Planning application no. ES/3379 by Island Gas Limited to drill at Springs Road, Misson, Nottinghamshire: Objection on grounds of geology and hydrogeology

By

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NON-TECHNICAL EXECUTIVE SUMMARY

I have been asked by Bassetlaw Against Fracking to write this **OBJECTION** to the development, based on geological and hydrogeological grounds. It is also submitted on my own behalf as an independent and impartial expert in the field.

The application to drill a test vertical well, followed by a contingent horizontally deviated well, is the first stage of an inevitable progression towards hydraulic fracturing ('fracking') of the Bowland Shale below the area. The application is for unconventional shale gas appraisal, but has been disguised as a conventional exploration project by the addition of spurious secondary and tertiary hydrocarbon targets. A more transparent and honest application would have included the appraisal stage of fracking the horizontal well. There is no valid reason for this part of the work to have been omitted, other than a desire by the Applicant to get the first stage approved, in a salami-slicing subdivision of its unconventional shale gas development.

The 300 m thick Sherwood Sandstone Group is the main Principal Aquifer and water supply for the East Midlands. The Applicant claims that the site lies on the Mercia Mudstone Group, a minor aquifer or aquitard. I demonstrate that the site is in fact partially or wholly on the Sherwood, and that a newly recognised fault, the Misson Fault, runs right through the site. The Applicant has failed to mention the other Principal Aquifer, the Magnesian Limestone, which lies at less than 500 m below the site. The Applicant has presented highly misleading maps and cartoon sections in an effort to convince the Council that there is no risk to the aquifers, even though the site lies within Source Protection Zones 3 (surface) and 3c (subsurface).

No satisfactory explanation has been supplied as to why the site was chosen. The explanation of how the search areas were defined is misleading. The primary shale target could have been selected from anywhere within the 182 km^2 of the licence area available to the Applicant. The secondary and tertiary targets have not been described in any detail; the latter is even claimed by the Applicant to target a rock which does not exist east of the Pennines.

A 3D seismic survey has been acquired, but since the proposed drill site is very near its edge, the survey is inadequate for the required purpose of high-resolution imaging of layers and faults down to 2500 m depth. Insufficient data have been supplied for objective and independent scrutiny of this survey. I show that the locality around the site is cut by many faults, which the Applicant claims not to have detected. No information on the well casing programme is provided, therefore the HSE will be unable properly to assess the application.

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. International research and industry practice in shale gas development concur in agreeing that faults should be avoided, whatever their scale. I provide three appendices detailing: the current understanding of faults; a case history of water contamination by fracking; and computer modelling of flow up faults. In the Gainsborough Trough it is therefore likely that some faults will leak fracking fluids and/or methane both to groundwater resources and to the biosphere; this is not a risk worth taking. No UK shale basin like the Gainsborough Trough has yet been fracked using horizontal wells.

I list 27 substantive errors, omissions, and misleading statements by the Applicant which need to be addressed. They suggest that the Applicant is treating the planning system with contempt. I also make a number of recommendations for supply of further information and data by the Applicant before the application can rationally be determined. However, it would be rational to refuse the application now, on the grounds that the proposed work has not been adequately described, that it is in crucial repects misleading, and that it reveals a poor understanding of the geology and hydrogeology of the licence area.

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1 INTRODUCTION

1.1 Relevant personal details from my CV

I am Emeritus Professor of Geophysics in the University of Glasgow. I have no current link with any research group at the University, nor would I wish to. 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 the local objectors' group Bassetlaw Against Fracking, and has been provided 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 PROPOSED EXPLORATORY DRILLING AND EVENTUAL FRACKING

2.1 Introduction

The application by Island Gas Limited ('IGas', hereinafter referred to as the Applicant) to drill at Springs Road, Misson, Nottinghamshire is the first such application in the Gainsborough Trough. Although the Applicant does not wish to hydraulically fracture ('frack') the wells at this stage it reserves the right to submit a later application to do so. It is therefore appropriate to consider the current application within the wider context both of fracking in general, and of the Gainsborough Trough in particular.

2.2 Production of gas by an 'unconventional' process

2.2.1 Introduction

The Applicant proposes to drill a test vertical well, followed by a contingent horizontally deviated well along the Bowland Shale.

It is the first stage of a progression towards hydraulic fracturing ('fracking') of the Bowland Shale below the area. There is no other possible outcome to this initial phase, apart from withdrawal from the site. Therefore the application should be considered in the context of the intention to frack.There is no conceivable scientific or economic merit in drilling the horizontal well *per se*, because **the shale cannot be exploited without fracking**. In addition, the horizontal well cannot be classed as proving whether or not the hydrocarbon deposit exists, because we already know that it is there. Therefore we need to examine more closely the purpose of the horizontal well.

'Fracking' does not mean just the narrow definition of injecting high volumes of water under very high pressure to fracture shale. **Fracking means, correctly and in popular understanding, the whole process of unconventional shale gas (or oil) production**, an essential part of which is the fracking of the shale. This starts with appraisal drilling and finishes with re-injection of produced water back down boreholes.

2.2.2 Exploration or appraisal?

The wells are described as exploratory. But inasmuch as they both concern the primary target, the Bowland Shale, neither of them conform to the modern definition of an exploratory well. For example, the US Securities and Exchange Commission, in seeking to modernise definitions to increase business transparency and reporting (Securities and Exchange Commission 2010), defines an exploratory well as follows:

> *"An exploratory well is a well drilled to find a new field or to find a new reservoir in a field previously found to be productive of oil or gas in another reservoir."*

The Norwegian Petroleum Directorate clarifies the definition somewhat better:

> *"Exploration well: a well drilled in order to establish the existence of a possible petroleum deposit or to acquire information in order to delimit an established deposit. Exploration well is a generic term for wildcat and appraisal wells.*
>
> *Wildcat well: exploration well drilled to establish (prove) whether petroleum exists in a potential petroleum deposit.*
>
> *Appraisal well: exploration well drilled to establish the extent and size of a petroleum deposit that has already been discovered by a wildcat well."*

(http://www.npd.no/en/Topics/Wells/Temaartikler/Well-definitions/)

Note that the Norwegian definitions define Wildcat and Appraisal wells as sub-categories of Exploration wells. The precise categorisation of well type has not mattered too much up till now, because in conventional hydrocarbon exploration it is usually obvious to which category a well belongs. But unconventional oil and gas exploitation is more of an industrial extraction process than a real 'exploration' to find an economic resource that may or may not be present, and this fact is changing the game.

In true Wildcat drilling the exact location of the well can be all-important. Target locations are specified to the nearest metre, both horizontally and in depth. There are many case histories of wells failing (coming in dry) because the oil-water contact was missed, or the well went down on the wrong side of a fault, by a matter of a few metres.

So the initial vertical well at Misson Springs could conceivably be classed as a Wildcat for the purpose of proving whether or not the secondary and tertiary targets exist; as far as the Bowland Shale is concerned, the well cannot be termed a Wildcat, because we already know that the Bowland Shale exists, and furthermore is very thick, below the whole PEDL licenced area. Therefore all shale drilling will be Appraisal, or, further down the line, Development and/or Production.

The contingent horizontal well certainly cannot be classified as a Wildcat; the definitions offered above show that it is an Appraisal well. This is borne out by the Applicant's work programme:

> "*The evaluation phase (Phase 3) itself will comprise the period during which the results of the logging and coring will be assessed by IGas. If the results show that flow testing of the well(s) (which could involve well stimulation including hydraulic fracturing) would be worthwhile, a further application for planning permission will be submitted.*" Vol. 3 Environmental Statement para. 4.4.2)

This statement is misleading, because it implies that flow testing (of the vertical and/or the horizontal wells) *might* be worthwhile. But there will be negligible gas flow from the shale, which is a 'tight' (extremely low permeability) rock; it only yields up its oil or gas very slowly, that is, over geological aeons. There is no shale from which, once drilled, the oil or gas flows freely under its own pressure. If there were, then shales would have been drilled routinely to extract conventional oil and gas, and the entire hydrocarbon exploration industry, devoted to finding progressively more subtle and obscure reservoirs over the last century, would have been redundant. One would simply drill down to the nearest shale, a commonplace rock, and extract the hydrocarbons.

2.2.3 Horizontal well superfluous

Another question to raise about the contingent horizontal well is, why is it needed? The shale will be unchanging in physical and hydrogeological properties along the kilometre or so of the horizontal path (unless an unforeseen fault is encountered), so there is no merit in drilling horizontally. All the required "*evaluation*" (appraisal) of the shale can be done from the samples taken from the vertical well, together with the appropriate electric logging.

After several years of development of the various US shale basins it became apparent that parts of the basins are so-called 'sweet spots', that is, local areas within the basin in which the oil or gas yield is much higher than elsewhere. If the Applicant wished to find a sweet spot within the Gainsborough Trough, then the appropriate course of action would be to drill several vertical wells within its licence area to appraise shale, before concentrating efforts on the most promising locality. So the drilling of the horizontal well cannot be said to aid the finding of such a 'sweet spot' - even if such a concept could be said to exist in the UK, where the areas of the shale basins are a tiny fraction of the US basins. The Marcellus Shale basin of the north-eastern USA is 15% larger in area than the whole of England. The area of the Gainsborough Trough is just 1.5% of the area of England.

The Applicant is thus seeking to mislead the Council into believing that the horizontal well is a necessary part of the current work programme. In truth, it is superfluous, other than to prepare the way for *high volume hydraulic fracturing*, ('fracking'). The Council therefore needs to seek clarification from the Applicant as to why the appraisal phase of the proposed horizontal well does not include fracking, and why it is justified at all.

It may be argued that the planning committee must base its decision purely on the documents presented, and that since fracking is excluded from the present application, the certitude or likelihood of future fracking cannot be used as an argument to dismiss the current application. But that view is maintained, it permits the Applicant to mislead the Council as to its true intention, which is, no more or less, the unconventional development of shales. The mention in the application of secondary and tertiary targets for the drill is just a smokescreen, as will be shown in the geological sections below.

2.2.4 A planning analogy

Here is an analogy which may help the Councillors in their deliberations. What if a preliminary planning application came forward to excavate the foundations of a skyscraper in an area where the applicable planning policy includes height restrictions on construction? The proposal itself would not exceed the height restriction, but its sole aim is to prepare for the skyscraper. For example, the proposal could be to demolish the existing three-storey New Castle House, on the south side of Castle Boulevard in Nottingham, some 100 m SE of the castle bluff (incidentally, composed of Sherwood Sandstone), and to replace it by a 60-storey skyscraper of some 300 m elevation. But the application in question is only for the excavation of the 20 m deep hole and the installation of 50 m deep piles, in preparation for the subsequent building – but not for the skyscraper itself. There is no conceivable social or economic benefit *per se* to the community of having the preliminary work done. Would such a preliminary planning development be permitted? Since the ultimate aim – the skyscraper – is *a priori* not permitted, and there are no intrinsic benefits to the community in the excavation itself, the planning committee would surely be justified in refusing the preliminary application.

2.2.5 Conclusions on ultimate purpose of the drilling

As for the analogy presented above, so it is with the present application, which should be refused firstly, on the grounds of being incomplete, misleading and erroneous (as I demonstrate below), but also, secondly, on the broader ground that it is nothing other than the first stage of an intensive industrial process – the whole process being known as shale fracking - which has a strong likelihood of permanently contaminating important groundwater resources. **In the present application, unconventional hydrocarbon appraisal is being disguised as a conventional exploration project. This is unacceptable.**

A more transparent application would have included the fracking stage of appraisal and development as part of the current application, even if the work is divided up into stages.

2.3 Geology of the Gainsborough Trough

The Gainsborough Trough is a basin hidden below the younger rocks that are seen ('crop out') at the surface. Figure 1 shows the Misson Springs proposed wells in the context of the solid geology, that is, the solid rocks with the superficial sediments removed. There is a very gentle dip of around 2° to the east as shown by the black arrow. A cross-section accompanying the British Geological Survey (BGS) 1:250,000 regional scale Humber map happens to run through the proposed site. Part of this is reproduced in Figure 2. These two figures – map and section – show that the older Coal Measures (Carboniferous age) crop out in the west, but are successively buried by younger rocks as one proceeds eastwards.

The Sherwood Sandstone Group (SSG) is a Principal Aquifer. Figure 2 shows that the Applicant proposes to drill through a few metres of Mercia Mudstone Group (MMG), then through the SSG and older rocks. The target rock is the Bowland Shale beneath, at 2000-2500 m.

The Gainsborough Trough, containing the Bowland Shale (Bowland-Hodder Unit), underlies the Millstone Grit. The BGS regional structural map reproduced in Figure 3 (Andrews 2013) shows that the Trough is aligned NW-SE, hidden below the younger east-dipping sediments shown in Figure 1. The word 'trough' is usually used when a narrow basin is faulted on one or both sides. Red shading is shallow depth, yellow through to blue indicates progressively deeper depths, and faults cutting the base of the basins are shown as red lines. It can be seen that at this regional scale, covering a large part of northern England (Figure 3a), the Gainsborough Trough is less faulted than the Bowland Basin of West Lancashire, and is not as deep as the Cheshire Basin. The Applicant's area of search, PEDLs 139 and 140, is shown outlined in red with black hatching in Figure 3b. The proposed site is shown by the red dot.

The north-eastern half of cross-section D of Figure 3a is shown in Figure 4, where the target Bowland-Hodder shales are shown in dark green. Note that they are 2-3 km thick.

2.4 Inaccurate and insufficient supporting data

2.4.1 Introduction

The current application comprises the first exploratory step both in the East Midlands and in the Gainsborough Trough in which high-volume fracking of horizontal well (the process now re-named '*super-fracking*' by Turcotte *et al.* 2014) will be eventually be employed, if a later appraisal application is approved. As such, it is incumbent on the applicant to supply full justification for the current stage of the work, and why the whole appraisal is not included in the current application. This has not been done.

2.4.2 Existing well and borehole data

Appendix F Groundwater, section 4.6, of the application discusses the bedrock geology, with reference to borehole SK79NW/30. This is the Rocket Site borehole shown in Figure 5, situated 540 m SW of the vertical wells and above the proposed horizontal well (the latter is shown in blue). But this borehole is not shown on the relevant Application Drawing no. 22, which forms the backdrop to Figure 5. Only five boreholes are marked on this drawing, shown by the black dots labelled with the well name in upper case.

The most distant borehole depicted by the Applicant is Scaftworth-2, which lies 6.6 km SW of the Misson site. But there are a further 8 boreholes, excluding Rocket Site, which should also have been taken into consideration, because they are nearer than Scaftworth-2. All these relevant boreholes are shown in Figure 5 and tabulated with correct grid coordinates in Table 1. Every one of the five boreholes depicted by the Applicant is mispositioned. The positioning error varies from 80 m in the case of Scaftworth-2 up to 2130 m for Misterton-1. Such gross errors are inexcusable and misleading.

The Applicant concedes that Sherwood Sandstone Group is at solid outcrop below superficial deposits at the Rocket Site borehole, but qualifies this admission: "*... it is possible that part of the recorded 'Drift' (superficial deposits) represents weathered Mercia Mudstone.*" (Appendix F section 4.6). Evidence for the solid rock outcrop around the site is discussed below. The nearest that the Applicant comes to portraying a geological cross-section through the proposed wells comprises two cartoons, reproduced herein as Figure 6, purporting to show the strata to be encountered. The errors in thicknesses depicted in these cartoons are discussed below.

Easting	Northing		Depth	Comments
		Borehole	(m)	
473238	397691	Broomstone BH204	1099	Missing from Igas map
474401	394740	Cornley	1200	Mispositioned 1350 m to N
472419	396772	Haxey	971	Missing from Igas map
475819	397004	Langholme	1163	Missing from Igas map
469510	395770	Misson	1226	Missing from Igas map
472037	399183	Park Drain BH203	1056	Missing from Igas map
470410	397369	Rocket Site	1140	Missing from Igas map
470600	399800	Rooks Farm Water Well	305	Missing from Igas map
474302	400269	Westwoodside	998	Missing from Igas map
		Oil or CBM well		
469320	401215	Blaxton Common-1	957	Missing from Igas map
470175	392960	Everton-1	2079	Mispositioned 200 m to NE
468850	392885	Everton-2	229	Mispositioned 210 m to NE
472662	393576	Misterton-1	560	Mispositioned 2130 m to NE
467179	392283	Scaftworth-B2	2326	Mispositioned 80 m to NE

Table 1. Relevant boreholes and wells omitted from or mispositioned by the Applicant.

2.4.3 Seismic surveys

The 3D seismic survey is, in principle, a necessary and welcome background dataset to the application (Vol. 3 Environmental Statement, section 5.5), but no further information is supplied, other than an outline of the surface survey coverage (shown by the green dotted outline in Figure 5), and the fact that the survey covered some 7000 Ha (it is actually 68 km^2).

But only within the area of *subsurface coverage* is the survey at its 'full fold', and therefore capable (in principle) of imaging all the structure below. Fold, or multiplicity of coverage, is the principal measure of the data quality. The surface coverage area and the inner subsurface coverage are both shown in Figure 7. I have estimated the latter from the former by assuming that the maximum source-receiver offset is 3 km, resulting in the fringe, or apron, zone of 1.5 km around the subsurface coverage area. Outside of this inner area, the data quality diminishes progressively from full-fold at the edge of the inner zone to 1-fold at the edge. So the 3D image below the proposed drillsite will be of poor quality, because both the vertical and horizontal wells lie within the fringe zone.

In order to clarify these deficiencies the applicant should have supplied for the 3D 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; approximately five E-W images and five N-S images passing through existing wells would have sufficed
3. These cross-sections should have been 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 have been shown, both for wells within the 3D area and, using the available 2D seismic, for other wells within the locality as shown in Figure 5.

