This report was produced in response to a request in October 2014 from a Lancashire Council official, to comment on submissions, which had been received from a former member of staff of the University of Glasgow, ostensibly in the name of the University, regarding planning applications for shale gas development.

The report was submitted to Lancashire Council in December 2014 and for several weeks was hosted on their planning website (and was, thus, placed in the public domain) in relation to these applications. It was subsequently taken down, along with many other documents pertaining to the applications (including the submissions that led to the report being written in the first place, which have since been posted online elsewhere), apparently because the website was becoming overloaded. However, it is cited in other documentation regarding the applications, so ideally a version needs to be accessible.

A Freedom of Information request, made to the University on 27 July 2015, requires disclosure of this report; it is therefore being made publically available. However, it needs to be understood that the report represents a snapshot of understanding of the topic, on which knowledge is constantly developing as research continues, at the time when it was written. Updated versions of its contents have indeed already been presented at several conferences and will in due course be published. In the meantime, it is important to note that some of the contents have been subject to revision and are no longer current in the form presented in the report. In particular, first, the argument that reverse faults in the study area most likely date from the Variscan Orogeny and so should be expected to reach the top of the Carboniferous sedimentary succession, which led us to infer that one of the objections to the planning applications may be valid, is not necessarily correct. It is now our understanding that the developer's interpretation of these faults is supported by seismic reflection evidence; we also understand that in the developer's view these faults most likely date from a Mid-Carboniferous phase of crustal shortening and not from the Variscan Orogeny. Second, the computer program, used for our calculations of whether or not the pressure of fracking fluid is high enough to 'lubricate' faults sufficiently that they can slip, causing induced earthquakes, has subsequently been modified. As a result, the particular numerical values stated in the report, for the minimum pressure of fracking fluid than can cause induced seismicity, are no longer supported. Nonetheless, the principle remains valid that calculations of this type should be undertaken, using data on the magnitude and orientation of the local stress field, on the geometry of faults in the vicinity of proposed fracking sites, and on the pressures of fracking fluid that it is proposed to use, to determine whether proposed fracking operations might induce seismicity. As our report states, the planning applications are therefore open to the criticism that no such supporting calculations were presented.

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27 July 2015

Review of the inputs of Professor David Smythe in relation to planning applications for shale gas development in Lancashire (planning applications LCC/2014/0096 /0097 /0101 and /0102) and associated recommendations

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17 December 2014

Professor Smythe has made a number of criticisms concerning these projects. Many of these criticisms relate to issues that are unrelated to any geological expertise, such as his suggestion that few, if any, UK academics can be trusted to provide objective advice about shale gas because of links to developers. Essentially his insinuation is that all of the other scientists with whom he disagrees have abandoned all professional standards of conduct. This is a serious allegation which he does not substantiate. However, as the scientists he criticises are (unlike himself) almost all members of Chartered professional bodies (mainly the Geological Society), which formally oversee their conduct and can strike them off if they violate such codes of practice, then Professor Smythe ought to submit any evidence of malpractice to those bodies. That he has failed to do so suggests that he has no such evidence, and that his allegations about the lack of integrity of others can be dismissed as unsubstantiated. We note that Professor Smythe has no current affiliation to any professional body which could guarantee the integrity of his own position. If he did, the very fact of making unsubstantiated allegations about the professionalism of others would in itself be a reportable offence against the code of conduct. Nor does he hold any current employment with any academic institution, which would ensure regular appraisal of his activities and outputs.

His essential criticisms of both the planning applications that propose fracking (i.e., LCC/2014/0096 and /0101) relate to the location of the proposed projects in relation to faults. He has argued that Cuadrilla, the developer, has underplayed the hazard from induced seismicity because they have omitted important faults from their maps and have also understated the hazard from the faults that they have considered by overlooking the possibility that fracking fluid may leak into these faults. In addition, he has stated that the presence of major faults in the area means that drilling and fracking for shale gas will inevitably pollute the surrounding region as a result of flow along the faults. He has also argued that there are mistakes in Cuadrilla's interpretation of the major faults. We consider both the Preston New Road (/0096) and the Roseacre Wood (/0101) projects together as the issues are the same for both.

The first of these aspects is trivial; although the planning applications include schematic maps that do not show every detail, elsewhere (in other documents submitted, including some of the illustrative material that Professor Smythe used in his submission) Cuadrilla also included definitive geological maps or cross sections, based on the most up to date geological background information, which show all the faults that are known (or interpreted) in the area. For example, the faulting interpreted in the vicinity of the Preston New Road site is illustrated in Fig. 1 and that in the vicinity of the Roseacre Wood site in Fig. 2. Indeed, Professor Smythe's depiction of the faults in Fig. 3 does not differ significantly from the depictions by Cuadrilla in Figs 1 and 2; the depiction of the same faults in the recent BGS / DECC Bowland Basin shale gas report (Fig. 4) is, likewise, very similar. Professor Smythe also makes much of an undocumented assertion (on p. 3 of both 'objection' documents) that **"…the density of faulting in the Weald, the Bowland Basin and the Midland Valley (Scotland) is 400 times greater, as measured by length of surface fault trace per unit area, than the average for the US shale gas and shale oil basins …"**. There are three points to be made in relation to this:

