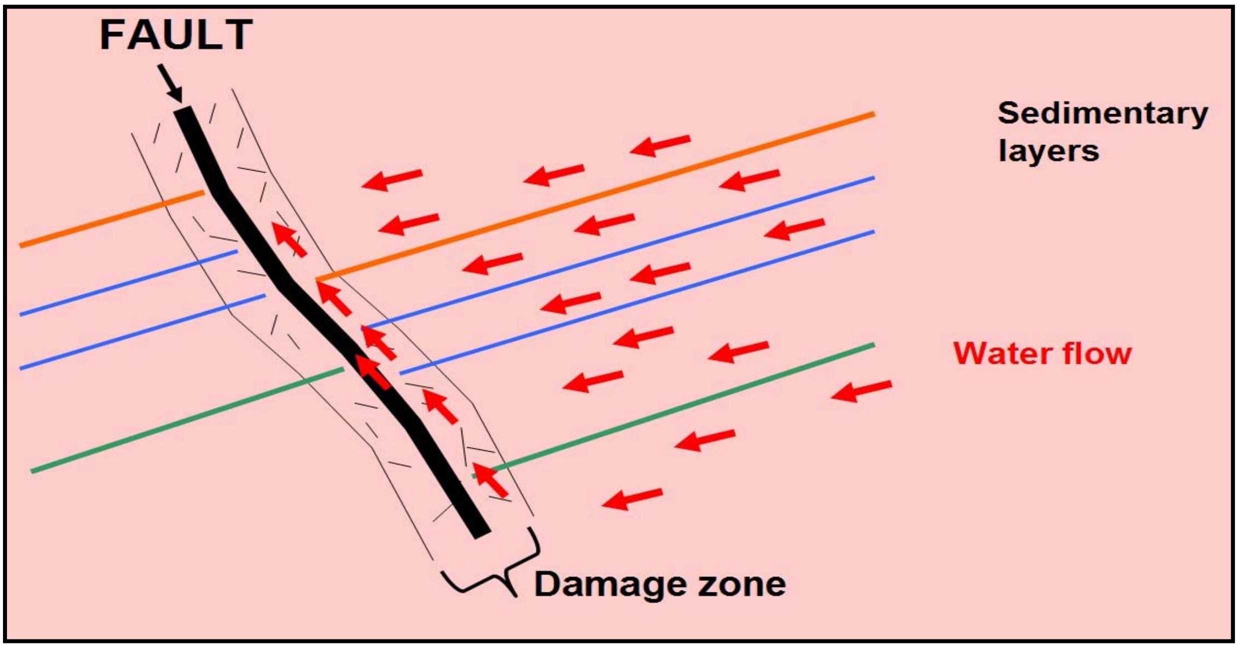

Fig. A.1. Cartoon of a fault zone and resulting fluid flow (red arrows). The core zone (black) could be a barrier, or it could be a conduit. The damage zone on either side is always a conduit because it is fractured.