No 2D seismic data have been used in the interpretations, even though these data are released and available for purchase, like the released well data, at minimal cost. Instead, the Applicant merely states "*exploration holes and seismic investigations in the last 35 years may provide more resolution on the structural geology but these data are not available to this assessment.*" [Appendix F Groundwater section 4.7].

My interpretation of faults, based on the available 2D dataset, is discussed in section 3.3 below.

The objectives of the drilling are said to be to:

> "*explore and evaluate the resource potential of the:*
>
> - *Bowland Shale (primary target);*
> - *Sandstones within the Millstone Grit Group which overlie the Bowland Shale*
>
> *(secondary target); and*
>
> - *Carboniferous Limestone Supergroup basinal facies (tertiary target).*
>
> *To achieve these objectives, a vertical well is to be drilled through each of the above targets in order to allow full characterisation of these strata. If the horizontal second well is drilled it will enable the areal extent and heterogeneity of gas bearing rocks to be identified in the target formations.*" (Vol 3 Environmental Statement, section 5.2).

Two areas of search were identified by the Applicant (Vol. 3 Environmental Statement, section 5.6). These are shown in cross-hatched yellow in Figure 5. The search criteria are stated to be as follows:

> "*These were defined as the best areas of search for exploration wells from a reservoir and structure point of view having had regard to factors including geological structure and the thickness and depth of the target strata as identified by the 3D seismic survey.*"

This sentence is essentially meaningless without the provision of extra information. The Applicant should have supplied the information required to justify the statement. Figure 5 shows that neither the Misson nor the Haxey well were used by the Applicant, even though they both lie within or at the edge of these two selected areas. In addition, the Rocket Site borehole does not have the necessary electric logs for tieing in well depths to the 3D seismic. Note again from Figure 5 the gross mispositioning by the Applicant of the Misterton-1 and Cornley wells. Therefore the well-to-seismic ties essential for the Applicant's geological interpretation could be grossly in error, and will therefore nullify any (unpublished) conclusions that the Applicant may have come to regarding geological structure and reservoir properties. This in turn means that **the site selection process is demonstrably inaccurate**.

2.4.4 Area of search

The Applicant has not demonstrated that the application site presents the best option in comparison with alternative sites within the area of search; that is, the contiguous Petroleum Exploration and Development Licence (PEDL) areas PEDL 139 and PEDL 140. Figure 3b demonstrates that the top of the Bowland Shale is to be found at a similar depth throughout the search area. The BGS report on the Bowland Shale (Andrews 2013) also shows that the shale is at its thickest north of the E-W fault shown in red in Figure 3b running through the Scaftworth-B2 well. So if maximum thickness of shale is a search criterion (but which is not actually stated by the Applicant) this still leaves about 75% of the area of search available.

Such failure contravenes the County Council's Minerals Local Plan (preferred approach), policy MP12: Hydrocarbon Minerals, which states, under the heading

Exploration:

> *"2. Where proposals lie within an environmentally sensitive area, evidence must be provided to demonstrate that exploration could not be achieved in a more acceptable location and that within the area of search the proposed location would have least impact."*

Given that the site lies just 125 m from the Misson Carr Nature Reserve, an SSSI, it is incumbent on the Applicant to show why, within the total PEDL area available of 182 km^2, no better site could have been selected.

The choice of the two areas of search within the overall PEDL search area, that is, the two yellow hatched polygons in Drawing 22 (reproduced with overlays in Figure 5), is not justified by the imprecise definition under the Applicant's heading Areas of Search:

> *"the best areas of search for exploration wells from a reservoir and structure point of view having had regard to factors including geological structure and the thickness and depth of the target strata as identified by the 3D seismic survey." (*Vol. 3 Environmental Statement, para.5.6.1).

We need further information. In addition, there is another unjustified assertion under the heading Site Selection:

> *"The significance of the areas of search in the context of site selection is that drilling from locations outside the boundaries would not achieve the objectives of the exploration programme." (*Vol. 3 Environmental Statement, para.5.7.1)

This assertion is discussed further below.

2.4.5 Secondary and tertiary targets

The secondary and tertiary targets are the Millstone Grit Group and 'Carboniferous Limestone Supergroup', respectively. Below the PEDL licence area; the top of the former is of the order of 1500 m deep.

The basinal facies of the 'Carboniferous Limestone Supergroup' is supposed to be the tertiary target, but according to modern BGS classification (Waters *et al.* 2009) this supergroup does not exist in the Gainsborough Trough. Perhaps the Applicant intends the basinal facies of the Craven Group. But due to the lack of detail provided and the error in lithostratigraphic nomenclature we do not know what the tertiary target is; if it underlies the Bowland-Hodder Group then it will be at a depth in excess of 4 km (see Figure 4).

2.4.6 Conclusions on targets and area of search

Given the fact that the primary target, the Bowland Shale, can be accessed essentially anywhere within the PEDL region, totalling 182 km^2 in area, we need much more detail as to what exploration criteria resulted in a narrowing down of the search to just 8 km^2 – some 4% of the PEDL licence area available.

It would also be surprising that the area of search for the secondary, conventional target, sandstones within the Millstone Grit, could be narrowed down to one or both of the tiny areas selected; but if that were indeed the case the presumed conventional target, such as a four-way closure, must be so small as not to be worth the effort.

The inevitable suspicion therefore arises that **the two search areas were selected on non-geological criteria, in which case the Applicant is misleading the Council.**

2.4.7 No information on well drilling and casing

The Applicant provides no substantive information about drilling and casing (Volume 3 Environmental Statement, 'Drilling and Casing Process', paras. 4.3.4 – 4.3.7). All the standardised description supplied could have come straight out of an elementary petroleum engineering textbook. In providing so little information the Applicant seems to be treating the application process with contempt. These are not brand-new Wildcat wells in an unknown basin; the geology is very well known and understood, and there is a deep borehole just 550 m SW of the development site, in line with the horizontal well trajectory.

Here is an example of the minimum detail that should have been supplied (local rock formation names have been omitted for clarity):

> *"In Wisborough Green 1 the 13⅜" conductor may be pre-set using a small augur rig before the drilling rig is moved onto location. This conductor is required to provide mud returns to the cellar while drilling the surface hole and prevent the cellar being washed out underneath the drilling rig. A 12¼" hole is then drilled down to the* [named rock] *at which point 9⅝" casing is run and cemented in place to surface to isolate and protect the* [named] *aquifers. The aquifer isolation program will be approved by the Environment Agency. Then the 8½" hole is drilled with some coring in the* [named rock layers]*, to the top of the* [named rock] *at which point 7" casing is then run and cemented to surface to isolate the* [named rock layers]*. Finally, a 6" hole is drilled to the target* [rock layer]*, and cores taken."*

This extract is taken from the planning application by Celtique Energie to drill an exploratory well at Wisborough Green, West Sussex, ref. no. WSCC/083/13/KD, available at:

http://buildings.westsussex.gov.uk/ePlanningOPS/loadResults.do;jsessionid=c0a8832b30d5b49a77d991a24963a6beb53d54bcb7b0.e38KchmQc3qObO0LbN4Sbx8Pb3qRe0

The description quoted above is accompanied by an accurately scaled and detailed diagram of the well in relation to the geology. The Wisborough Green application, like the present application, was for drilling a vertical well, a contingent horizontal well, but neither with fracking envisaged in that application. The application was refused.

The Applicant's work programme should have included details of the well construction, including:

- Shallow conductors
- Deep conductor
- Surface casing
- Drilling liner and tie-back
- Production liner

- all in the context of the reasons for each type of casing required, depths, cementing, and the like.

It is therefore impossible for the EA and the HSE properly to assess the proposed work programme and the competence of the Applicant. This alone is sufficient reason to refuse the application.

2.4.8 Conclusions on supporting data

In conclusion, there can be little or no confidence in the technical qualty or reliability of the Applicant's geological interpretations. At least two statutory agencies, the EA and the HSE, will be unable adequately to assess the impact of the proposed development.

The justification of site selection is flawed because of the lack of information. The local search areas may have been selected on non-geological or exploration criteria.

The sparseness and third-rate quality of the Applicant's proposed work programme, together with its demonstrably poor understanding of the geology and hydrogeology could open the application to Judicial Review in the event that it be approved.

3 FAULTS

3.1 Summary of the general fault problem

Appendix A comprises a detailed summary of current research on faults, with emphasis on their hydrogeological properties. Faults are near-planar surfaces cutting through rock layers. In the UK sedimentary basins 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, particularly re-injection of produced water, can induce earthquakes.
- USA fracking history provides no guide for the UK geological environment.
- Leaks of fugitive (released) methane up faults, once started, may continue for decades.

3.2 Geophysical exploration imaging technology

3.2.1 Resolution of seismic data

An onshore 3D seismic reflection survey, if thoroughly carried out, should be capable of indirectly imaging faults by revealing the offset or displacement of layers on either side of the fault surface. The resolution attainable should be down to 4 or 5 m. This contrasts with a 2D seismic survey line, in which the minimum observable displacement will be about five times bigger, i.e. poorer, at 20-30 m of displacement. Rarely, it is also possible to image the fault plane directly as a reflecting surface. In a thick shale sequence such as the Bowland-Hodder Unit of the Gainsborough Trough it will be very hard to image faults, either directly ot indirectly, because of the uniform physical properties of the shale. The essence of seismic reflection imaging is that a contrast in density and/or seismic velocity is required across a surface for an image of the surface to be created. If such physical contrasts do not exist, as, for example, in a thick shale layer, there is nothing to be imaged.

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 high and uniform standard that the method can be applied onshore.

3.2.2 Microseismic monitoring

Microseismic monitoring is used in conjunction with the fracking operations to control the progress of the latter. It does not image faults or fractures directly, but locates the microseismic event in 3D space. But it has a major drawback, in that it cannot record the silent progress of fracking fluid up pre-existing fractures. These passageways are called 'stealth zones' (e.g. Pederson and Eaton 2013). This has been demonstrated in the USA (Pettitt *et al.* 2009, van der Baan *et al.* 2013). Therefore it cannot be claimed that microseismic monitoring will obviate the risk of frack fluid leaking upwards.

3.3 Fault interpretation in the vicinity of the site

3.3.1 Introduction

Doubts expressed above about the validity of the Applicant'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. The Applicant states that there is "*an absence of faulting shown on geological maps that could provide a vertical pathway for ground gas at the Proposed Development*" [Appendix F Groundwater, section 4.12]. This assertion is not backed up by any evidence. Absence of evidence cannot be taken to be evidence of absence.

Firstly, the inadequacies of the existing geological maps for surface fault mapping are admitted by the Applicant. Secondly, it could mean that the quality of the 3D data obtained by the Applicant in 2014 was such that faults were not seen. We simply do not know. It does not imply that faults are absent, as I shall now show.

3.3.2 Coalmine evidence

There are two former collieries in the vicinity of the proposed development, Rossington to the west and Harworth to the SW. A review for the Department of Trade and Industry (IMC Group Consulting Limited 2004) includes detailed maps on the coal seams, including faulting, at these two collieries. Figure 8 shows the areas outlined by a black dashed line within which faults have been mapped (red dash-double-dotted lines). The depth of the seams proving the faults is of the order of 1000 m.

The map for Rossington, in the north, shows faults cutting the Barnsley seam, and the Harworth area in the south it is the Deep Soft seam that is shown. The structure at Harworth is described as follows:

> "*In the northern area of the reserves is the large east-west Lings Fault, which has been identified from surface seismic surveys. At the southern edge of the Deep Soft workings is a northwest-southeast fault (also from seismic surveys) with an expected throw of 25-30m.*"

The Ling's Fault is labelled in Figure 8. The structure at Rossington is described thus:

> "*The Barnsley is the only seam worked in the present areas of the mine. Because of this, the structure over areas of unworked Barnsley has been based on provings from past workings at Rossington Colliery to the west, Markham Colliery workings to the north and a surface seismic surveys to the east, north and partially south of the main laterals. Data from boreholes is also used to help in the structural interpretation.*
>
> *In general there is a low density of faults above the limits of seismic resolution (10m to 15m throw). Faults trend south-west to north-east. There is a regional gradient to the north and north-east of 1 in 15 or lower. The surface seismic data is of reasonable quality.*
>
> *Based on the area proved by past workings, the intensity of below resolution faulting is expected to be low. The proving of the anticipated faulting on B100's tailgate improves confidence in the revised interpretation of surface seismic. The 4m to 5.5m fault proved in the east laterals and B102's main gate, has been picked on surface seismic to the North East. It is expected to increase in throw to between 12m and 15m. This fault has a significant effect on the layout to the north of the main laterals and resulted in a major redesign of the proposed Five Year layout after B102's*."

These two areas show that faulting is significant, and that faulting in the Coal Measures can be identified using seismic reflection data. It is therefore inexplicable that the Ling's Fault, together with the sub-parallel fault to the north, was not identified on the

Applicant's 3D survey.

By extrapolation to the east from the two coalmine areas it can be seen that faulting in the proposed development can be expected within the Coal Measures at a spacing of at least one per kilometre, and probably trending NE-SW, but possibly E-W.

It is also noteworthy that Rossington Colliery closed in 2006, with major geological problems being cited as the reason. The most likely geological reasons would be (a) the faulting was more severe than anticipated, and (b) there was unforeseen seam splitting.

3.3.3 Evidence from existing 2D seismic data

I have inspected the released 2D seismic data, made available as images at the UK Onshore Geophysical Library. The base of the SSG is a very strong reflector, the top of the Magnesian Limestone. Identifiable faults at this level around the area of the proposed development are shown in Figure 9. I have simply marked the location on each seismic line (shown in green) where a fault can be seen (red, with teeth on the downthrown side), but have made no attempt to correlate the structure from one line to another, even though it can be assumed that each fault is probably a kilometre or more in length. This preliminary interpretation suggests that there is faulting present, with throws of 20-30 m or so, at an approximate 1 km spacing.

Confidence in my interpretation is increased by the fact that the fault marked twice, some 1.8 km WNW of the proposed wells where two seismic lines cross, coincides with a NE-SW fault independently identified on the Rossington colliery map (Fig. 8).

An E-W seismic line (BP75/07) running less than 6 km south of the proposed site has been interpreted by the BGS on behalf of the Department of Trade and Industry (Holliday *et al.* 2004). An extract from this interpretation is shown in Figure 10. It shows many faults cutting the Carboniferous rocks. Some of them extend into the overlying Permian and Triassic; the fault just east of the Scaftworth-B2 well cuts from the target shales all the way up to the Sherwood Sandstone Group aquifer (labelled as 'Mesozoic').

3.3.4 Evidence from the boreholes near the proposed development

The feather-edge of the Mercia Mudstone Group (MMG) in the vicinity of the proposed development, as marked on the BGS Doncaster 1:50,000 map, mismatches the evidence from boreholes which were drilled after the map was published in 1969. But the Applicant persists in using the out-of-date information in this regard. Figure 11a shows the feather-edge of the MMG from the 1969 map (yellow dotted line) in relation to the site and surrounding boreholes. Solid rock encountered in the boreholes is indicated by the old names; Keuper Marl (KM) is now the MMG, and Bunter (Sandstone) is the Sherwood Sandstone Group (SSG). But the feather-edge is discrepant at two localities, circled in red in Figure 11a, where SSG was drilled at solid rock outcrop, and not MMG, as would be expected from the mapped boundary.

A more detailed area around the site is shown in Figure 11b, which covers the area shown in Figure 11a outlined by the dashed black rectangle. Thirty-one Misson Springs shallow boreholes are shown in this detailed map by small well symbols; all these boreholes indicate that bedrock was either not reached, or that it may have been weathered MMG. So the feather-edge of the MMG has to be revised to honour the data, and this is shown by the heavy red dotted lines in Figure 11b.The only feasible way to account for the offset is by postulating a fault, which I call the Misson Fault, trending NE-SW through the proposed development. It is constrained to lie north of the Rocket Site borehole, which lies on the trajectory of the proposed horizontal well. Geometrically, the data could be also fitted by a sinistral wrench fault, but since this style of faulting does not occur in this region, such an alternative explanation is unlikely.

The fault may be curved, but interpreting it as rectilinear fits better the fault style in the area. The trend also matches that of the coal seam faults seen in the Rossington colliery data (Fig. 8). The vertical displacement on the Misson Fault in the near-surface is of the order of 30 m; this is calculated as the lateral offset of the feather-edge (1800m) multiplied by tan(1º) .

The existence of the Misson Fault is supported by the several references to springs in the locality. It is true, as the Applicant observes, that springs would be expected at the feather-edge of the MMG – but if so, as seems reasonable, why only here and not elsewhere along the boundary? In fact the springs are present here because of the coincidence of the edge of the sealing overlying MMG with the fault cutting across the boundary; the fault is even more transmissive than the unfaulted aquifer, the SSG - hence the springs.

3.3.5 Conclusions on faulting at the proposed development

There is ample evidence of faults, with throws of 20 m and more in size, in and around the site. The Applicant's assertion that no faulting is seen is unfounded. Moreover, there is a significant fault, the Misson Fault, running right through the site.

3.4 Fluid flow through permeable layers and up faults

Appendix B discusses a recently-published case history from Pennsylvania in which irremedial contamination of water wells and of a major river occurred as a result of fracking. The pathways from depth to the near-surface involve a combination of uncased vertical wells, passage along near-horizontal bedding (rock layers), and vertical passage up previously unmapped faults. The contamination occurred within a few months of fracking.

Appendix C is a summary review of the state of research by computer modelling of migration of fluids up faults or fracture zones. This research field is relatively new, having only been started in the last five years or so. Many different approaches have been taken, both within the context of geological assumptions and of the mathematical basis of the modelling, within the wider context of how and whether such contamination can occur. In summary, this is a rapidly evolving field, but there is agreement that contaminated fluid from depths of 1-3 km can reach the near-surface within timescales of less than 10 to up to 1000 years. The Pennsylvania case history tends to support the low end of this range of timescales. Gas can migrate up to groundwater supplies in a matter of days or weeks.