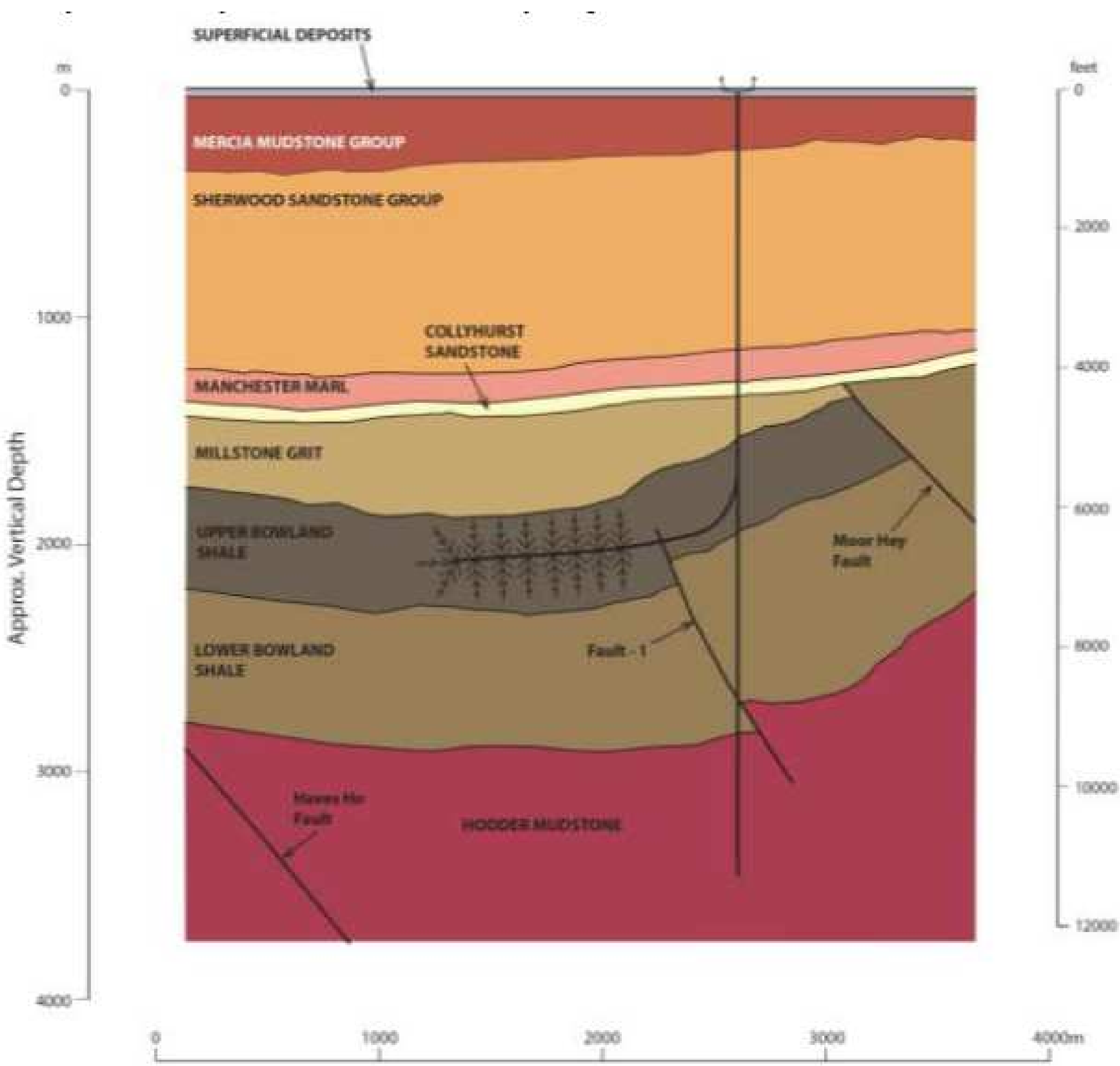

Fig. 1. Cross-section illustrating the geometry of the faulting in the vicinity of the Preston New Road site, from Fig. 6 of Appendix L of planning application /0096

1. Given the very different structural histories of these three UK areas, with markedly varying degrees of Caledonian, Variscan, and Alpine orogenic influences, it would be nothing short of miraculous if they all turned out to have identical faulting densities.

2. Even if the assertion is accepted at face value, it immediately raises at least two other questions:

a. Are the densities of geological data (outcrop, borehole, mine plans) absolutely comparable between the two areas? We doubt it. For instance, in the Midland Valley of Scotland, faults are unusually well-mapped because of evidence from mine plans, which are not available in areas that never had coal / oil shale mining in the shallow subsurface.

b. Were the mapping paradigms identical? Different geological surveys apply different standards as regards the scale of structures worth recording, depending on the purpose of the mapping. Typically, with much larger territory to map, US survey teams undertaking general mapping record less detail than their UK counterparts.

3. Even if fault density IS greater in the UK than in the USA, this makes no difference to the risk assessment for fracking unless either:

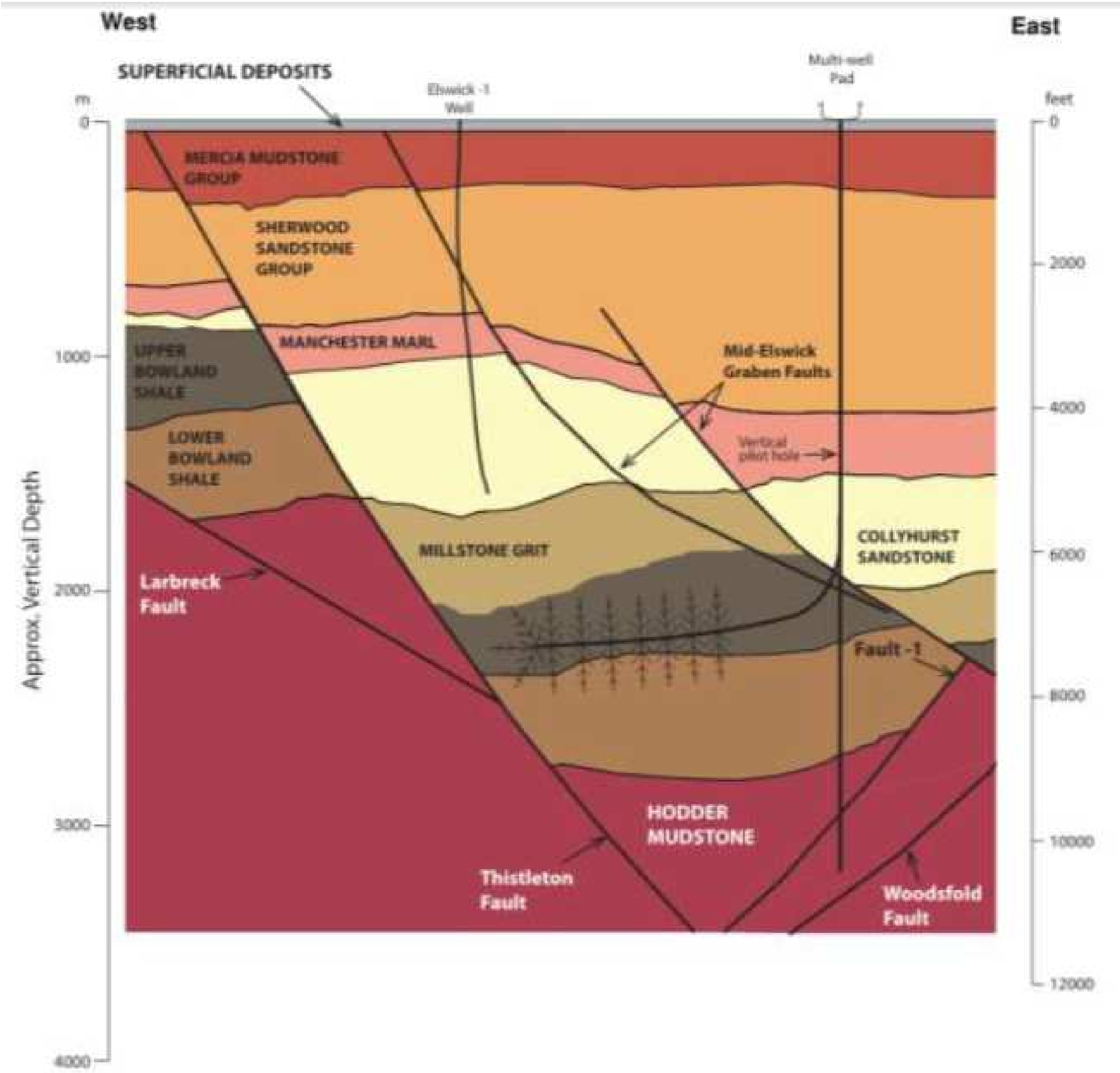

Fig. 2. Cross-section illustrating the geometry of the faulting in the vicinity of the Roseacre Wood site, from Fig. 6 of Appendix L of planning application /0101. Note that this diagram is not drawn to horizontal scale. Based on other information provided, the Elswick 1 well and proposed well are ~1.1 km apart along the line of the section, making the length of the section ~2.7 km. The horizontal scale is thus stretched relative to the vertical by a factor of ~4/3, equivalent to a vertical exaggeration of ~0.75. This means that the true dips of the faults are steeper than the apparent dips depicted. Thus the Thistleton Fault updip of its intersection with the Larbreck Fault has a true dip of arctan(tan(60°) x 4/3) or ~67° and the Larbreck Fault has a true dip of arctan(tan(30°) x 4/3) or ~38°.

a. the faults are permeable – which (as we discuss in relation to groundwater pollution) is a function of several factors, most notably the likely presence of fault gouge where the faults traverse mudstones, and the orientation of non-gouge-filled fault planes relative to the present azimuth of maximum compressive stress; or

b. The fracking process might increase the fluid pressure within any nearby fault sufficiently to enable this fault to slip, and the fault is large enough to slip in a potentially damaging earthquake. We show that this is not the case for the present project area; although large faults are present, the proposed project is safe, provided the pressure of the fracking fluid is kept to the minimum required for the task.