4 IMPLICATIONS FOR ENVIRONMENTAL CONTAMINATION

4.1 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 a Halliburton petroleum engineer (Warpinski 2011):

> "*Any amount of height growth out of zone is undesirable because it wastes fluid, horsepower, chemicals, and time. The point of hydraulic fracturing is to stimulate the reservoir, not the unproductive rocks around it.*"

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 (Pennsylvania), 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 probability 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.

Appendix B, mentioned in section 3.4 above, recounts a case history from Pennsylvania in which fracking has undoubtedly caused pollution of drinking water supplies.

4.2 Evidence of seeps

Selley (1992) has described and tabulated 173 occurrences of surface petroleum seepages and impregnations in the UK. The East Midlands is absent from his compilation, but this omission is justified by the following statement:

> "*It was felt unnecessary, however, to document the numerous reports of petroleum from the Upper Carboniferous Coal Measures. This would have been the study of a lifetime, if indeed it could be accomplished.*"

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."

The well to which Selley refers is Preese Hall-1 in the Fylde, drilled by Cuadrilla in 2011. Selley depicts Everton-1 (2012, fig. 9) as a 'gasfield or discovery'. DECC (2013) mentions, under the heading 'Other Significant Discoveries' that the well tested a modest quantity: 3 mmcfd of gas and 20 bpd of condensate from Alportian (Namurian) sandstones. Everton-1 was drilled by Enterprise in 1988, but there is no mention of an Everton gas field in Fraser and Gawthorpe's comprehensive atlas (2003); therefore it should be regarded as a very minor discovery. Neighbouring well Everton-2 is a much more recent coal bed methane well which terminated in the Triassic. However, the relevance herein of the Everton gas trap is that the Upper Carboniferous Passage Group, to which the sandstone belongs, must be at least partially, if locally, sealed by the overlying Lower Coal Measures – but only in the absence of faults.

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 advanced 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 (Aminzadeh *et al.* 2013).

In conclusion, the Earth is far from perfect at keeping hydrocarbons trapped underground.

4.3 Groundwater resources

4.3.1 Provision of inaccurate and misleading geology by the Applicant

The Applicant has provided a groundwater map (Appendix F figure F1) which shows the groundwater contours in the SSG. The map shows the drawdown of contours around abstraction boreholes. The map and its accompanying inset cross-section (reproduced in Figure 6a) of the path to be followed by the horizontal well are highly misleading, in that they seek to distance the Principal Aquifer, the Sherwood Sandstone Group, from the drill bore:

"*As shown on Figure F1, the sub-surface works pass beneath the Source Protection Zone 3 but at considerable depth below the base of the Sherwood Sandstone Aquifer. Due to the significant thickness of strata between the sub-surface works and the aquifer there is considered to be no potential for the sub-surface works to impact on water quality in the aquifer*."

The figures quoted by the Applicant in both cartoon cross-sections (Figure 6) contain gross errors. Firstly, we compare the cartoons with an annotated version of the BGS cross-section traversing the Doncaster 1:50,000 geological map. This cross-section passes the proposed development 1.8 km to the north. The annotated cross-section is shown in Figure 12. It has been vertically exaggerated by a further five times, on top of the original's x2 exaggeration, so it is now x10 vertically exaggerated. The hydrogeological implications of this cross-section are discussed below.

Secondly, I have redrawn the Applicant's cartoons (Figure 6) as a properly scaled cross-section along the line of the proposed horizontal borehole. This is shown in Figure 13. The Rocket Site borehole is projected onto the section from 55 m to the SE. The position of the Misson fault is uncertain by about ±150 m either way along the section from its marked place, but it has to lie to the NE of the Rocket Site borehole. I have put an arbitrary slight hade (inclination from the vertical) on the downthrown side, and retained a constant estimated 30 m throw for the whole depth. The actual dip and the throw may be somewhat different.

Formation tops from Everton-1, some 5 km along strike to the south, and Scaftworth-B2, 6.6 km to the SW, are used to estimate the thicknesses of the Lower Coal Measures and the Millstone Grit. According to the BGS (Andrews 2013) the Bowland-Hodder Unit reaches more than 2 km in thickness (Fig. 4), of which only 234 m was penetrated at Scaftworth-B2. The Applicant's cartoons (Figure 6) lump together the Millstone Grit and the Bowland Shale into one geological unit, the thickness of the Bowland Shale being stated as about 300 m. Even if this last figure is supposed to represent net shale in the upper Bowland Unit only, the actual figure for this is 474 m at Scaftworth-B2 (Andrews 2013). Such errors are unacceptable.

4.3.2 Hydrogeology at the site

The hydrogeological summaries on the left-hand side of Figure 13 are taken from the BGS:

> "*The Millstone Grit constitutes a multilayered aquifer in which the thick, massive grit and sandstone horizons effectively act as separate aquifers with the intervening mudstones and shales acting as aquicludes or aquitards.*"
>
> "*The Coal Measures Group form* [sic] *a complex multilayered minor aquifer. Argillaceous strata predominate, acting as aquitards or aquicludes, isolating the occasional thicker sandstone horizons which effectively act as separate aquifers.*" (Jones *et al.* 2000, pp. 178-180).

The 174 m thick Permo-Triassic sequence below the SSG comprises two Magnesian Limestone aquifers with a combined thickness of 93 m. They are separated by marls which act as aquitards. Allen *et al.* 1997 state:

> "*Further south* [from the Durham area] *it is divided into two: the Upper and Lower Magnesian limestones, again separated by marls and siltstones. The limestones comprise compact fractured dolomite, which is brecciated and cavernous in some areas … There is some hydraulic continuity between the* [upper and lower] *units and they are generally treated as one aquifer. ... however the permeability of the whole aquifer is extremely variable as a result of the fracturing.*"

The Magnesian Limestone is classified by the EA as a Principal Aquifer (see, for example the BGS web page:

http://www.bgs.ac.uk/research/groundwater/shaleGas/aquifersAndShales/maps/aquifers/home.html).

As seen in Figure 13, these two aquifers lie between 338 m and 475 m depth, and will therefore contain fresh water. Since these aquifers (or effectively one aquifer, following the BGS view stated above) lie shallower than 500 m below the development site, they (or it) have to be considered as potentially at risk as well as the SSG aquifer.

The Sherwood Sandstone Group is a Principal Aquifer. It is at outcrop above about half the length of the proposed horizontal well, and covered by about 30 m of Mercia Mudstone Group to the NE of the Misson Fault.

4.3.3 Extent of the Sherwood Sandstone Group aquifer

The EA defines groundwater Source Protection Zones (SPZs) to show the "*risk of contamination from any activities that might cause pollution in the area*". The aim is to protect "*groundwater sources such as wells, boreholes and springs used for public drinking water supply.*" (from the EA website:

http://apps.environment-agency.gov.uk/wiyby/37833.aspx).

The proposed development lies within the total catchment, SPZ 3, defined as:

> "*the area around a source within which all groundwater recharge is presumed to be discharged at the source. In confined aquifers, the source catchment may be displaced some distance from the source. For heavily exploited aquifers, the final Source Catchment Protection Zone can be defined as the whole aquifer recharge area where the ratio of groundwater abstraction to aquifer recharge (average recharge multiplied by outcrop area) is >0.75. There is still the need to define individual source protection areas to assist operators in catchment management*".

There is a separate category, SPZ 3c, for "*subsurface activity only*". (EA website, op. cit.). But the Applicant's map (Appendix F figure F1) unaccountably omits this latter category, despite the fact that what it is seeking planning approval for undoubtedly constitutes 'subsurface activity'.

Let us be quite clear about the extent of the Sherwood Sandstone Group aquifer. It is an *unconfined* aquifer where it is at the surface, and *confined* where it lies below younger rocks. The BGS hydrogeological map of the northern East Midlands (Institute of Geological Sciences 1981) shows contours on the base of the SSG, which lies at almost precisely 300 m below MSL at the proposed development. The 500 m contour lies some 10 km to the east. This depth is generally taken to be the approximate limit of potable water within the aquifer, since below that depth the water will be saline. But the top of the SSG aquifer occurs at 500 m depth an additional 10-15 km further east of the site, so technically the extent of fresh water within the aquifer extends that distance eastwards, I.e 20-25 km to the east. It is therefore highly misleading of the Applicant to mark the limit of water to be protected as west of the site.

The BGS hydrogeological map also shows the zero height contour (relative to MSL) of the potentiometric surface of the aquifer lying some 350 m east of the development. This is the 'water table' (as of March 1978).

Allen *et al.* (1997) state, concerning the SSG aquifer:

> "*In Nottinghamshire the Sherwood Sandstone Group is an important source of water for Nottingham and Mansfield. … The aquifer is also usable to the east beneath the Mercia Mudstone outcrop to a greater degree than in the north*."

Therefore there is no question that the SSG aquifer extends under the entire development area, encompassing all the quadilateral area shown in the Applicant's site location plan where 'subsurface development' may take place. Indeed, the aquifer underlies all the PEDL licence area shown in Figure 3b.

The Applicant's statement that the "*Site is ... 300 m to the east of a Groundwater Source Protection Zone (SPZ) 3*" (Vol. 3 Environmental Statement para. 3.5.8) is wrong and misleading. The publicly available geology shows that the site lies partly in SPZ3 and partly in SPZ3c.

4.4 Potential groundwater contamination paths

4.4.1 Introduction

We can now synthesize the information of the preceding sections, by applying the general current knowledge about faults, sealing rocks, and seeps to the hydrogeology at the proposed development.

4.4.2 Regional groundwater paths

According to Downing *et al.* (1987) there are two major systems of groundwater flow in the East Midlands. Their cross-section and map are shown in Figure 14. The development locality is shown by the red rectangle in the cross-section of Figure 14a, and the site is marked on the map of Figure 14b by the red star. The SSG flow continues for a considerable distance to the east under the MMG cover rocks; it is northerly directed, with a small component down-dip to the east. The cross-section shows that flow goes down-dip (to the east) in the plane of section, and that flow does come up through the MMG. The groundwater is stated to be "*remarkably fresh*" even to the east of the Trent valley.

The flow within the Carboniferous is upwards and to the east below the proposed development, and separated from the SSG flow system by the Upper Permian.

4.4.3 Sealing or trapping property of the overburden

The MMG is clearly to be ruled out as a potential seal, or low permeability layer, because it is only a few metres thick, at most, at the proposed development. It may only act as a hydrogeological barrier for downward migration of contaminants from the surface. This problem is not of concern herein.

The rock sequences overlying the target shale are the Millstone Grit and the Coal Measures, both being multilayered aquifers totalling some 1500 m in thickness at the site (Figure 13). It may be argued that the alternation of aquifer with aquitard is sufficient to make the pair of sequences an aquitard overall, but this view does not take account of the faulting. Reference to Figures 8 and 12 shows that it can be inferred that faults cutting the entire pair of sequences occur every 1 km or so. The four faults marked to the left of the BGS cross-section of Figure 12 provide an incomplete picture, because the BGS Doncaster solid geology map and its cross-section, on which they are shown, were published in 1969, before the extension of the mineworkings to the east.

The alternating sequence of layered aquifers, together with the near-vertical faults, comprises a network of ascending pathways through the Carboniferous rocks up to the sub-Permian erosional unconformity (Figure 12). Note how some of the Middle and Upper Coal Measures sandstones and coals subcrop under this unconformity (coals are hydraulically transmissive, as any coal miner will tell you, because of the cleats and other fractures). The few metres of weathered rock at the unconformity comprise yet another transmissive pathway.

The sequence of two Magnesian Limestone Principal Aquifers, each below a marl, tends to separate the regional groundwater flow of the Permian-Triassic above (including the SSG) from the Carboniferous below. This is the Upper Permian Aquiclude shown in Figure 14a. However, local through-penetrating faults, as shown in Figures 12 and 13, will provide a connection, to say nothing of the Misson Fault at the site itself.

4.4.4 Hydraulic transmissivity of faults

Allen et al. (1997) discuss the physical properties of faults cutting the SSG:

> *"The hydraulic effects of faults in the Permo-Triassic sandstones vary widely, ranging from impermeable features which form barriers to groundwater flow, to*

highly transmissive structures which may act as recharge boundaries. Evidence for the presence of impermeable faults includes; drawdown effects during pumping tests, potentiometric head differences across the structures and hydrochemical changes across the faults, (for example the Roaring Meg Fault in Merseyside). Such faults can effectively dissect the aquifer into a number of distinct blocks. …

Permeable faults may be revealed as recharge boundaries during pumping tests. It is possible that increased transmissivity may result from a permeable brecciated zone adjacent to a fault, (the Topcliffe fault in North Yorkshire may act in this way), but direct evidence for such an effect is sparse."

The evidence for impermeability mentioned above refers to flow *across* a fault, but fault zones are highly anisotropic; that is, their physical properties along the fault are different from those across it. As shown in Appendix A, fault zones may be barriers to flow across them, while being transmissive along their length (Figure A1).

I have reviewed the literature on fault permeability (Appendix A) and conclude more pessimistically (and by applying the precautionary principle) that faults should be assumed to be transmissive unless we have positive evidence to the contrary.

In the case of fracking, 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. Being more buoyant, the flowback and/or produced water will therefore have a propensity to flow upwards and displace the brine downwards. Free, or fugitive, gas such as methane will, of course, migrate very rapidly, possibly in days (Appendix C). The effects of liquid contaminated groundwater migration may take months, possibly many years, to make themselves felt.

4.4.5 Conclusions on contamination risk

The Applicant has provide only minimal, but at the same time inaccurate, geological information. The Applicant's presentation of the hydrogeology, and of protection of the Sherwood Sandstone Principal Aquifer, is highly misleading. No mention has been made of protection of the other Principal Aquifer, the Magnesian Limestone below the site.

There is a myriad of potential contamination paths from the Bowland Shale, once fracked, to both principal aquifers. Even discounting major faults, the overburden itself largely comprises rocks that are highly transmissive.

No details whatsoever have been provide by the Applicant on how the two wells will be cased to mitigate contamination risk. In fact, it is not even clear whether the deeper portions of both wells will be cased at all. We have no clear idea, due to the inaccurate geological account provided by the Applicant, how deep each well will penetrate, and at what depth it will terminate. The provision of such information is normal practice.

Even if fracking is not carried out, the provision of insufficient and/or misleading information by the Applicant is unacceptable, and is a sound basis on which to refuse the application.

5 DISCUSSION AND CONCLUSIONS

5.1 Misleading and/or incomplete aspects of the application

Here is a list of the misleading and/or incomplete aspects of the application, summarised from the documentation above:

1. The horizontal appraisal well serves no useful purpose, other than as the preparatory hole to be fracked.
2. No details are provided as to what 'evaluation' will be carried out in this well.
3. No accurate depths or prognoses have been provided for either the vertical or the horizontal well, contrary to normal practice.
4. No details of the well casing programme have been provided, contrary to normal practice.
5. The locations of the two yellow-hatched local search areas have not been justified, and have probably been selected using non-geological or non-exploration criteria.
6. The statement that slant drilling from outside these areas to a target within would not be possible is erroneous, given the 1500 m or greater depth to all the targets.
7. The Millstone Grit 'secondary target' is vague and incompatible as a viable conventional hydrocarbon prospect within the small area of the two local search areas.
8. No mention is made of the significance or otherwise of the minor gas discovery at Everton-1, a 1988 exploration well drilled 4.9 km south of the site and within the 3D seismic survey area.
9. The so-called 'Carboniferous Limestone Supergroup' tertiary target (presumably a conventional prospect) does not exist as a recognised rock formation east of the Pennines, therefore this target is undefined; the Craven Group does not belong to this Supergroup.
10. The secondary and tertiary conventional targets appear to be fictitious, inserted as a cover to disguise the true aim of the drilling, which is unconventional.
11. The borehole and well data compilation allegedly used by the Applicant in preparing the application is grossly incomplete.
12. Nine boreholes or wells which should have been considered in the application have not been included.
13. Four existing wells said to have been used have all been mispositioned, one by over 2 km; even the least mispositioned well, at 80 m off true, will have affected the well-to-seismic tie.
14. Cartoons have been provided instead of accurate scaled cross-sections of the expected geology, contrary to normal practice.
15. One of these cartoons mismatches the other by up to 50%.
16. The numbers quoted in the cartoons have gross errors.
17. The thickness given for the Bowland Shale (300 m) is less than one-tenth of the BGS estimate for the site.
18. No details for, nor examples of, the 3D seismic survey have been supplied.
19. The 3D seismic survey is manifestly inadequate for imaging the rocks at the target site, which lies in the fringe area of reduced 3D coverage.

20. The Applicant failed to incorporate 2D seismic data into its interpretation and assessment, to the detriment of the geological understanding.
21. The 3D seismic survey allegedly failed to reveal any faults, when in fact many examples of faults on all sides of the site can be seen on the existing 2D seismic data.
22. Coal mining and 2D seismic data evidence together suggest a fault density of at least one per kilometre, but the Applicant allegedly sees no faults.
23. There is strong borehole evidence for the existence of a NE-SW trending normal fault (the Misson Fault) traversing the site, but the Applicant failed to recognise this fault.
24. As a result of the above failure of elementary geology on the part of the Applicant, most or all of the site may be sited on the Sherwood Sandstone Principal Aquifer, and not, as claimed, on the Mercia Mudstone Group.
25. The Applicant has failed to mention the Magnesian Limestone Principal Aquifer, which runs at less than 500 m depth below the site and will therefore hold potable groundwater and be at risk from the development.
26. The Applicant has wilfully misled the Council as to the extent of the Sherwood Sandstone Principal Aquifer below the site, despite it being clearly shown on BGS maps cited.
27. The two cartoons depicting the Source Protection Zone 3 of the SSG Principal Aquifer seek to mislead the Council into believing that the SPZ3 is well away from the proposed surface and subsurface activities.