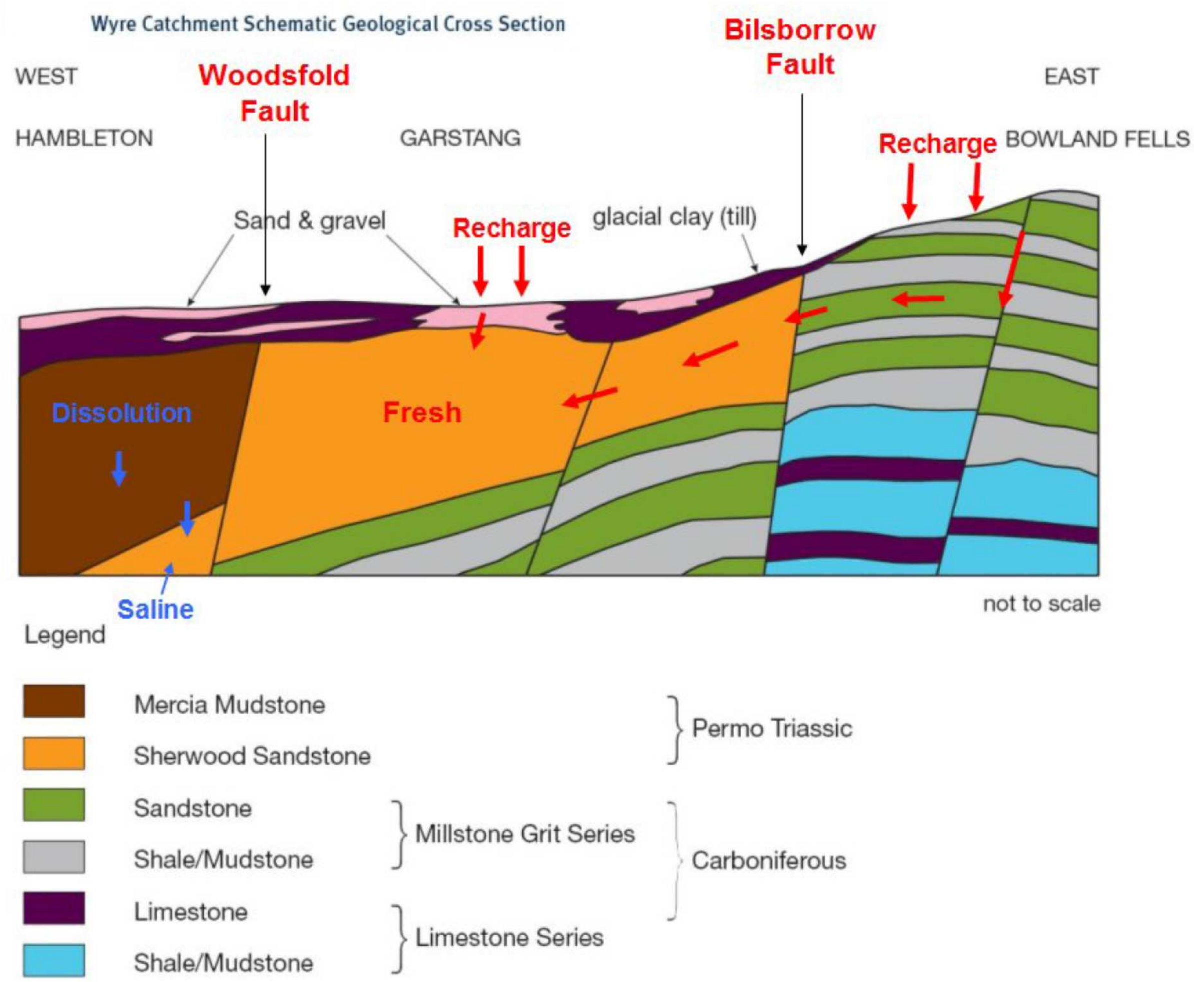

Fig. 3. A copy of Professor Smythe's Fig. 5.1 from his objection to planning application /0096. He has taken a cross section prepared by the Environment Agency for a 2006 report and has added fault labels and flow arrows, showing groundwater flowing down one fault and through beds of permeable rock (sand and sandstone), including across faults where sandstone is juxtaposed on both sides. However, he offered no evidence that groundwater does indeed flow down any of the faults within the Millstone Grit in this area. In any case, as is discussed above, the issue on hand is whether groundwater flows across or along faults within the impermeable Bowland Shale (the unit beneath the Millstone Grit, depicted here for some reason as the 'Limestone Series').

If Professor Smythe is going to rely on his arguments on this topic, then he really ought to present his study for peer-review to a reputable journal – there are many that would be suitable publication targets for such work. This would allow resolution of the points raised above. In the absence of such a peer review, this assertion is essentially worthless.

The last of Professor Smythe's issues, that some of the fault interpretation by Cuadrilla may well be incorrect, also has no significant consequences. He has argued that the interpretation of Fault 1 in Fig. 1 makes no sense and that this fault more likely continues upward through the Bowland Shale and the overlying Millstone Grit, dying out at the unconformity between that and the younger sediments above. He is probably correct about this; at any locality in northern England (see De Paola et al.. 2005, and others) the most likely timing of reverse slip such as this is during the Variscan orogeny (i.e., ~300 million years ago), after the Millstone Grit was emplaced but before the younger deposits were laid down. This means that the vertical extent of this fault should be estimated as ~1.8 km rather than the ~1.3 km indicated by Cuadrilla. However, whether it is ~1.3 km or ~1.8 km, it is still an important fault with implications for the hazard of undertaking the project in this area.

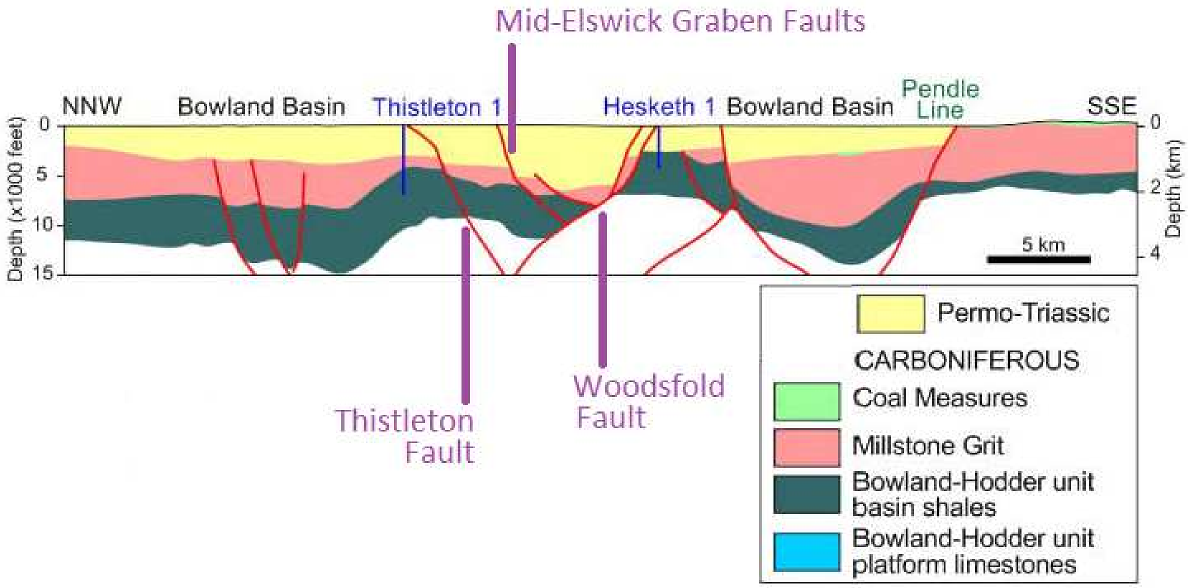

Fig. 4. Cross-section A from Fig. 19 of Andrews (2013), illustrating the BGS / DECC interpretation of the disposition of the Bowland Shale in the study region. The Thistleton 1 borehole, depicted, is located ~3.5 km WNW of the proposed Roseacre Wood shale gas well and ~6 km NNE of the proposed Preston New Road well; thus, the former well is within the Bowland Shale between the Thistleton Fault and the Mid-Elswick Graben Faults and the latter well projects to the left of the Thistleton Fault.