5.2 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 Gainsborough Trough. Faults are complex features, and difficult to understand. In the USA faults at the fracking 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 with faults simply does not arise in the USA.

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 Gainsborough Trough has none of these crucial barriers.

5.3 Baseline surveys

5.3.1 Introduction

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 the Applicant to undertake before the drilling envisaged in the present application include monitoring of deep groundwater and possible natural leakages of methane.

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 Gainsborough Trough be constructed by an independent research organisation, but funded by the Applicant. 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. However, the universities of Edinburgh (Scotland) or Duke (North Carolina), for example, have the requisite international expertise and 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.

5.3.2 Deep monitoring boreholes

I have already called for a minimum of three monitoring deep boreholes around the site, to provide firstly the baseline, and then the ongoing monitoring, of any future shale gas production. In view of the geology (Figure 13) and the need to protect the Principal Aquifers *before* any contamination reaches them, it is evident that the boreholes need to be bored into the Millstone Grit at 1500 m depth. The Rocket Site borehole could be deepened to provide one of these boreholes.

5.4 Conclusions

The geology of the UK shale basins 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 in a matter of days or weeks.

The Applicant's geological model in the vicinity of the site is not based upon sound data, since the site lies on the very edge of the 3D seismic survey volume. There are many possible and likely flow pathways within the complex geology whereby fluids could escape upwards. This includes the possibility that the Principal Aquifers of the Sherwood Sandstone and the Magnesian Limestone lying directly above the fracking zone could be contaminated irreversibly. The risk, however small, of permanently contaminating one of England's main water resources should not be contemplated. It is reprehensible of the Applicant to have sought to minimise the true proximity of the site to two major groundwater resources.

The Council should consider the following questions when determining 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 does the appraisal of the horizontal well exclude fracking, given that without fracking it the well has no purpose?
- Why should parts of Nottinghamshire be put at potentially grave environmental risk, when the main beneficiaries will be the Applicant and the Exchequer?
- Will the trivially small Community Benefit of £100,000 for the site, plus the promise of a 1% of supposed production revenues (if they ever come to pass) 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, Scotland 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, as a minimum requirement request further information from the Applicant. Here is a list of what, in my opinion, is required:

1. Acquisition and processing reports and other information on the 3D seismic survey.
2. Example images from the 3D volume as detailed above.
3. Correction of maps to place all relevant boreholes and wells in the correct locations.
4. Inclusion of the existing available 2D seismic data to enlarge the geological interpretation around the site.
5. Well-to-seismic tie examples.
6. Velocity data used in time-to-depth conversion.
7. Structure contour maps for the principal seven horizons: Top Permian, Top Carboniferous unconformity, Top Middle Coal Measures, Top Lower Coal Measures, Top Millstone Grit, Top Bowland Shale, Top Craven Limestone Group.
8. Correction of the solid geology to take account of the Misson Fault.
9. Justification of how the two yellow local search areas were selected, together with an account of how the rest of the two PEDL licences were deemed unsuitable.
10. Detailed well casing programe for both wells.
11. Monitoring borehole plan incorporating the necessary deep boreholes to the Millstone Grit.
12. A full 3D hydrogeological model of this part of the Gainsborough Trough, constructed by an independent research organisation.

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

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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 Haynesville-Bossier shale play of east Texas and Louisiana is entirely omitted. The answer may simply be that Halliburton did not have contracts with 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; my study of that well shows that the vertical section of the well penetrated the Paddockhurst Park Fault without it being recognised, where it has a throw of about 10 m, and, further, it cut yet another unrecognised fault just where the drill string was landing horizontally in the target limestone.

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 <u>very large</u> 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 A1). 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.

APPENDIX B

CASE HISTORY OF CONTAMINATION OF DRINKING WATER BY UNCONVENTIONAL GAS PRODUCTION

An important paper about contamination of groundwater resources by fracking was published in the prestigious journal *Proceedings of the National Academy of Sciences* (of the USA) on 4 May 2015 (Llewellyn *et al*. 2015). The relevance for fracking in Lancashire, and for the UK shale basins in general, is that the research proves beyond reasonable doubt that contamination of drinking water was caused by passage of frack fluid and/or produced water through the geology. Up till now only faulty well construction has been implicated in the contamination process in the many US water contamination case histories.

Here is a brief summary of the history and results of the research. Chesapeake Energy, one of the major players in the Marcellus Shale play of Pennsylvania, drilled five wells in Bradford County, NE Pennsylvania, in 2009 and 2010. Contamination of private water wells in the vicinity (1200 m away) started almost immediately. In May 2011 the Pennsylvania Department of Environmental Protection fined the company $900,000. Chesapeake promised to pay for water treatment equipment on selected wells (http://thedailyreview.com/news/dep-fines-chesapeake-1-1m-for-violations-chesapeake-and-dep-come-to-agreement-1.1148316), while maintaining that the problems arose from “*pre-existing detectable levels of methane*”. The company had previously drilled three new water wells to replace three existing wells, but the contamination continued in these replacement water wells. In June 2012 the homeowners won a civil case against the company, which had to buy the properties and compensate the owners. The five gas wells were identified as the probable source of the stray gas.

The consultant hydrogeologists acting for the former homeowners are co-authors of the new research (Llewellyn *et al*. 2015). They used a sensitive analytical technique, novel in the field of environmental forensics, to identify the source of the contamination, which included white foam in the water wells, vapour intrusion in the basement of a house, and bubbling of gas in the Susquehanna River. The new technique identified a specific compound called 2-BE, used in drilling additives, as well as organic unresolved compound mixtures (UCMs) in the impacted wells, whereas no detectable levels of these compounds were found in the background and comparison samples. The analysis rules out the possibility of surface spills of drilling products or naturally occurring methane as sources of the contamination. The US Environmental Protection Agency (EPA) has suggested (2015) that 2-BE could be a useful indicator of contamination from fracking activities.

Figure B1 shows a schematic cross-section of the geology in the locality, redrawn and simplified from Llewellyn *et al*. Vertical exaggeration is about 2.5. The authors discuss how the contamination from the fracked layer, the Marcellus Shale, could have reached the water wells. The geological layers above the shale are gently folded, and a low-angle thrust fault (the solid red line in Figure 1) is interpreted from seismic data to run from the surface south at an angle of about 16º to 'sole out', or flatten asymptotically into, the Marcellus Shale.

The water wells lie in a narrow linear valley, one of two such parallel features seen on very high-resolution digital elevation models (DEMs) and interpreted by the authors as fracture zones, but not previously mapped on published geology maps. The word *fracture* implies a break or crack in the geology, but where the offset of the rocks on one side relative to the other is either unknown or is zero. This contrasts with a *fault*, in which there is a measurable offset. The fracture interpretation may appear on its own to be somewhat weak; however, a pump test (a technique in which water is removed from a central well, and the effect on other wells around it is observed) showed that the water flow pattern in the district is aligned along the valley. This suggests a deep structural control such as the putative fracture zone. The authors cite the evidence of small-scale joints seen in the rock exposures at the surface, also running in the same direction. In addition, but not mentioned by the authors, there are small normal faults elsewhere in Pennsylvania running in the same direction, and occupying the same structural location (on the foreland just in front of the Appalachian thrust belt) as this part of Bradford County. The two fracture zones identified by Llewellyn *et al*. are therefore probably minor normal faults.

The authors rule out the thrust fault as being a conduit for the contamination, even though it intersects three of the five offending gas wells below the level of the casing shown schematically in blue in Figure B1. This is because the dip of the fault (angle to the horizontal) is low, meaning that vertical rock stress will tend to keep such a fault held tightly shut. In addition, the rate of progress of the contamination would be very slow along such a feature, although I disagree with the reference cited here in support by the authors, which claims that the migration time would be thousands to millions of years. The thrust fault is an interpretation from seismic data which are not publicly available. I believe that this interpretation is, in any case, questionable, because elsewhere in NE Pennsylvania the few published interpretations of the subsurface faulting suggest that the thrust faulting is divided into two zones; (1) an upper set of shallow-angle thrusts which sole out downwards into the Tully Limestone (light blue layer in Figure 1), (2) and a deeper, steep set of thrusts or reverse faults which cut the Marcellus Shale. In conclusion the thrust fault, even if it has been accurately identified, is not suspected to be a pathway.

The authors conclude that the most likely pathway for the groundwater contamination is initial passage up the wells from the Marcellus, followed by lateral passage along bedding planes, inclined gently upwards to the south, and vertically upwards along bedrock joint planes and fractures. Overpressured gas well annuli are also implicated as one driving mechanism.

What are the lessons for the UK, and in particular the two applications to which I am objecting? The Bradford County experience shows that **faults and fractures can and do act as conduits for contamination by fracking and subsequent production**. This case history has occurred in geology that is simpler than that in northern Nottinghamshire.

Pre-drill water sampling is essential. UK legislation should also include a requirement for a benign unique marker product to be added to fracking fluid at each well, so that any contamination can be traced back to a specific well. Knowledge of the geological structure is clearly crucial. In my view this knowledge is currently inadequate in the area of Cuadrilla's licence. The density of faulting and fracturing in NE Pennsylvania is two to three orders of magnitude lower than it is in the UK shale basins, and yet a serious pollution incident occurred. The faults and fractures in the Gainsborough Trough are normal faults dipping at steep angles, and will not be held shut by vertical pressure, as appears to be the case in the thrust fault shown in Figure B1.

UK legislation and monitoring is way behind jurisdictions like Pennsylvania, despite government claims to the contrary. For example, the high annular pressure (377 psi) discovered at Preese Hall-1 in 2014 has been allegedly 'mitigated', and permission was then given to plug and abandon this well, with no ongoing monitoring. The Bradford County history also illustrates the long fight for remediation and justice that local residents have had to suffer. There is no reason to believe that the UK residents who become the victims of fracking contamination would fare any better.

APPENDIX C
HYDROGEOLOGICAL MODELLING OF FAULTS

C1 Introduction

This is a very brief summary of what has emerged as a large and complex field of study within the last five years. Only five modelling studies have been published to date, worldwide, on the influence of faults on fluid flow resulting from fracking operations. The aim of these studies is to create a computer model of the geology of interest, including natural geological faults, then add in the hydraulic fracturing process and predict where and how rapidly the fluids (gas and water) migrate. Given that such studies can be carried out on a PC, and can be achieved with a few months' work in the office, it is remarkable that so few have been undertaken.

The first mentions of faults as pathways for contamination by fluid flow in the context of fracking date from 2010. Figure C1 is an organogram showing the time evolution, progressively downwards, of the various reports and papers of which I am aware, and the main links between them. There are peer-reviewed reports published in established scientific journals, and non-peer reviewed reports listed in italics. The extensive and thorough, but non-peer reviewed German report of Ewen *et al.* (2012) was subsequently published as two peer-reviewed papers.

The organogram shows that the paper by Myers (2012) aroused a lot of interest, much of it being critical. Myers was the first to attempt quantitative hydrogeological modelling of a fault, and have it published in the peer reviewed literature, although the German study is contemporary with Myers, and more comprehensive.

Table C1 summarises the principal results of the five model studies that predict a time for contamination to ascend.

Year	Authors	Locality	Shale	Transit time (years)
2012	Myers	New York State	Marcellus Shale	<10
2012	German study	NW Germany	Various	30
2013	Gassiat *et al.*	Canada	Utica	<1000
2014	Cai & Ofterdinger	England	Bowland	100
2015	Reagan *et al.*	Generic	Generic	<0.7 (gas)

Table C1. Five numerical modelling studies of flow up faults

C2 Myers 2012a and critiques thereof

Myers used the Marcellus Shale as a basis for simulation, modelling it with MODFLOW-2000. His work was funded by two environmental NGOs. He assumed a 30 m thick layer of shale and an overburden of 1500 m thickness, based on typical values for southern New York state. He assumed a homogeneous vertical fault 6 m wide traversing the overburden comprising a mixture of sandstone with subordinate components of shale, mudstone and limestone. The imposed head provided the driving force for flow. He considered five conceptual models, the first of which is the steady state solution for the model with no faulting and no fracking. One of his models took into account the transient nature of the fracking, when a volume of water is injected, inducing changes in the target fracked shale. The fracking does not pass out of zone, i.e. into the overburden, but can connect with the fault.

His findings were that faults through the overburden could speed the upward travel time considerably in the steady-state model (before fracking). When fracking occurs the transport times of contaminated fluid from the fracked shale to the near surface can be reduced to a few tens of years "*or less*". He argues for pre-fracking fault mapping, a 'setback' distance between the frack zone and the nearest faults, and for a system of deep and shallow monitoring wells before development begins.

Saiers and Barth (2012), of Yale University, criticised Myers for neglecting variations in salinity in the groundwater at the Marcellus level, and also for ignoring temperature influences. A modelling approach that uses equations for coupled energy transport and fluid flow would be more realistic. The boundary conditions for the model are unrealistic, as is the assumed homogeneity of the overburden. Myers (2012b) provided a robust response to Saiers and Barth, disputing, *inter alia*, the latters' view of Appalachian geology, the requirement for a 3D model, the need to incorporate density variations, and details of the staged fracking process. He also pointed out that injected fracking fluid is less dense than the briny groundwater at the shale level, and that the resulting convective instability, ignored in his model, would enhance the upward flow.

Cohen *et al.* (2013), consulting hydrogeologists in Maryland, added additional criticism to the original Myers paper to that of Saiers and Barth. They were concerned about the constant-head assumption combined with fixed boundaries too close to the modelling zone, which forces the flow to be upwards, regardless of the particular scenario modelled. It also implies an unlimited source of water coming into the model from the formation below the shale. Myers's reply (2013) dismisses Cohen *et al*.'s claims of model errors as wrong, and goes on to restate his claim that his 2012 model is generally valid.

A group of authors representing the Pennsylvania Council of Professional Geologists and the Pennsylvanian Geological Survey (Carter *et al.* 2013) wrote a 13-page technical rebuttal of Myers (2012). They make a very sound point about the lack of faults in the Appalachian Plateau, and the nature of those that do exist:

> *"There are very few faults mapped at ground surface on the Appalachian Plateau, and those faults that have been imaged in seismic surveys are: 1) mostly confined to Middle Devonian and lower stratigraphic units, and 2) not vertically-dipping. "*

The relative lack of faults in the US basins connecting the fracked shale to the surface is a point I have long argued as one (of many) differences between US and UK geology. However, it does not prevent the Myers model being applicable to areas such as the UK shale basins where faults are prevalent, connect the shale to the potable groundwater zone, and are near-vertical.

Carter *et al.* assert that fracking has been employed for half a century. This is the common error of comparing low-volume fracking of vertical wells with high-volume fracking of extended horizontal wells ('super-fracking' in Turcotte *et al*.'s (2014) parlance). Other criticisms by Carter *et al.* on the hydrogeological modelling are similar to those of the other critics of Myers.

Despite its length and detail the Carter *et al.* rebuttal has been cited by just two documents. The first, by Meakin *et al.* (2013) is a review apparently extolling the benefits of shale gas; the second is a submission by Halliburton to the Environmental Protection Agency enclosing 17 pro-fracking papers for the EPA's consideration.

Flewelling and Sharma (2013) cite Myers (2012), but nowhere in the context of pre-existing faults. Flewelling *et al.* (2013) do refer to Myers in the context of faults:

> *"The notion of upward fluid migration, as discussed in this paper, assumes that naturally occurring joints and faults are sealed and that upward fluid migration can only occur along these features when they are opened or induced to slip. Not all*

faults are sealed, however, and other analyses have focused on potential upward migration through open, permeable faults [e.g., Myers, 2012]. There is an inherent paradox regarding permeable faults and upward migration, in that hydrocarbons cannot accumulate where there are permeable pathways for buoyant oil and gas to leak upward. Thus, the occurrence of permeable faults and significant hydrocarbon accumulations are mutually exclusive. For this reason, the issue of potential upward HF fluid and brine migration is only relevant where sealed faults are present (i.e., possible locations of hydrocarbon accumulation), and in these cases, fracture height growth and fault slip are the primary mechanisms to consider."

The supposed mutual exclusiveness of transmissive faults and hydrocarbon accumulations quoted here is wrong, and betrays a surprising misunderstanding of conventional hydrocarbon exploration, given that Flewelling and his co-authors work for Halliburton. In addition, the comment is superfluous in the context of fracking shale, because until the shale is fracked it is, by definition, impermeable. A shale may well be transected by permeable faults, but the contamination problem will only arise once the shale has been fracked.

Cai and Ofterdinger (2014), whose own fault modelling is discussed below, misunderstand the nature of faults in their critique of Myers:

"*... most importantly, upward flows in fractures were represented by a 6 m wide high-permeability column connecting the Marcellus Shale directly to the surface by using particle tracking method. The assumed 1500 m vertical fracture just represented one of the extremely rare cases of upward fracture growths. This model setting may be incapable of representing flow in an open fracture with a typical aperture of less than millimeters. In addition, the particle tracking method could not represent complex solute transport phenomena as it could not account for mass exchange between open fractures and the rock matrix.*"

Cai and Ofterdinger appear not to recognise that Myers was modelling a geological fault, not an upward-propagating frack of exceptional length.

C3 German study (Ewen *et al.* 2012)

This comprehensive study, funded by ExxonMobil Production Germany GmbH, was published in German (Borchardt *et al*. 2012), and is therefore not widely known. I have translated about two-thirds of it into English, for personal study. The English summary report (Ewen *et al.* 2012*)* does not provide details of the modelling. The report was later published as two peer reviewed papers, of which one (Kissinger *et al.* 2013) deals with the modelling, but without all the detail of the original German-language report. The report deals in detail with passage of fluids up faults.