As regards the third issue, groundwater / surface water pollution risks, Professor Smythe has claimed that '**The hydrogeology of the area immediately east of the site shows that regional faults are transmissive**.' The annotated version of an Environment Agency cross-section relating to the Sherwood Sandstone Group is presented and discussed by Professor Smythe, and is repeated here as Fig. 3. The argument he is basing upon this diagram is nowhere explained in detail, but it would appear that the point he is attempting to make is that, if the Woodsfold Fault is transmissive where it cuts sandstones, faults must also be permeable where they cut the Bowland Shale at greater depth. Professor Smythe thus considers that all geological faults should be regarded as leaky unless proved otherwise. He implies that this is the standard assumption made in hydrogeological investigations. However, this is not so. There are at least three issues here which Professor Smythe fails to consider:

(i) Where faults cut low-permeability strata such as shale (and even locally where the fault passes from a shale into a more permeable bed) there is a marked tendency for the fault plane to be lined with a fine-grained clay-rich material known as "fault gouge", which typically renders these portions of the fault planes effectively impermeable (e.g., Younger 2007). In contrast, where the same fault cuts a permeable rock such as sandstone (and the displacement has not smeared clay-rich gouge from an over- or under-lying mudstone into the fault zone, then the fault plane may well be occupied by relatively permeable breccia; minor fractures either side of the fault plane in a sandstone might also be relatively clean and open. This explains where the faults cut sandstones in the recharge area described by Professor Smythe (Fig. 3) they are believed to be permeable. HOWEVER, because of the formation of fault gouge where the same faults pass down into mudstones, there is no *a priori* reason to suppose that these faults are permeable throughout their depths: where they cut mudstones they are overwhelmingly likely to be of low permeability.

(ii) Even where a fault is not so lined with gouge as to render it impermeable, it is subject to the present crustal stress regime, which tends to favour faults being more permeable where they are aligned fairly closely to the current maximum compressive stress azimuth, but tends to make them far less permeable if they are otherwise oriented (e.g., Ellis *et al.* 2014). Note that this does not override the basic permeability control provided by fault gouge.

(iii) Crucially, even where a fault is continuously permeable over a large vertical interval (which is unlikely in sequences, like those in the region under consideration, that contain thick mudstones) groundwater flow can only occur if there is a sustained driving head from one area to another. There is no evidence of any such upward-oriented hydraulic gradient in this region, and the extremely short-lived pulses of increased head close to the boreholes during fracking operations are insufficient to overcome the head in overlying strata. Where conventional oil and gas reservoirs occur, natural upward hydraulic gradients may exist, but oil and gas only accumulate where permeable pathways upwards are insufficient to allow dissipation of fluid pressure over geological time. It is inherent in the very definition of UNCONVENTIONAL gas that such over-pressure does not occur – hence the need for reservoir stimulation and depressurisation of the target horizon in order to get gas to move into boreholes. These points were addressed in the Joint Royal Academies' report (Mair *et al.* 2012), although Professor Smythe seems to have overlooked this.

It is for the above reasons that the actual consensus amongst hydrogeologists is that faults are *not* everywhere to be assumed to be permeable, let alone pathways for upwards migration of water in the absence of a driving head. Rather, faults are hydrogeologically ambiguous: the same fault can be impermeable where it passes through mudstone, and locally permeable where it cuts sandstones – provided of course it is oriented appropriately vis-a-vis the present crustal stress regime. In neglecting the above factors, Professor Smythe has failed to account properly for the most likely hydrogeological behaviour of the faults in the areas considered, at least as regards the overwhelming likelihood that they will be of very low permeability where they pass through the Bowland Shales. For this reason, the alarming scenarios of pollution of shallow groundwater and surface waters due to fracking operations, as suggested by Professor Smythe, are not credible. Consideration of fault permeability is also relevant to the decision by Cuadrilla to not attempt to propose drilling or fracking near the Woodsfold Fault but to propose these activities near other faults: the Woodsfold Fault has such great displacement that it offsets the impermeable Bowland Shale and juxtaposes potentially permeable rocks against it (Fig. 4), whereas the other faults have much smaller displacements and thus juxtapose Bowland Shale against Bowland Shale. In this respect, the Woodsfold Fault may well be hydrogeologically different from the others in the area. Professor Smythe moves on to suggest the drilling of several 1 km-deep boreholes to characterise the hydrogeology of the Woodsfold Fault, even though the planning applications specifically state that the projects are designed to avoid this particular fault. If his assertion that this fault plane is permeable is actually correct, drilling boreholes through it would introduce potential flowpaths where none currently exist; it might thus alter the pressure of groundwater within this fault in a manner that might affect the state of stress so as to make the conditions more conducive to this fault (or part of it) slipping in a future earthquake. Setting aside the expense of drilling such boreholes, this is therefore a foolish suggestion and demonstrates a lack of knowledge on the part of Professor Smythe. Although he has evidently not considered why the Woodsfold Fault should be regarded, from the point of view of hydrogeology, as different from the others, it should be noted that this aspect could have been explained much more clearly by Cuadrilla in the first place.

The second of Professor Smythe's points, however, is of the utmost importance. In principle, as a worst-case scenario, the possibility exists that during fracking operations at the proposed sites, fracking fluid will leak into the faults depicted (such as Fault 1 in Fig. 1 or the 'Mid-Elswick Graben Faults, Thistleton Fault, or Larbreck Fault in Fig. 2), because this fluid might flow to these faults through the network of new fractures created in the Bowland Shale by the fracking, notwithstanding the low permeability of the unfractured Bowland Shale (see above). In principle, the presence of this fluid might then lubricate any part of any of these faults that it reaches sufficiently to bring it to the condition for shear failure, potentially resulting in an earthquake. If so, the resulting earthquake might (again, as a worst-case scenario) rupture the entire area of the fault; thus, since the faults depicted are all >1 km in vertical extent and at least several km long, the fault areas are many square kilometres, so earthquakes of the order of magnitude 5, at least, might thus occur. Earthquakes of this size would be readily large enough to cause damage to property and might well result in injuries or even fatalities, for example from falling masonry (e.g., falling chimneys collapsing onto victims). It is essential, therefore, to demonstrate that the design of the proposed projects precludes the possibility of any such eventuality.