Seven geological type-localities, or 'settings', were studied. One of them, Quakenbrück-Ortland in the Lower Saxony Basin, has a geological structure which is remarkably similar to the shale basins of the north of England. The modelling found that contaminated fluid could reach the groundwater resource zone in around 30 years.

C4 Gassiat *et al.* 2013

Gassiat and her co-authors are researchers at Canadian institutions. They modelled, using SUTRA-MS, the fluid transport up a 10 m wide fault zone; a width which they say is consistent with a regional fault having hundreds of metres of displacement. The fault is situated in a regional basin, with a shale having the properties of the Utica Shale being simulated. This shale has a low permeability; the value adopted is 10 ndarcy for unfaulted shale To contaminate the presumed shallow aquifer they find that the shale must be overpressured, and that it has to have been fracked. The timescale for the migration of contamination is of the order of 1000 years or less. The driving force for flow is overpressure in the shale.

They highlight some caveats in their modelling; single-phase flow only is simulated, and the salinity distribution assumed affects the migration time. An interesting and important result is that a tracer added to the shale fluid reaches the surface at 90% of its original concentration; in other words, 'slugs' of fluid travel upwards without getting significantly diluted. The 'dilute and disperse' model formerly used to justify ocean dumping of contaminants (for example, radioactive waste) does not apply to migration of contaminants up a fault.

Gassiat *et al.* were criticised by Flewelling and Sharma (2015), who make the same criticism of the Canadian work as others did of Myers, that is, that the faults in the region are not vertical, and that the modelling assumptions force the fluid to go upwards. They also criticised the permeability values chosen for the overburden, and the assumption that the tracer representing contamination is conservative.

In response, the Canadian group pointed out that the modelling was not specifically intended to represent the St Lawrence Basin; they merely used conveniently accessible data from that basin. They re-assert that continuous faults connecting the depth to the surface do exist, and that they are not necessarily self-healing. In summary, they conclude that their main original finding still stands, that "*fluid migration along permeable faults from hydrofracturing zones is plausible under some specific conditions and thus needs to be considered, and that assessment has to consider a long-term time frame.*" Regarding the generic tracer, they note that it could represent a conservative species such as chloride, which could degrade groundwater quality or even limit its use.

C5 Cai and Ofterdinger 2014

This modelling study concerns the Bowland Shale in Lancashire (Cai and Ofterdinger 2014). The authors built a layer-cake computer geological model based on the geology at the Preese Hall-1 well, then added in hydraulic fractures (fracks) in the Bowland Shale near the bottom of the model. No faults were built in to the model to start with. So the 11 geological layers, comprising overburden and underburden, plus the shale, is a realistic simulation of Fylde geology, but without any faults. In addition each layer is treated as anisotropic, with differing hydraulic conductivities. They did not have data on the physical properties of the Bowland Shale, so those from the Marcellus Shale were used as a proxy.

They used HydroGeoSphere subsurface flow code. The effect of faults was crudely simulated in some models by extending six of the fracks upwards into the SSG. They found that the SSG aquifer could become contaminated on the order of 100 years under certain conditions. Because they put in a sideways-directed head to simulate regional flow from the Bowland Fells west to the Irish Sea, most of the flow was diverted sideways within the Collyhurst Sandstone, which is a high permeability layer between the SSG (above) and the Bowland Shale at depth.

The Cai and Ofterdinger study is flawed as a fault study, principally because the representation of major faults by vertical fractures up to 1 mm in width is unrealistic as a model for major pre-existing faults. Their critique of Myers (2012), quoted above, reveals this misunderstanding. However, the study may be applicable for the unlikely case of fracks propagating a long distance upwards.

C6 Reagan *et al.* 2015

Researchers from the Lawrence Berkeley National Laboratory, funded by the Environmental Protection Agency (USA) have published the first of what is intended to be a series of papers on modelling of the impact of fracking. This paper (Reagan *et al.* 2015) studies two generic failure scenarios: "*(1) communication between the reservoir* *and aquifer via a connecting fracture or fault and (2) communication via a deteriorated, preexisting nearby well*." The results are similar in both cases, except that migration *via* the faulty well is faster. They emphasise that their study is parametric, using generalised representations of pathways that might lead to rapid gas transport. The depth to the fracked shale is shallow; overburden thicknesses (between the shale and the aquifer) were either 200 m or 800 m. The timescale for the modelling is limited to 2 years. Simulations (i.e. combinations of parameters) that show significant flow but where gas 'breakthrough' (into the aquifer) does not approach a steady state are reserved for a future paper.

The 3D finite element modelling was carried out with MeshVoro software using the TOUGH mesh format. Two-phase flow was modelled. The driving forces were buoyancy and fracking well pressure

Their conclusions, as stated in the Abstract, are principally that gas transport is aided by high permeability of the connecting pathway (fault or well) and its overall volume – an unremarkable result. They also conclude that production of gas from the shale will mitigate upward migration – again, not a surprising result.

The authors do not mention calculated breakthrough times either in the Abstract or in their Summary, Conclusions, and Comments section. For the fault simulations and an 800 m separation distance, the breakthrough times are of the order of 0.02 to 200 days (The former figure is under one hour). The times are shorter or longer depending on gas production strategy.

C7 Conclusions

All the five studies to date have their own flaws and limitations. How one defines the 'boundary conditions' is especially important, and can greatly affect the results. In short, the results depend largely upon how one sets up the model. For example, if one sets the fluid flow into the model to enter at the bottom, then naturally the fluid flow is going to be upwards. The Bowland Shale study (Cai and Ofterdinger 2014) did that, which is acceptable, but it also defined the MMG, the top layer, as impermeable. This is somewhat unjustified, as the MMG is poorly permeable but not a complete seal to fluids. So where does the fluid flow? In the Bowland study the flow is upwards and out to the side (actually out along the right-hand-side only, because a horizontal gradient, or 'head' was also defined to mimic the effect of regional groundwater flow from the Bowland Fells westwards towards the Irish Sea).

The Myers (2012a) study may not be applicable in the Appalachian Plateau, but there is no reason why it cannot apply to the UK basins, with their near-vertical faults. Similarly, the Reagan *et al.* (2015) gas flow study could apply to shallow shale layers in the UK such as in the Weald. The German study also has results applicable to the Bowland Shale basins because of the similar structural style.

In conclusion, modelling studies to date suggest that contaminated water from a fracked layer is likely to reach shallow potable water resources within a generation *via* faults. Transport of methane gas can be far faster; a matter of hours or days.

The case history discussed in Appendix B suggests that rates of contamination may be much higher than predicted by modelling.

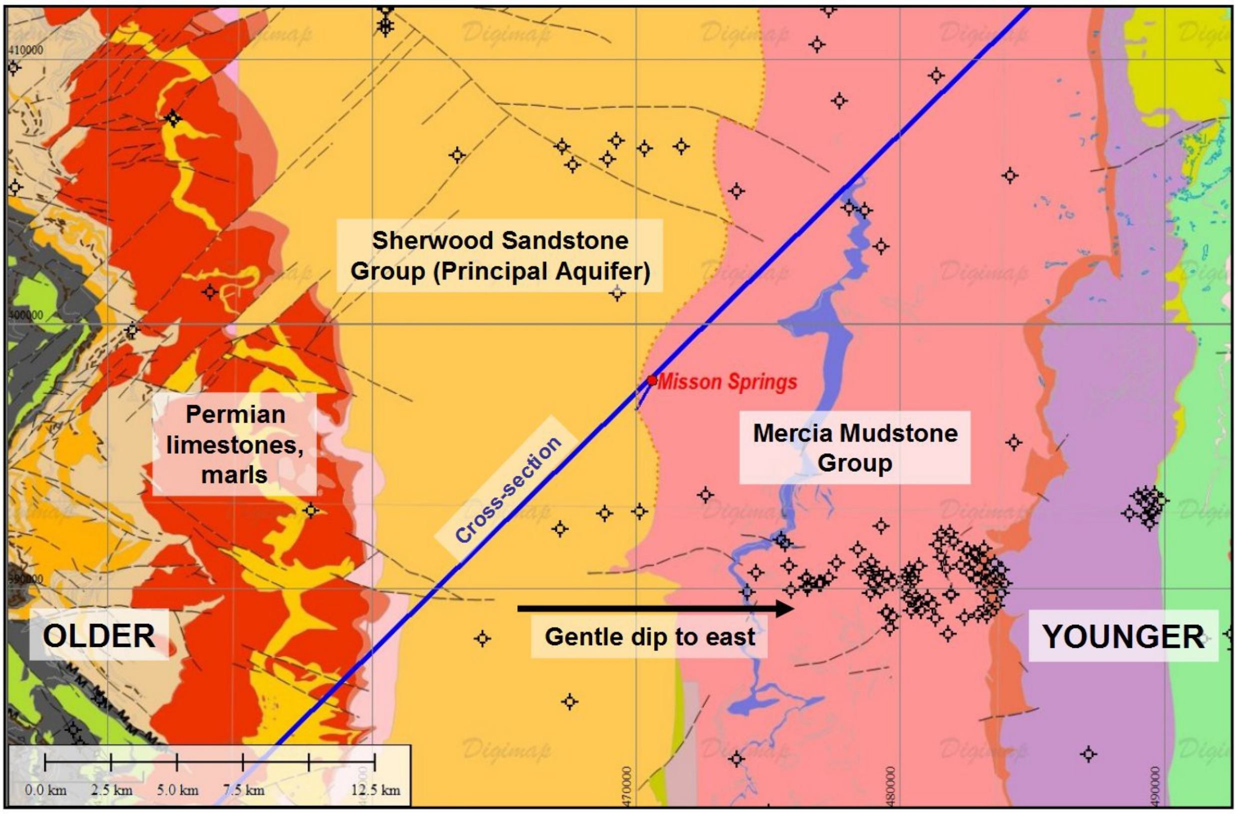

Figure 1. Regional solid geology around the Misson Springs site (red dot). The location of the BGS regional cross-section (reproduced in Figure 2) is shown by the blue line. Hydrocarbon wells are shown by the circle/cross symbol. The geology goes from old to young in an eastward direction.

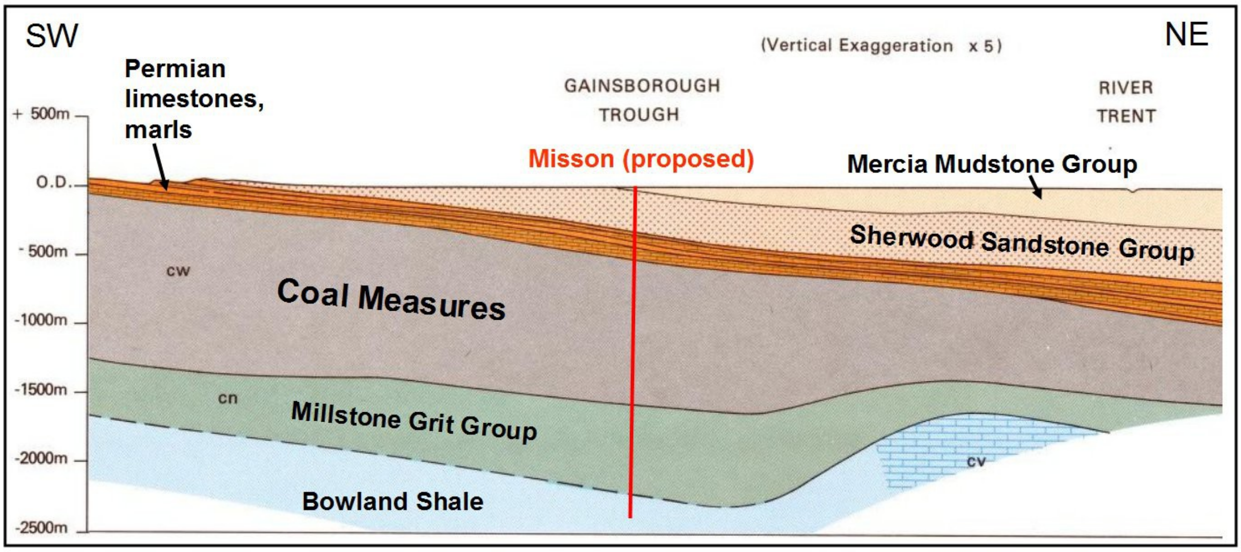

Figure 2. Part of the BGS regional cross-section from the 1: 250,000 Humber map, which passes through the Misson site (red line). The extract, which is about 40 km long, runs from Worksop in the SW to Scunthorpe in the NE.

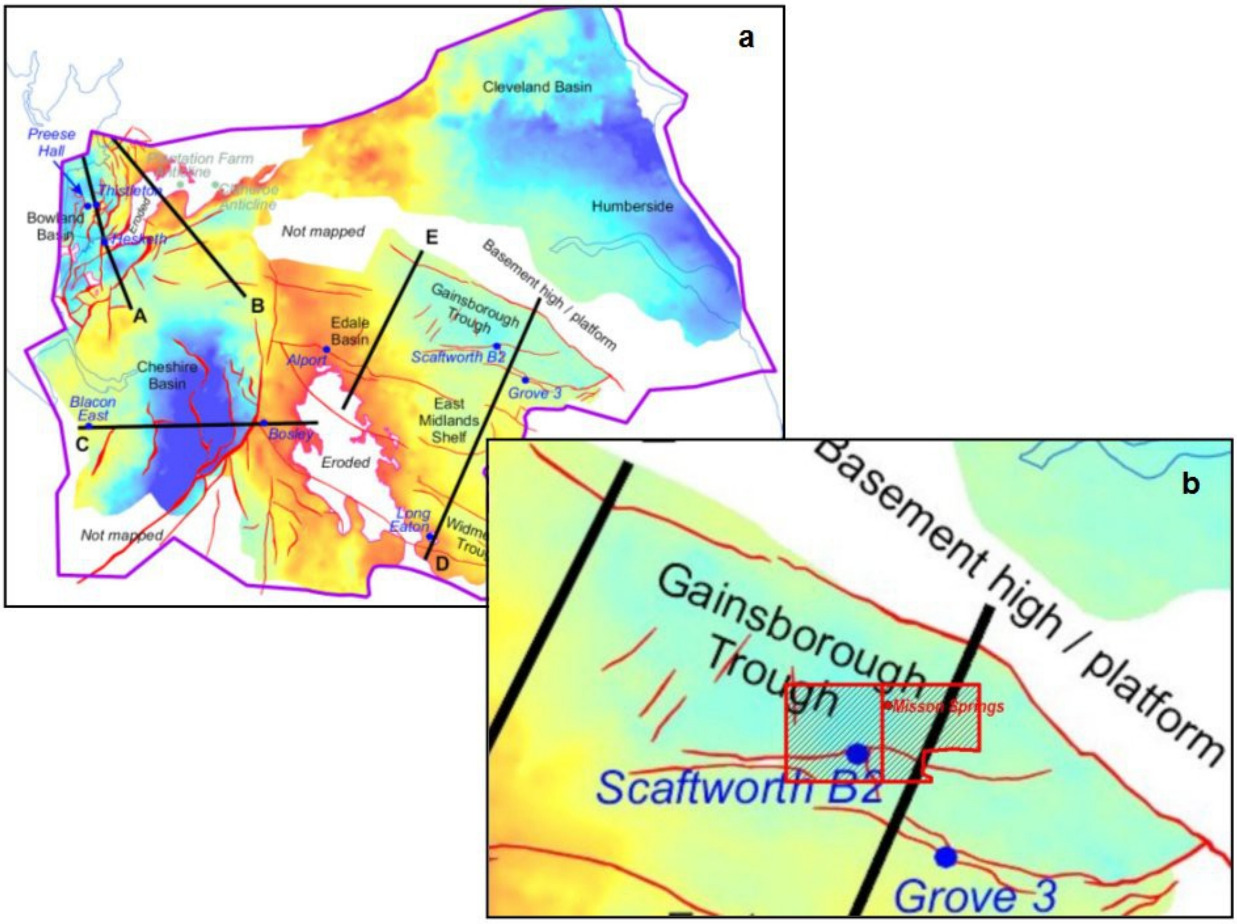

Figure 3. (a) Colour map of depth to the base of the Bowland Shale in the north of England (Andrews 2013). Dark blue is deepest, red is shallowest.

(b) Detail of the Gainsborough Trough showing the Misson Springs well (red dot) and the two contiguous PEDLs. Part of cross-section D is shown in Figure 4.