Before proceeding, it is worth recapping on some background material, especially since there is some confusion in the materials submitted by Cuadrilla. In the time since their applications were submitted, Westaway and Younger (2014) have published a paper that clarifies many of these issues. First, is the matter of definition. Anthropogenic (human-induced) earthquakes can be subdivided into 'triggered' and 'induced' events; a triggered event is one that would have occurred anyway, because the state of stress in the area was tending towards the condition for shear failure, so that the human activity merely brought the earthquake forward in time or 'advanced the clock'. An earthquake is 'induced' if there is no reason to consider that, in the absence of human activity, the state of stress in the area was heading towards the condition for shear failure: in other words, without the human activity the earthquake would never have occurred. This is a standard definition, also used by others (e.g., Klose, 2013); the different definition used in the Cuadrilla documentation is not helpful. Furthermore, fracking may induce earthquakes in two ways. First, the act of creating fractures obviously involves fracturing the rock, which releases seismic energy; second, fracking fluid may get into faults and bring them to the condition for shear failure. Westaway and Younger (2014) developed theory that enables, for the first time, the size of the largest possible induced earthquake of the first type to be calculated as a function of the volume of fracking fluid that is used (cf. their equation (A32)). The statement by Cuadrilla that this volume will be limited to 765 m^3 per frack operation, if they get permission to proceed, means that the largest possible fracture that can form has a length of ~200 m; if this were to form in a single fracturing event it the resulting earthquake would have magnitude ~3. However, an earthquake as large of this would have a low probability of occurrence. Even so, an event of this size would cause ground vibrations at the Earth's surface roughly equivalent to the limits allowable for quarry blasting in the UK.

Of greater potential significance to the present planning applications is the second type of induced earthquake, involving the lubrication by fracking fluid of pre-existing faults. It is apparent that the proposed fracking operations are planned to occur within ~100 m of important faults (Figs. 1 and 2). Professor Smythe has written '**Cuadrilla has defined so-called 'regional' faults, which will be avoided by the fracking operations, and 'local' faults, through which drilling and fracking may take place. Its definitions are inconsistent and illogical. All faults should be avoided, whatever the scale; if this results in the Bowland Basin being unexploitable for shale gas, then so be it**.' Cuadrilla thus regard the Woodsfold Fault depicted in Fig. 2 as 'regional' and so to be avoided; thus the Roseacre Wood site has been chosen to be more than a kilometre away from it (Fig. 2). However, Professor Smythe is entirely correct to note the illogicality of attaching less importance to the other faults, from the point of view of induced seismicity, when they are of sufficient size to rupture in damaging earthquakes. We nonetheless consider his second sentence to be itself illogical: faults should be avoided IF they are large enough to slip in damaging earthquakes and IF the effects of fracking have a demonstrable likelihood of bringing the fault to the condition for shear failure.

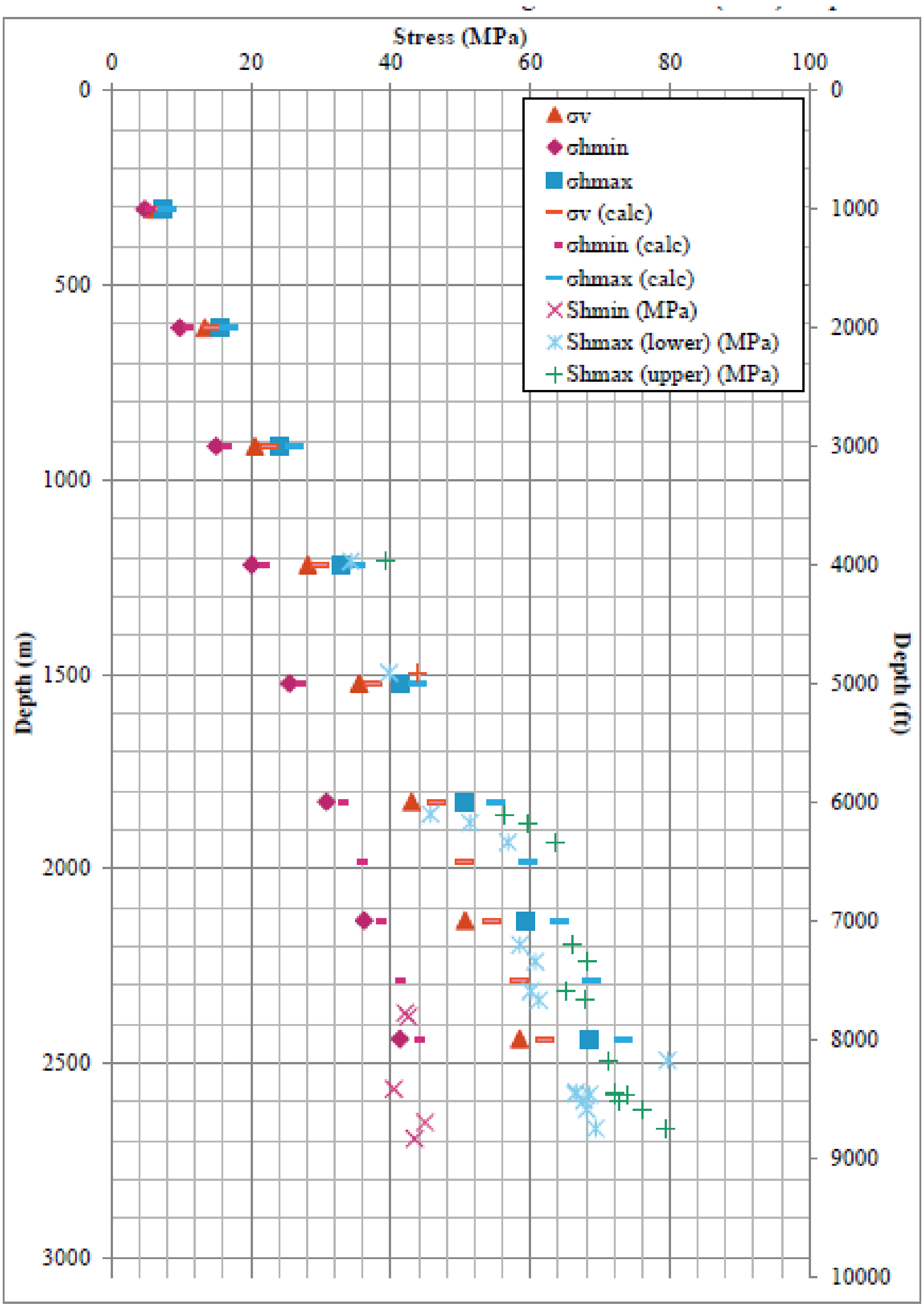

Fig. 5. Graph of in situ stress measurements from the Preese Hall-1 well as presented in Fig. 12 of Appendix L of planning application /0096. At a depth of 2440 m, the proposed depth of fracking at the Preston New Road site, the best estimates of the three measured stress tensor elements are quoted as 62.2 MPa (σ_v – vertical stress), 73.4 MPa ($\sigma_{h\,max}$ – maximum horizontal stress), and 43.6 MPa ($\sigma_{h\,min}$ – minimum horizontal stress).