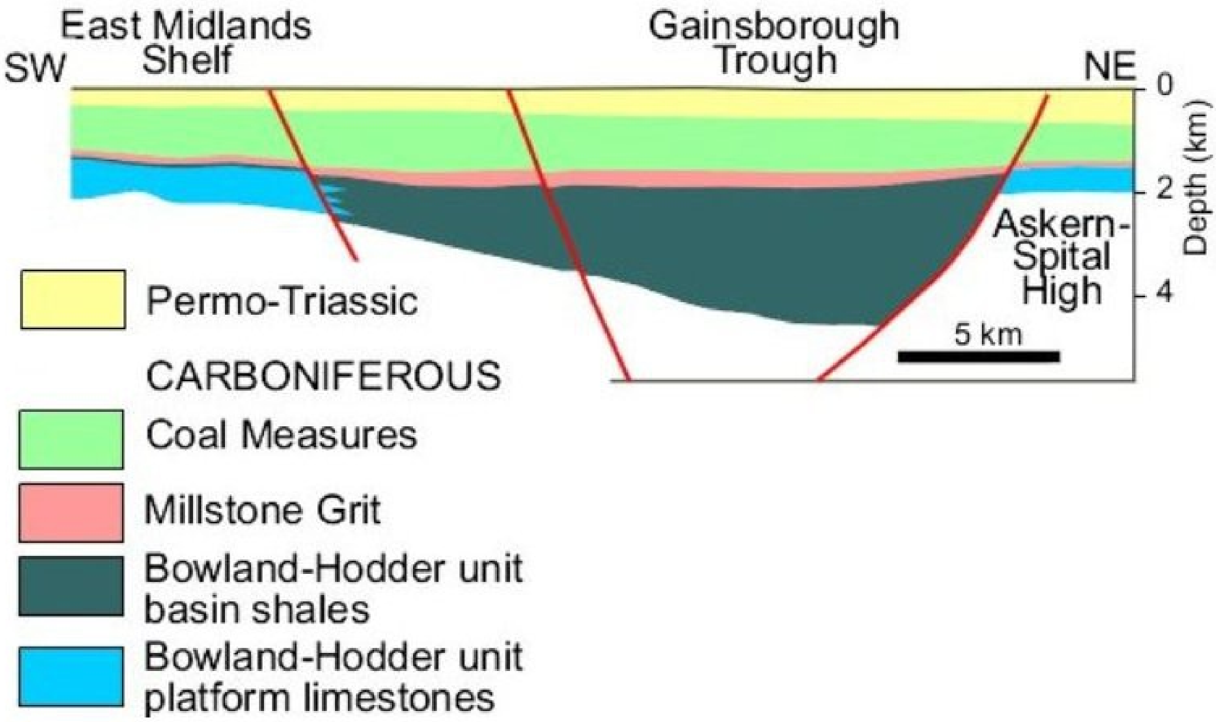

Figure 4. NE end of BGS cross-section D through the Gainsborough Trough (Andrews 2013).

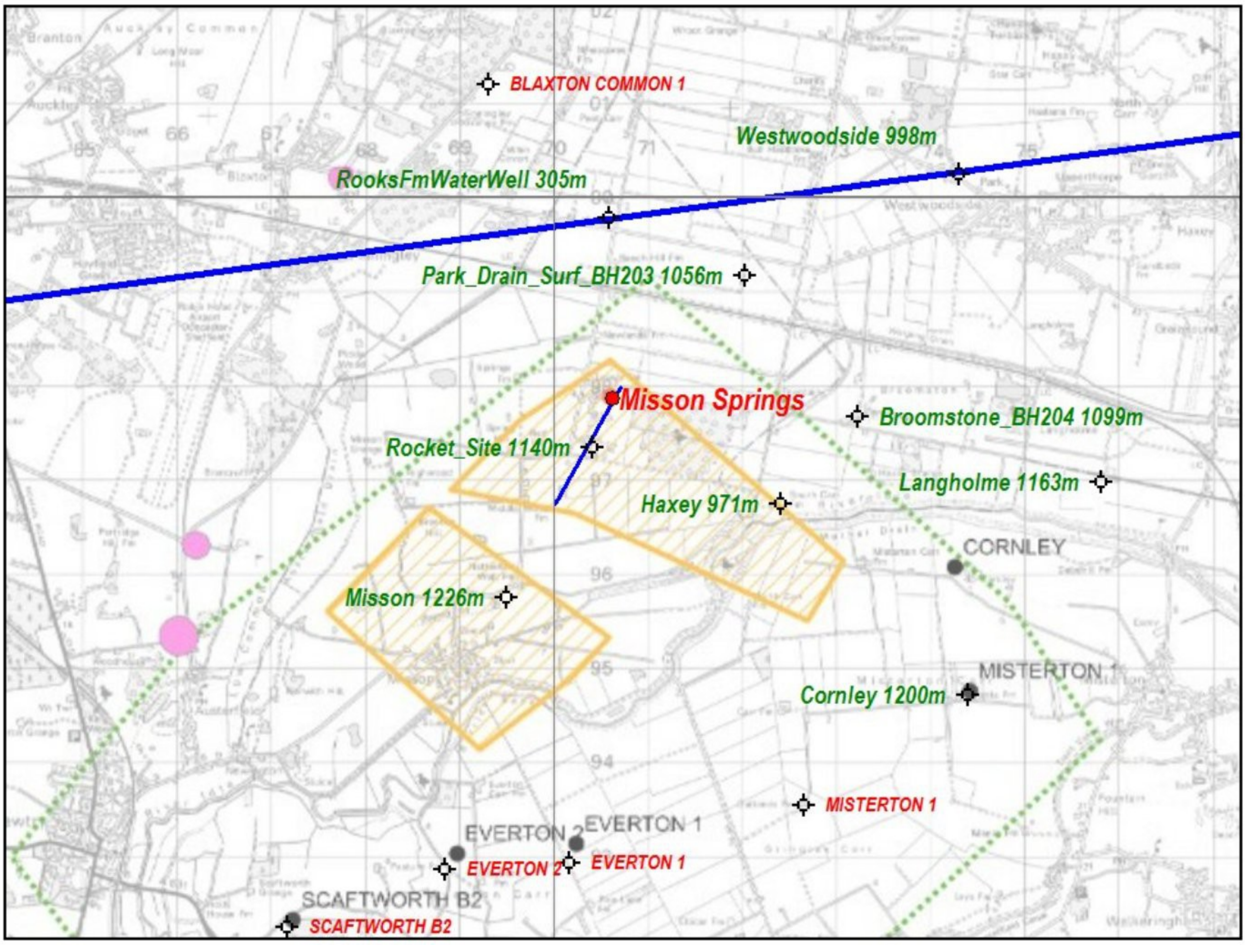

Figure 5. Reproduction of part of the Applicant's figure 22 showing the 3D seismic surface coverage area (green dotted line) and the detailed search areas (yellow hatching). Existing hydrocarbon wells as positioned by the Applicant are shown as black dots; the correct positions are shown by the circle/cross symbol and red upper case label. Deep water and coal boreholes are shown with their name and depth in green. The location of the BGS cross-section from Sheet 88 Doncaster, 1: 50,000 map is shown by the blue line.

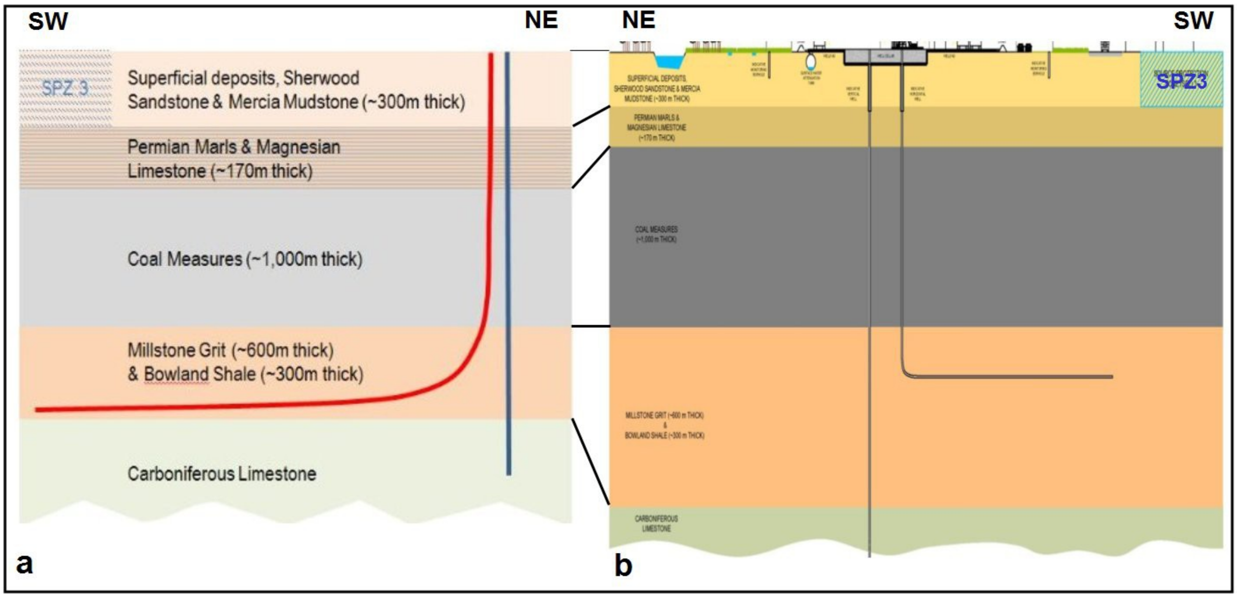

Figure 6. Two cartoons from the Applicant's drawings purporting to show the geology to be encountered. The right-hand picture has been mirrored for easier comparison of the two images. The two images have then been scaled so that they match horizontally at the surface and at Top Millstone Grit. There is no horizontal scale. SPZ3 is Source Protection Zone 3, misleadingly marked at the corner of each diagram, far from the wells.

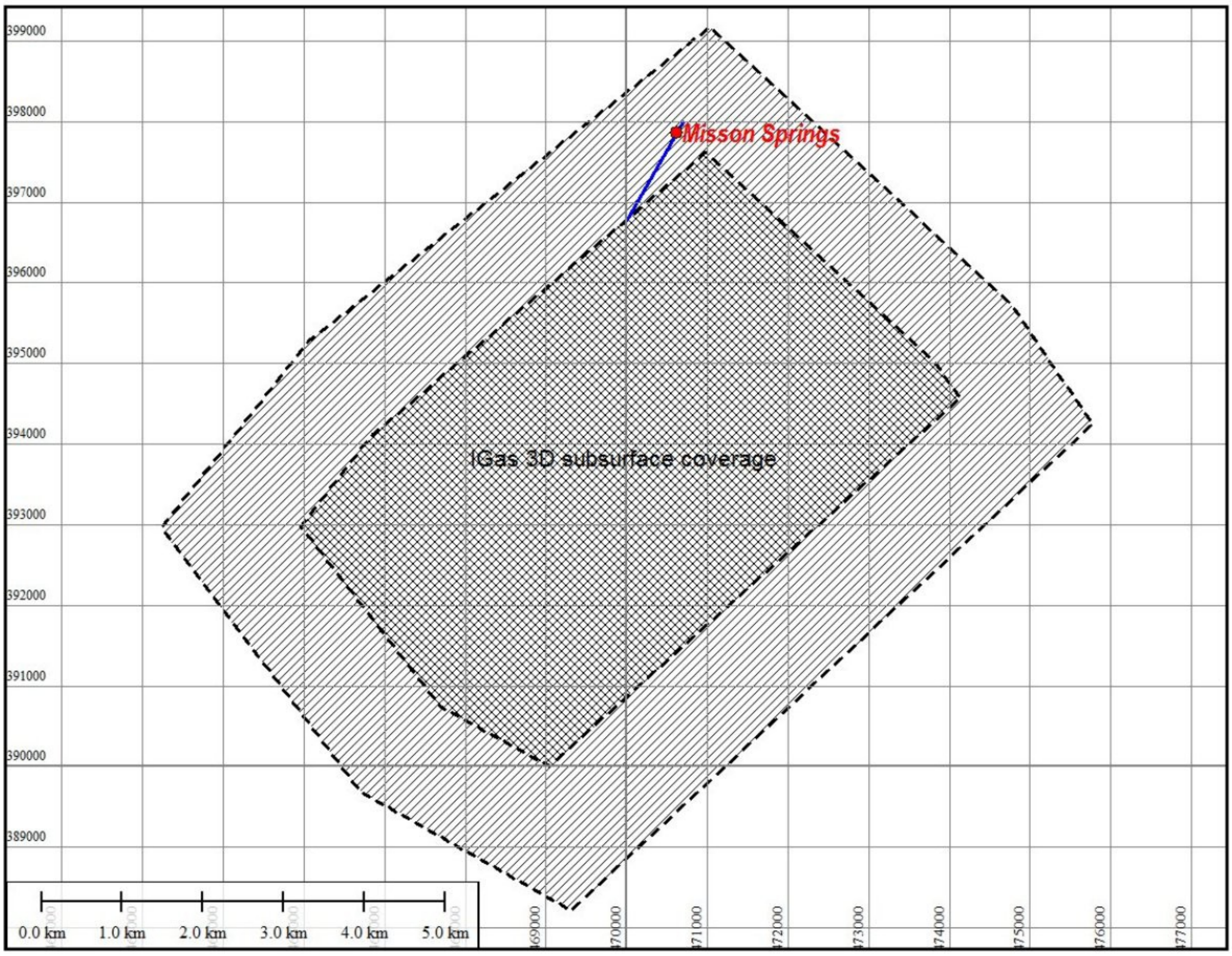

Figure 7. Surface coverage of the 3D seismic reflection survey (outer hatched area). The proposed Misson wellsite is shown by the red dot, with the proposed horizontal trajectory to the SW shown by the blue line. The inner cross-hatched area is the estimated subsurface coverage of the 3D seismic survey, assuming maximum source-receiver offsets of 3 km. This yieds a fringe around the subsurface coverage area in which the quality progressively diminishes to zero at the outer edge. The proposed wells lie in the zone of poor data.

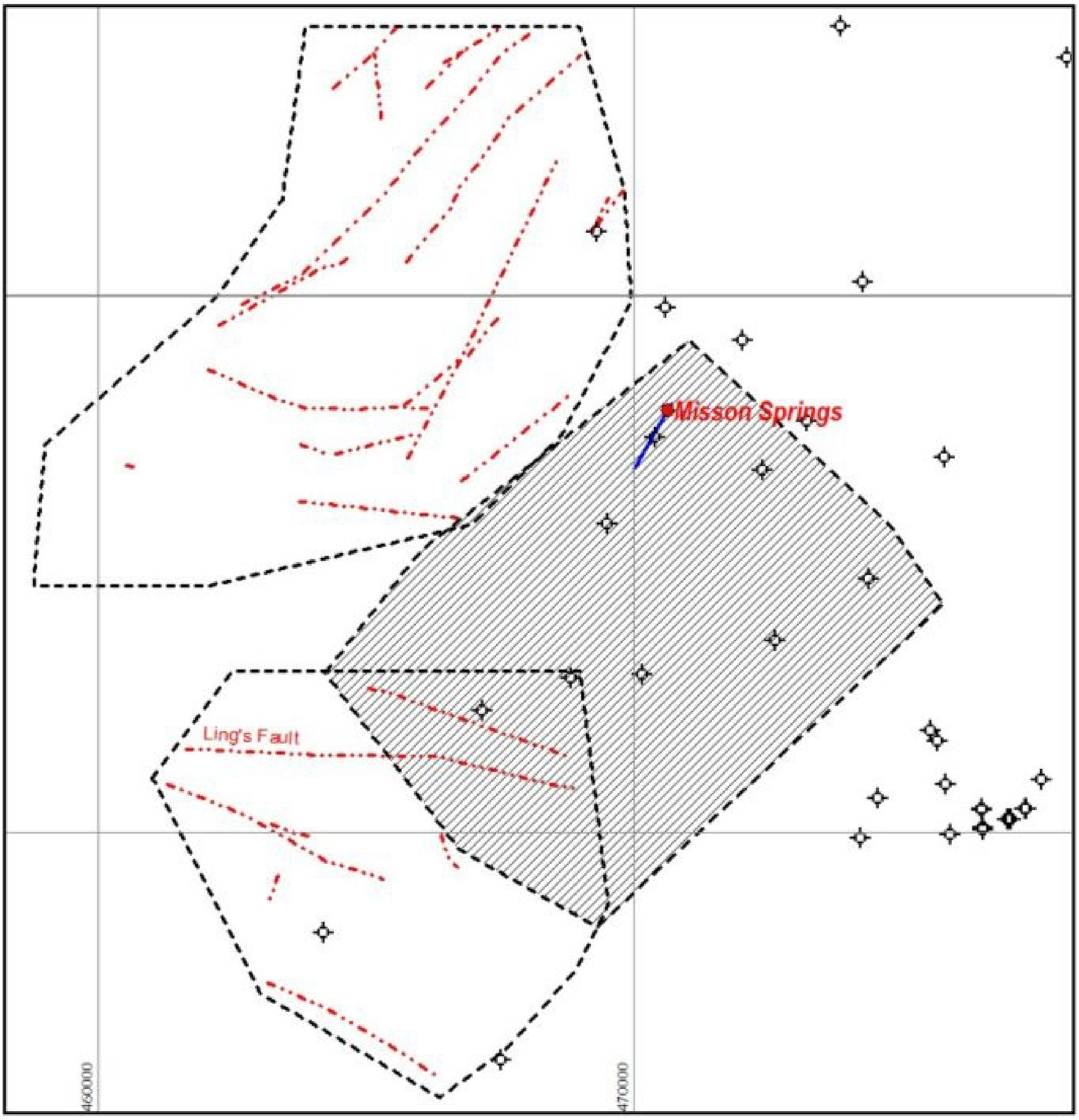

Figure 8. Faults identified at depth by coal mining (red dash-double-dot lines). The extents of the subsurface workings within which the faults are seen are marked by black dashed lines: northern area – Rossington Colliery, Barnsley Seam; southern area – Harworth Colliery, Deep Soft Seam. 3D seismic surface coverage shown by the hatched area. Hydrocarbon wells and other deep boreholes are shown by the circle/cross symbol. Ordnance Survey gridlines are shown at a 10 km interval.

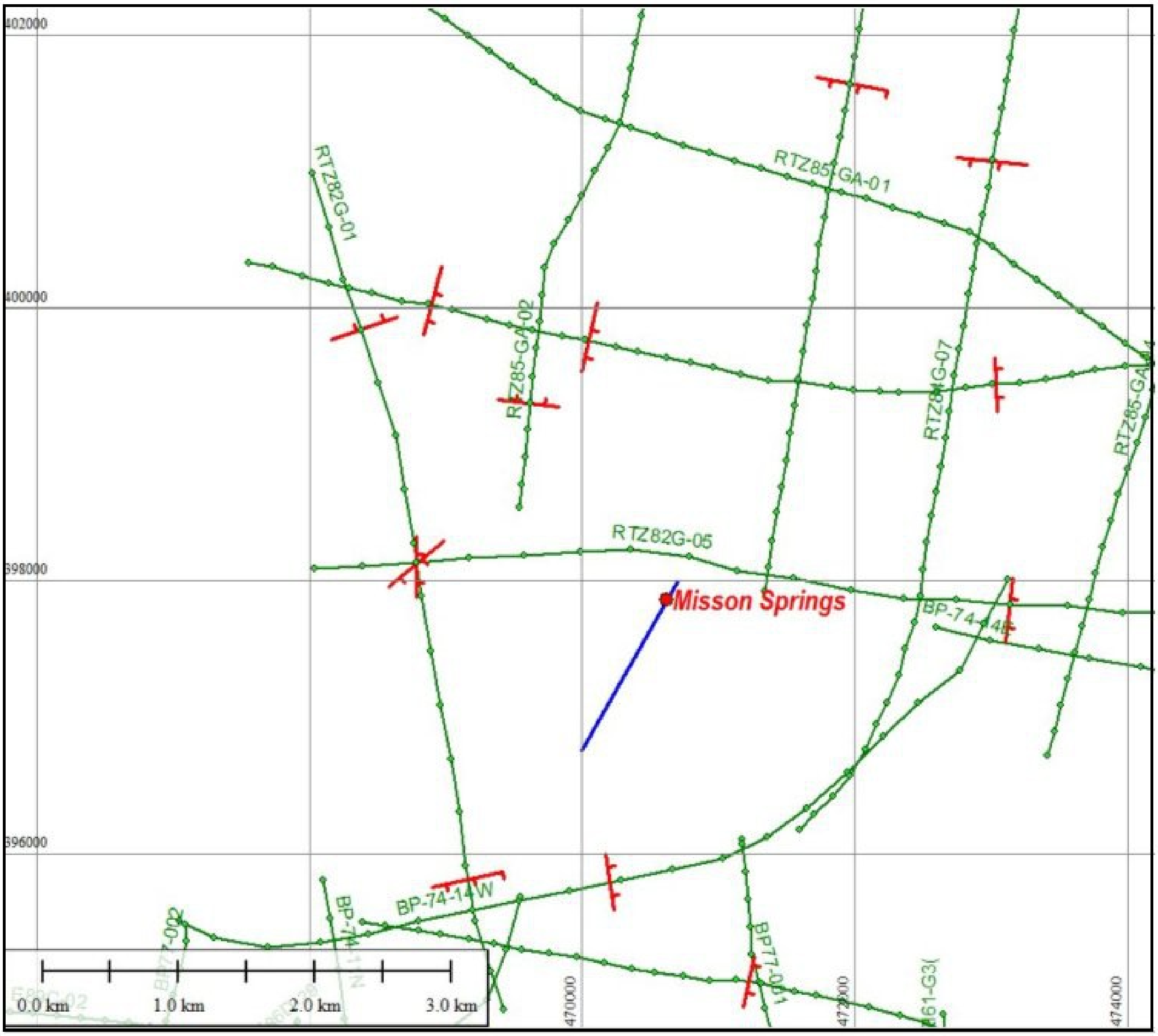

Figure 9. Existing 2D seismic reflection coverage around the site (green lines with shotpoints shown by dots). The Misson Springs proposed site is shown by the red dot, and the trajectory of the proposed horizontal well is shown by the blue line. Short red lines show faults that can be identified on the seismic data at the Top Permian, a very strong shallow reflector. Downthrown side is indicated by the teeth. The throws are of the order of 20-30 m. No attempt has been made to correlate the faults from line to line. Ordnance Survey gridlines are shown at a 2 km interval.

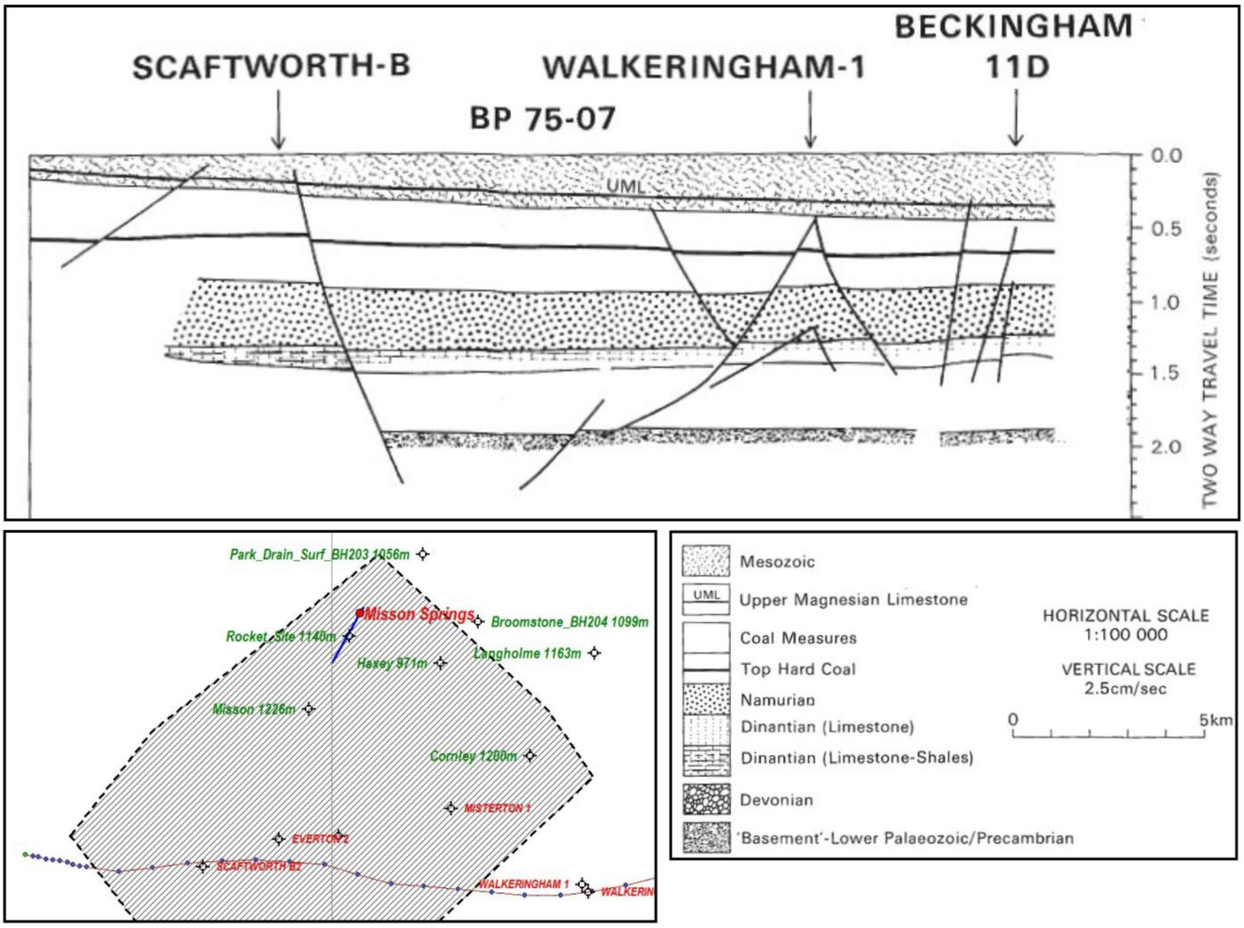

Figure 10. Part of the BGS-interpreted version of 2D seismic line BP75/07 (top). The E-W line runs through Scaftworth-B2 (lower left), about 6.5 km south of the Misson site, and within the area of the Applicant's 3D surface seismic coverage (hatched area). The horizontal scale shown in the key at the lower right is inapplicable to the extract; the distance from Scaftworth-B2 to Walkeringham-1 is about 9 km. Note that the faults marked towards the west end of the section cut the Mesozoic (Sherwood Sandstone) but they do not reach the surface because the seismic data cannot reveal information shallower than about 200 m (around 0.2 s of two-way travel time on the scale on the right).

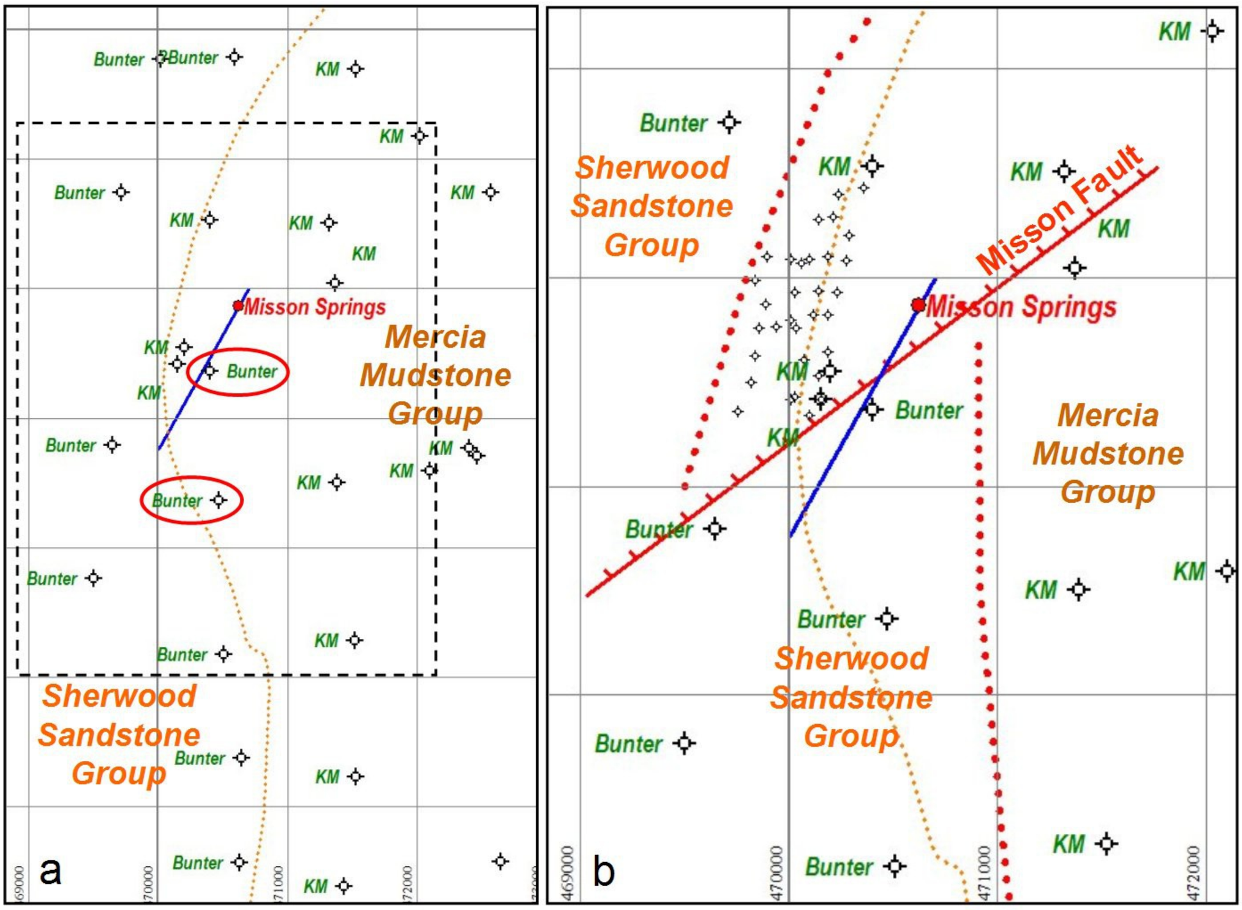

Figure 11. (a) Shallow boreholes proving Bunter (= Sherwood Sandstone Group) or Keuper Marl (KM = Mercia Mudstone Group) at subcrop below drift (unconsolidated material). The feather-edge of the MMG (the western limit where it wedges out), taken from the BGS Doncaster geology map, is shown by the yellow dotted line. But this boundary mismatches the two boreholes outlined by the red ellipses.

(b) Detail of the site locality (the black dashed-line rectangle in Figure 11a). The revised location of the MMG boundary is shown by the two red dotted lines. These honour the solid rock data as shown by the boreholes. Given the absence of folding, the only feasible way to explain the offset of the boundary of about 1800 m is by faulting. I have labelled this the Misson Fault, with a normal downthrow to the north.

Ordnance Survey gridlines are shown at a 1 km interval.

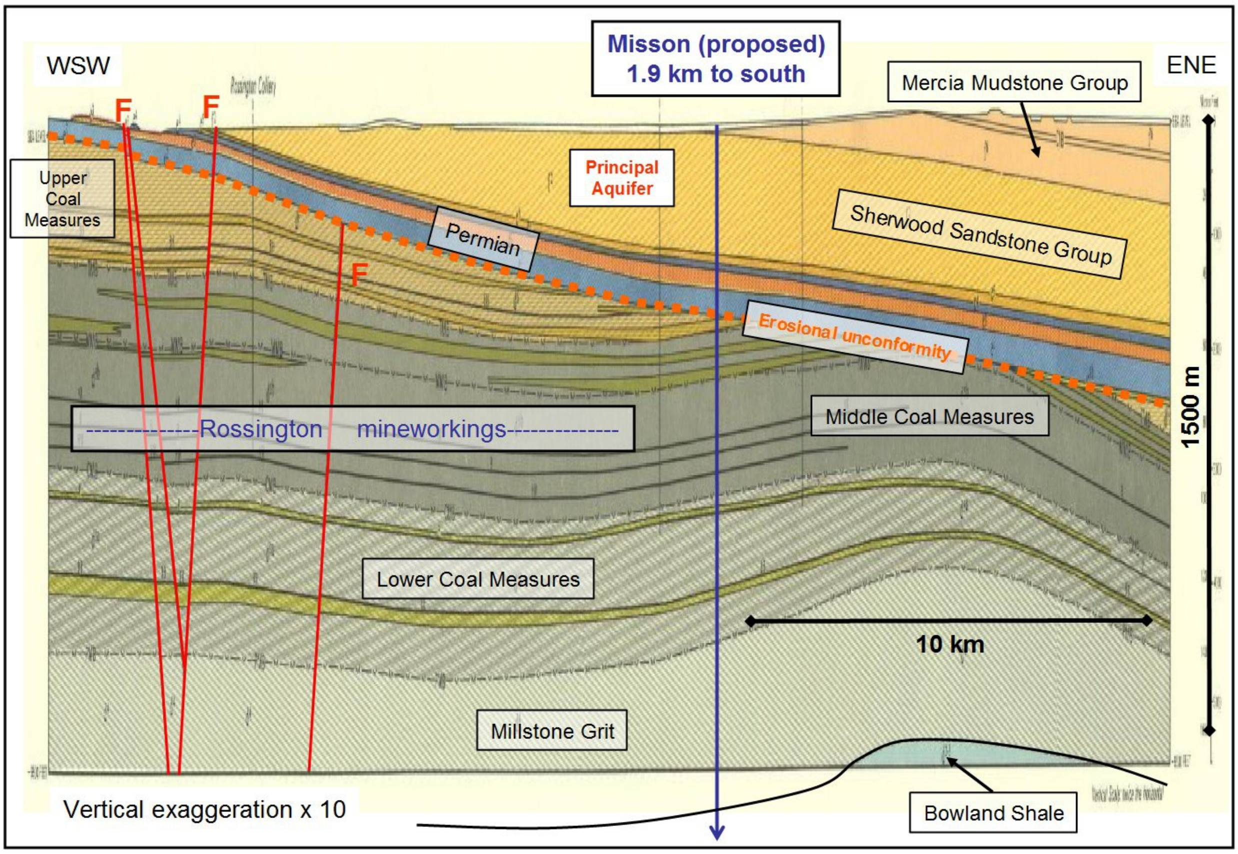

Figure 12. Cross-section from the BGS Doncaster 1:50,000 solid geology map, horizontally compressed by x5; the total horizontal compression is x10. The proposed Misson site is 1.9 km to the south of this cross-section; I have located it at the feather-edge of the MMG. The Rossington mineworkings have been extended about 8 km further east than the extent when the map was made, and more normal faults than shown here have since been found in the Coal Measures.