In their Appendix L documents for both planning applications Cuadrilla repeatedly mention mitigation measures but the essential point is that they state that the orientation and magnitude of the local stress field will be measured during the vertical drilling phase and will inform the applications for permission to subsequently begin fracking operations. This is stated on p. 45 of Appendix L of the Preston New Road planning application and p. 46 of Appendix L of the Roseacre Wood planning application. On subsequent pages the documents disclose measurements of the state of stress at the Preese Hall 1 borehole (Fig. 5), which Cuadrilla consider representative of the proposed drilling sites. This is a reasonable starting assumption. Cuadrilla also propose to make multiple in situ stress measurements in their proposed boreholes, if these go ahead, during their initial vertical drilling phases, which is also a valid strategy. However, they then say that they will present the resulting data to DECC as part of making the case for being allowed to initiate fracking in these boreholes. This is not satisfactory; first, they do not present any calculations to demonstrate that the proposed projects are safe on the basis of existing stress measurements and plans. Second, it should be apparent that there is no-one at DECC with sufficient expertise to assess this type of technical argument, and since officials at DECC are open to political pressure, there is the possibility of interference in the decision. The correct time to present such a safety case is in the planning application; this is done below, where it is demonstrated that the proposed projects are safe provided the pressure used for the fracking is kept to the minimum necessary. Rather than being examined by DECC, a better strategy for examination of safety plans such as this is to make use of the expertise of academics, who include people with the most relevant skills and experience.

A first-order analysis of the safety case for the proposed project can be made using data from Cuadrilla's planning applications along with relevant theory from a standard textbook (equations 8-28 and 8-29 of Turcotte and Schubert, 1982) and from an appropriate publication (equation (3) of Westaway, 2006). The latter equation defines a 'failure parameter', called Φ, which can be calculated for any orientation of fault at any point in a rock mass; if $\Phi<0$ then friction prevents the initiation of slip on this fault at this point, whereas if Φ increases to 0 at the point then slip is able to initiate at the point, and may propagate across the fault, potentially resulting in a large earthquake, the size of which is limited only by the overall area of the fault. Fort this analysis, we assume the best estimates of the three measured stress tensor elements from the Preese Hall-1 well at 2440 m depth of 62.2 MPa (σ_v – vertical stress), 73.4 MPa ($\sigma_{h\ max}$ – maximum horizontal stress), and 43.6 MPa ($\sigma_{h\ min}$ – minimum horizontal stress), reported in the planning applications. We also note that the maximum horizontal stress is reported at an azimuth of 173$\pm$7°, i.e., roughly north-south, and that the region is characterized by normal faults that are oriented roughly N-S and dip east of west. Cuadrilla have argued that any induced seismicity will involve strike-slip earthquakes, governed by the difference between $\sigma_{h\ max}$ and $\sigma_{h\ min}$, but given the orientation of the stress tensor and the faults this is incorrect; no faults in the area are suitably oriented to accommodate this sense of relative motion. On the contrary, the most likely induced seismicity will involve normal slip on these faults, which is governed by the difference between σ_v and $\sigma_{h\ min}$. The possibility of normal fault reactivation is calculated by comparing, for a depth of 2440 m, an initial state where the water pressure is hydrostatic with a state during fracking where the excess pressure of fracking fluid affects the fault. The Bowland Shale is assumed to have a cohesion S=4 MPa and a tensile strength T=2 MPa (cf. Westaway and Younger, 2014). The minimum pressure of fracking fluid necessary to initiate fractures is taken as $\sigma_{h\ min}$ + T and so is 45.6 MPa. The calculations are carried out for three values of the coefficient of friction of the fault, c=0, 0.5 and 1.0, although in the first of these cases the changing fluid pressure makes no difference to the value of Φ. Calculations are carried out for all fault dips between 0 and 90°, encompassing the range of ~35-70° that is applicable to the faults in the area (cf. Figs 2, 5).

Figure 6 shows that for all conditions considered, the calculations indicate that the proposed project is safe; for no combination of fault orientation and coefficient of friction does Φ rise to zero.

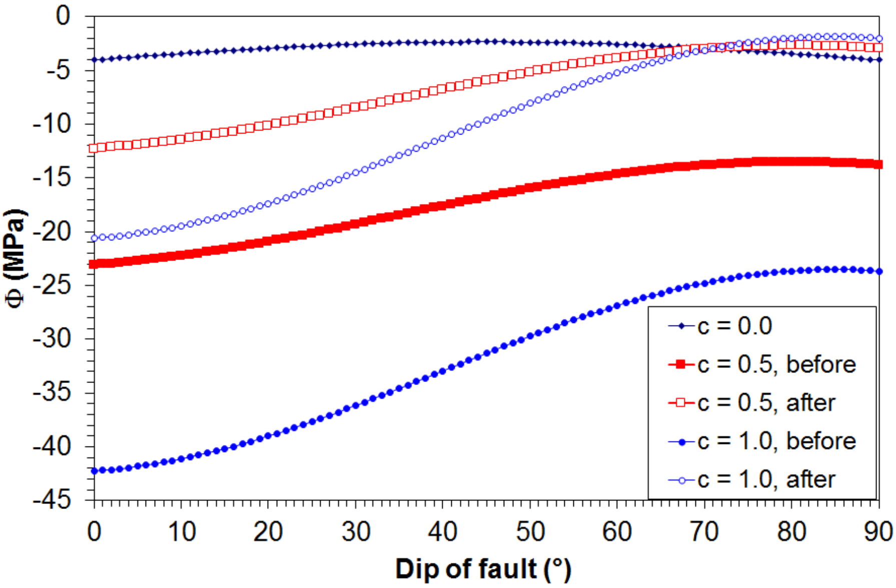

Fig. 6. Graphs of variations in failure parameter Φ against fault dip for the data discussed in the text, for coefficients of friction c of 0.0, 0.5 and 1.0. 'before' values denote the assumed initial state under hydrostatic conditions; 'after' values denote the conditions where fracking fluid at the specified pressure leaks into the fault.