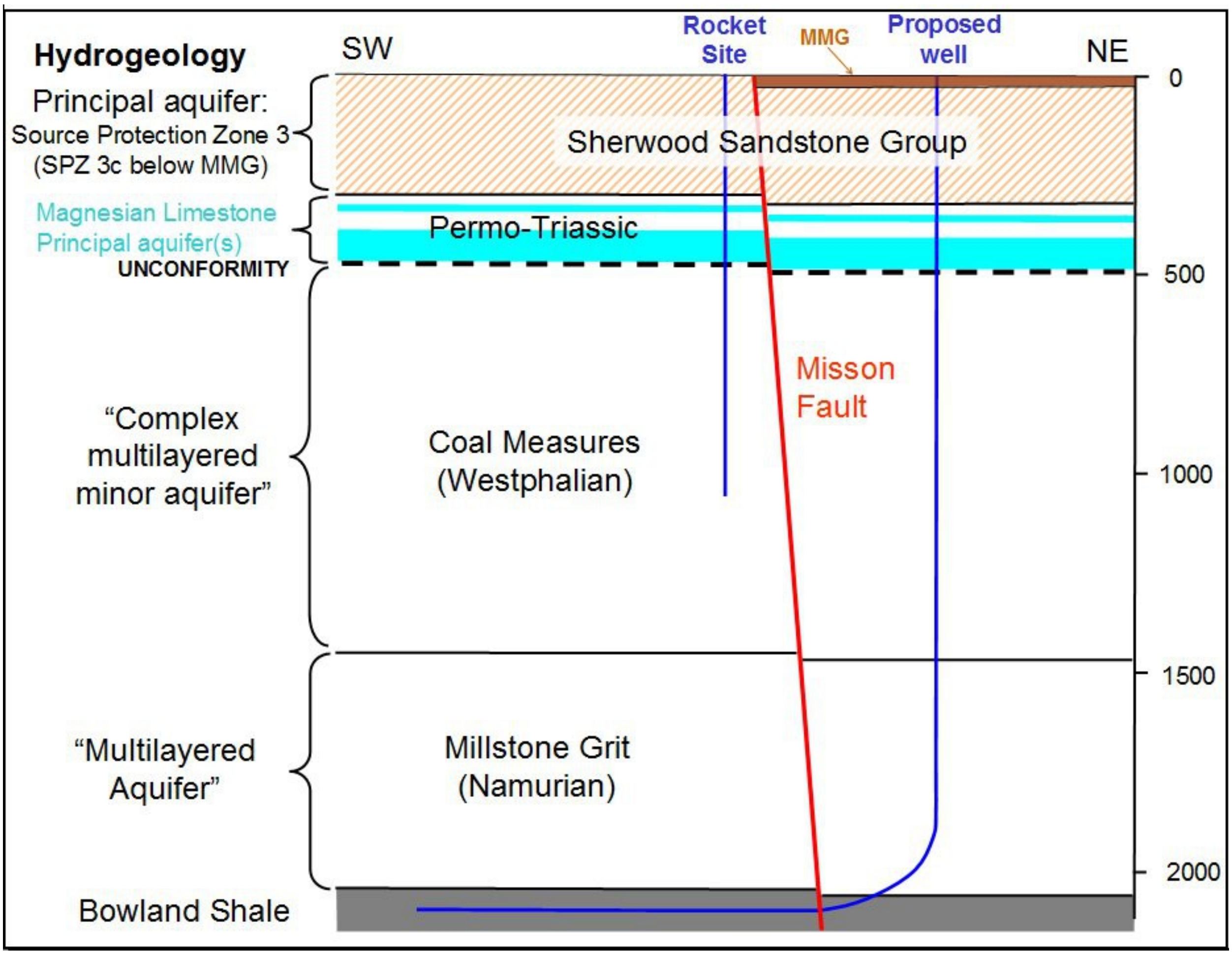

Figure 13. Properly scaled cross-section along the line of the proposed horizontal borehole, for comparison with the Applicant's cartoons (Figure 6). No vertical exaggeration. The Rocket Site borehole is projected onto the section from 55 m to the SE. The position of the Misson fault is uncertain by about ±150 m either way along the section from its marked place, but it has to lie to the NE of the Rocket Site borehole. There is an arbitrary slight hade (angle from the vertical) on the downthrown side, and I have retained a constant estimated 30 m throw for the whole depth. Summary hydrogeological information is shown on the left; the quoted classifications are from BGS authors.

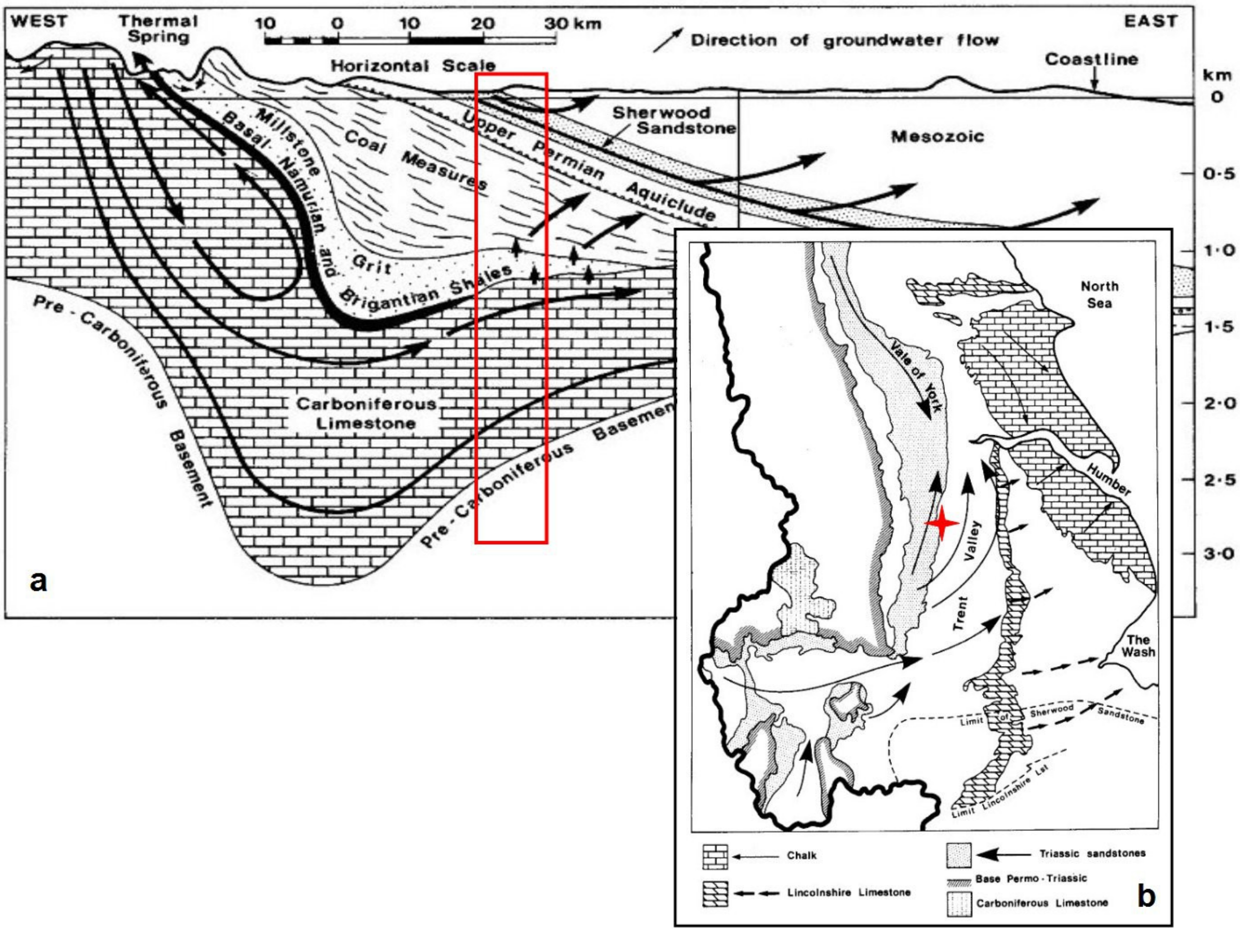

Figure 14. Regional groundwater flow in the East Midlands.

(a) East-west cross-section from the Pennines to the coast. The proposed development occupies the locality shown by the red rectangle.

(b) Map of regional groundwater flow through the Principal Aquifer, the Sherwood Sandstone Group. The proposed site is marked by the red star. Note the generally northward flow in the aquifer below the Mercia Mudstone Group, and under the Trent valley.

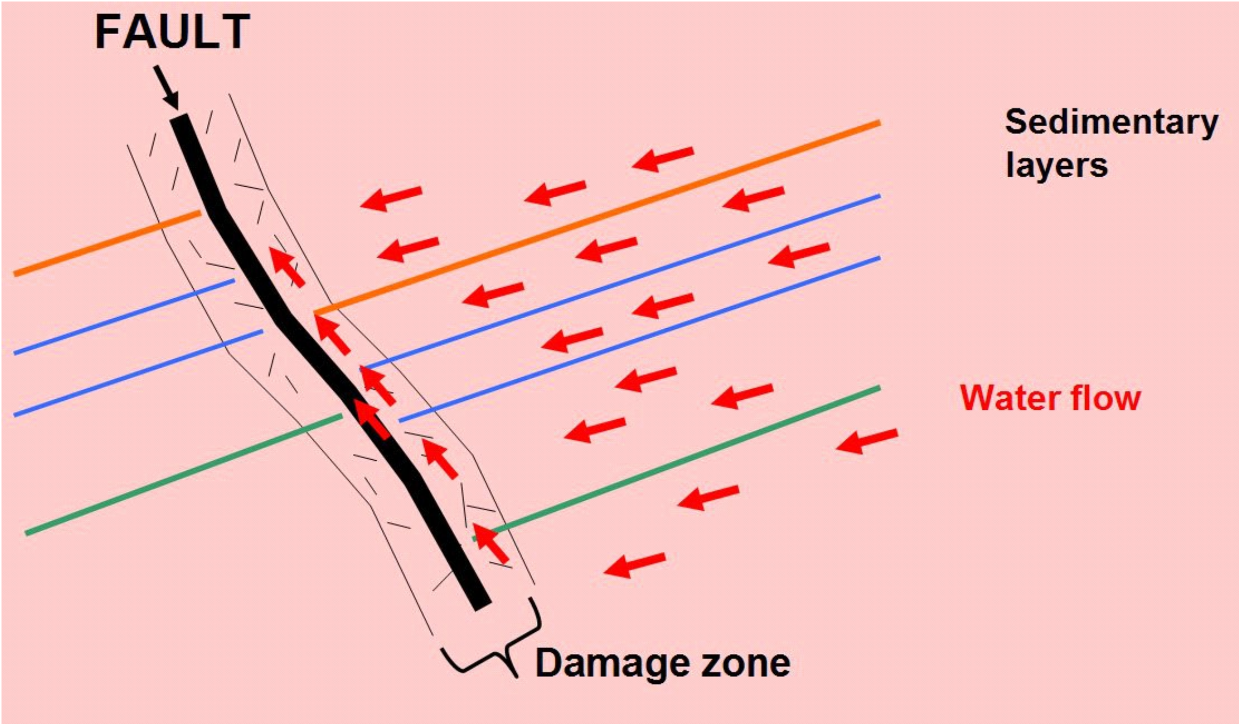

Fig. A1. Cartoon of a fault zone and resulting fluid flow (red arrows). The core zone (black) could be a barrier, or it could be a conduit. The damage zone on either side is always a conduit because it is fractured.

Migration paths, SE Bradford County, Pennsylvania

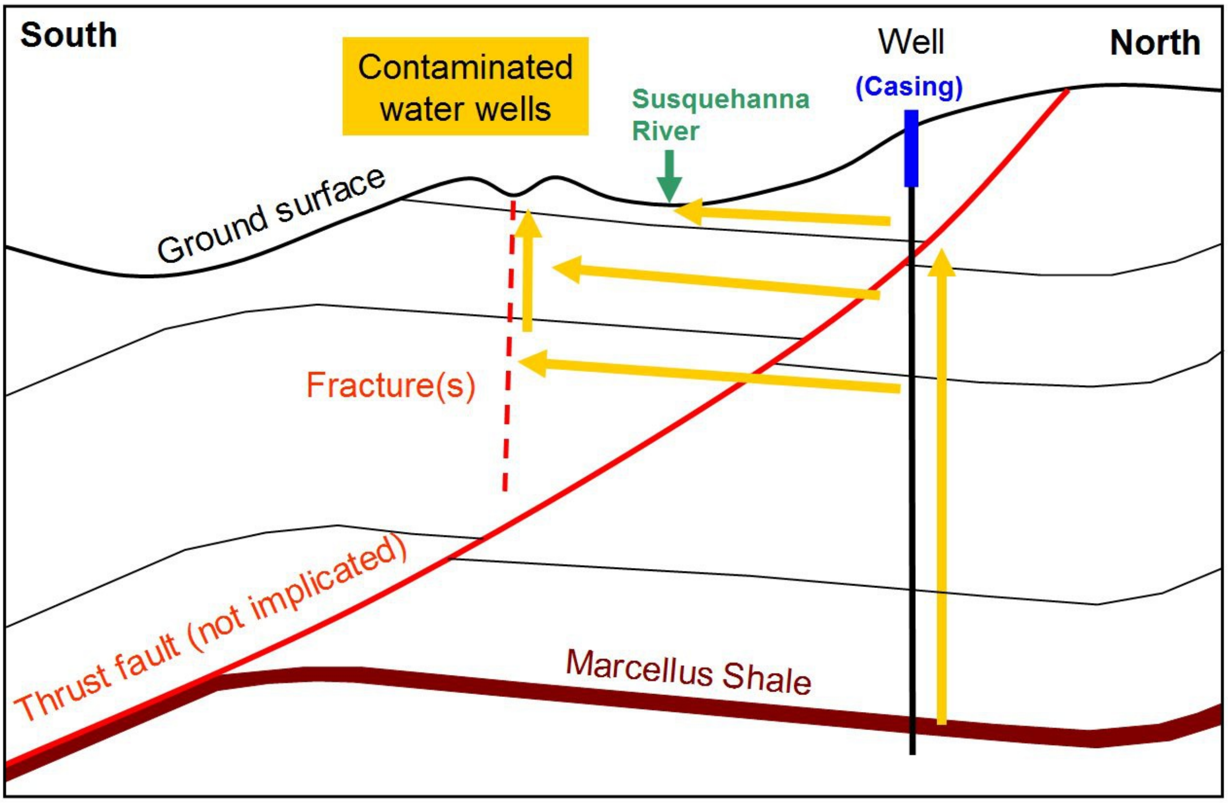

Fig. B1. Schematic cross-section to illustrate the salient features of the contamination pathways (yellow arrows) identified by Llewellyn *et al.* (2015) in Bradford County, Pennsylvania. The profile is about 10 km long, and the depth from the ground surface varies from about 2000 m to 2400 m. Representative geological layers, which are gently folded, are shown by thin black lines. Vertical exaggeration is about 2.5:1.

A NNW-SSE fracture zone (one of two), identified only by a linear topographic feature, is shown by the vertical dashed red line. It is not known how deep it penetrates. The thrust fault offsets the layering (the left side, above the thrust has been displaced upwards and to the right, relative to the rocks below). The schematic well (only one of the five is shown) penetrates vertically to the Marcellus Shale (the fracked layer), but is only cased to about 300 m below the ground surface (thick blue line). The Susquehanna River, where gas bubbling was observed, is shown by the green arrow.

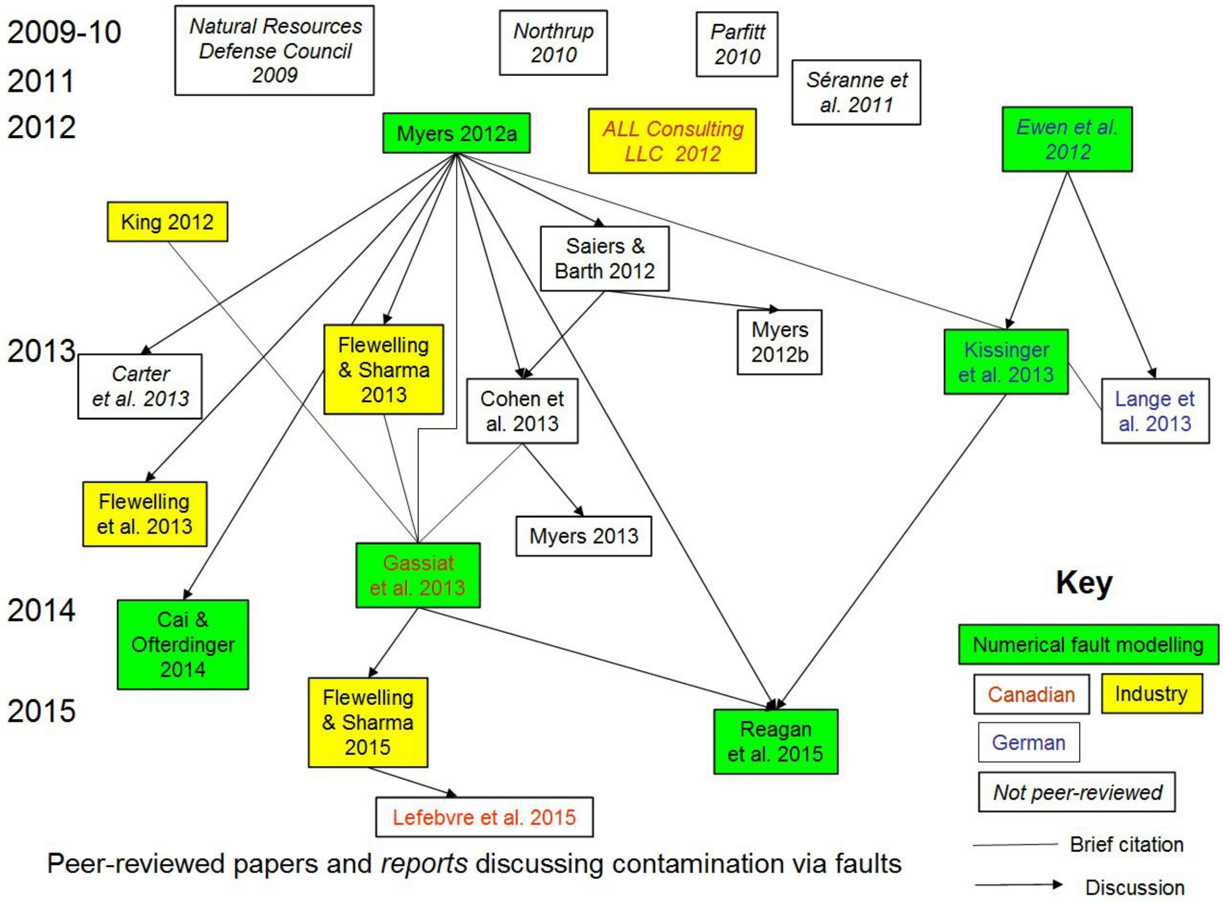

Figure C1. Organogram of published papers (upright text – peer-reviewed) and reports (italics – not peer reviewed) related to fluid flow up faults. The green boxes indicate numerical modelling papers. Yellow boxes are papers from industry authors. The links illustrate whether a paper or report has been cited briefly (line) or discussed in depth (arrow).