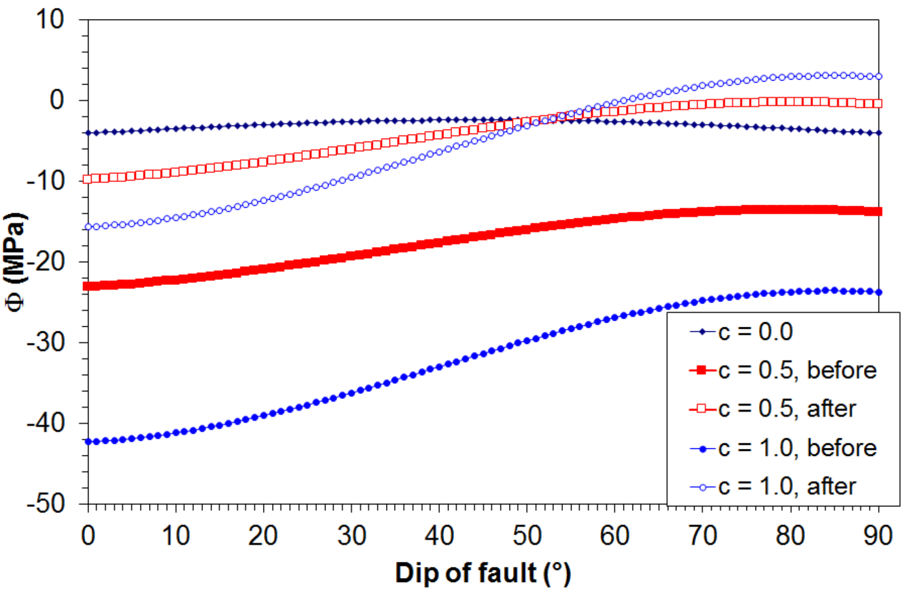

Fig. 7. Alternative solutions for which the fracking fluid is assumed to be at a pressure 5 MPa higher than was assumed for the calculations for Fig. 6.

However, Fig. 7 shows an alternative set of calculations, in which it is assumed that the fracking fluid is at a pressure 5 MPa higher than for the previous set of solutions. In this case, it is predicted that Φ can exceed 0 for c=1.0 provided the fault dip is 61° or steeper. Since the Thistleton Fault is steeper than this (Fig. 2), this set of conditions might well result in an induced earthquake on this fault. The implication of this analysis is that for the project to be safe, Cuadrilla must be required to limit the pressure of the fracking fluid used in their fracking operations.

Overall, we conclude that Professor Smythe's assertion that the proposed projects are inevitably unsafe because there are faults in the vicinity is unfounded. Whether the projects are safe, in the sense that they cannot induce earthquakes on the large faults in the area, depends on the combination of the in situ stress measurements, the mechanical properties of the rocks, the geometry of the faults, and the fluid pressure to be used in the fracking operation. On the other hand, Cuadrilla made no attempt to demonstrate that their proposed projects are safe, in this sense, and there are a number of mistakes in their documentation (the mistake in the estimation of the size of Fault 1 in Fig. 1; the wrong definition of induced seismicity; the wrong assumption about the slip sense in the induced earthquakes that they should have been concerned about, etc.) and there are also important omissions in their applications: although they specify a limit on the volume of the fracking fluid that will be used in any individual fracking operation, they do not specify any limit to its pressure, nor do they seem to have appreciated that the choice of pressure can impact on the safety case; they have not specified what they think the relevant mechanical properties of the rocks will be or how they impact on the safety analysis; and, although they have said that they will undertake in situ stress measurements and microseismic monitoring in the proposed boreholes, they have not specified what their strategy will be for using these data as the projects progress.

We conclude that there is no reason on the basis of considerations of fault hydrogeology or induced seismicity to refuse planning permission for the two borehole projects (planning applications /0096 and /0101). The two projects for microseismic monitoring are appropriately designed and are necessary for monitoring the fracking process in the boreholes; the associated applications for planning permission (/0097 and /0102) should likewise be granted if the applications for the two borehole projects succeed. However, we recommend that, if granted, the planning permissions for the two borehole projects should be subject to certain conditions, namely:

-The initial phase of vertical drilling should be accompanied by in situ stress measurements using an established technique (i.e., micro-fracking or overcoring). Representative samples of core should be collected, and should be subject to testing to determine the mechanical properties of the rock.

-The above-mentioned data should be analysed before any decision is made to allow the fracking of the horizontal parts of the boreholes. This analysis should be carried out by specialists who have established track records in the fields of induced seismicity and/or rock mechanics, not by anonymous individuals working for consultancy firms, whose credentials for undertaking this kind of work are not at all evident.

-The above-mentioned analysis will result in the determination of the maximum pressure of the fracking fluid that can be considered 'safe' for these projects. Cuadrilla could then be required to adhere to this limit.

-The data and results of the microseismic monitoring should be likewise made available to appropriate specialists with suitable track records for thorough analysis. This analysis to include estimation of the strength of ground vibration at points at the Earth's surface to determine whether any unacceptable nuisance has affected any of the local population, in accordance with the approach advocated by Westaway and Younger (2014).

-All data and results from the drilling and microseismic monitoring should be published, maybe after an embargo period (say, 3 years).

-Cuadrilla should agree to pay for the above investigations to analyse the drilling and microseismicity data.

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