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Solid Earth Discussions

Interactive comment on "Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald Basins, UK" *by* David K. Smythe

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Introduction

In this comment on the Smythe (2016) discussion paper I shall try to avoid distraction by this author's record in the field of shale gas and fracking (e.g., Smythe, 2014, 2015), and will concentrate on technical issues related to three topics: the geometry of the 2011 occurrence of induced seismicity at Preese Hall in northwest England; the risk of drawing mistaken conclusions by selective citation of the literature; and the implications of this 2011 case study for the regulation of a future UK shale industry.

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Discussion paper

Geometry of the Preese Hall induced seismicity

The 2011 Preese Hall, Lancashire, case study of induced seismicity that was strong enough to be felt, caused by fracking for shale gas, has been investigated by many workers; my own outputs on this topic (none of which are cited by Smythe, 2016) include the Westaway and Younger (2014) and Westaway (2015, 2016) publications and the Younger and Westaway (2014) report, which was placed in the public domain as a result of a freedom of information request from an environmental activist. Smythe (2016) has proposed an interpretation in which the seismogenic fault transects the Preese Hall-1 borehole within the Hodder Mudstone Formation, one of the shale formations that was fracked. Deformation of the Preese Hall 1 wellbore, which was documented several days after the largest of the induced events in 2011 (with magnitude 2.3), can thus be interpreted as a direct consequence of the coseismic slip, rather than being some sort of independent phenomenon as was inferred in the consultancy reports that were commissioned by the well operator, Cuadrilla, in the aftermath of this induced seismicity.

Notwithstanding differences in detail relating to the geometry, to be discussed below, essentially the same interpretation has been proposed by Westaway (2016); moreover, the latter version has also been presented at conferences (Fig. 1) during which it has been discussed at some length with representatives of Cuadrilla and other subject specialists. Smythe's (2016) interpretation is based on projecting an inferred fault plane from the hypocentral location deduced by Clarke et al. (2014), which is ~500 m east of and ~300 m deeper than the observed wellbore deformation, updip at a 30° angle, as is illustrated in his Figures 4 and 5. Smythe (2016) was highly critical of the reliability of much of the Preese Hall dataset, but based his argument on uncritical acceptance of the accuracy of this Clarke et al. (2014) hypocentre. On the other hand, his 30° assumed dip of the fault plane differs from the 70° value determined by Clarke et al. (2014) in their fault plane solution, and also differs from the 45° dip at which Clarke et al. (2014) drew this fault plane on their seismic section (repeated here in Fig. 1(b)).

Smythe (2016) also noticed a number of other vagaries in the Clarke et al. (2014) paper, including apparent mismatches of hundreds of metres between positions of features in different diagrams and problems with the display of the 3-D seismic data, which were also noted by Westaway (2016). The great public interest in this type of dataset and the need for confidence in interpretations to give a future UK shale industry a 'social licence to operate' mean that disclosure of data (such as the Preese Hall 3-D seismic dataset) is a necessity, as Westaway (2016) has suggested. Smythe (2016) has made the same point; somewhat to my astonishment, I therefore find myself for once agreeing with something he has stated.

The unexplained mismatch between these 70° and 45° dip values is one of many vagaries and mistakes in the Clarke et al. (2014) paper that were recognized shortly after its publication and prompted the Westaway (2016) reassessment of the Preese Hall dataset. This reassessment led to the realization that the Clarke et al. (2014) hypocentre is unreliable for two main reasons, making it an inappropriate starting point for analysis of the geometry of the induced seismicity and related rock mechanics. First, Clarke et al. (2014) used a seismic velocity structure around the depth of the Hodder Mudstone Formation that was representative of crustal basement, rather than Carboniferous mudstone, i.e., much too fast, which had the effect of 'pulling' the hypocentre too deep. Second, the WNW deepening of each sedimentary formation in the vicinity (evident in Fig. 1) makes the true seismic velocity structure faster to the ESE than to the WNW. The use by Clarke et al. (2014) of a seismic velocity structure with no such lateral variation thus had the effect of 'pulling' the reported epicentre ESE of its true location. A third issue considered by Westaway (2016) concerned the vagaries in picking of some of the arrival times of seismic phases by Clarke et al. (2014). Taking all these factors into account, Westaway (2016) inferred that the most likely location of the Preese Hall induced seismicity was south of the borehole, rather than east of it as Clarke et al. (2014) had suggested. Since the local stress field will have caused the induced fracture network to develop in a vertical plane oriented north-south, it can thus be presumed that the southward component of fracture propagation resulted in

Full screen / Esc

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Discussion paper

it intersecting the fault, allowing fracking fluid to leak into the fault and causing the induced seismicity (cf. Davies et al., 2013). However, Westaway (2016) was unable to resolve the depth of the seismicity relative to the fracking. Another vagary of Clarke et al. (2014) concerned the focal mechanism of the induced earthquakes: it is evident even from a cursory inspection of their paper that their fault plane solution is not drawn correctly and the angles used to represent it are not reported using the standard definitions. Westaway (2016) determined a new fault plane solution, for which the inferred fault plane has strike 030°, dip 75°, and rake -20°, indicating almost pure left-lateral slip on a steep normal fault dipping ESE.

The fault plane inferred by Westaway (2016) projects closer to the Preese Hall-1 borehole than the Clarke et al. (2014) fault plane, and - as Fig. 1(b) shows - can be projected through part of the seismic section where seismic reflectors are offset. This fault is evidently steep in the Clitheroe Limestone Formation (CLL), then its dip evidently flattens upward into the Hodder Mudstone Formation (HOM), this being explained by Westaway (2016) as an instance of 'stress refraction' caused by the different mechanical properties of these lithologies. The induced seismicity might thus have occurred in the Clitheroe Limestone Formation, thereby accounting for the steepness of the seismogenic fault plane.

When the illustration in Fig. 1 was first presented in November 2015, its inference, that this fault plane might continue upward, possibly reverting to a steep dip in the Pendleside Limestone Formation (PDL) and maybe also in the overlying Bowland Shale Formation (BSG), carries the implication of possible fluid migration to and contamination of rocks at shallower depths (see also below), as was immediately noted by members of the audience. Representatives of Cuadrilla were equally quick to assure me that no evidence of upward propagation of this fault exists in the part of this 3-D seismic section excerpt (Fig. 1(b)) that they obliterated with their unnecessarily large label, even though a fault in roughly the same place is depicted in the older 2-D seismic section in Fig. 1(a). Publication of the 3 D seismic dataset will resolve this matter.

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Selective referencing

Westaway (2016) emphasized the need for objectivity in dealing with uncertain datasets such as that discussed above. Although the preceding text indicates that I agree with some of Smythe's (2016) points, I do not regard his approach as good practice: he has uncritically adopted some existing data (notably, the Clarke et al., 2014, hypocentre), rejected others without good reason (or omitted any mention of them), and has 'tweaked' others (notably, the dip of the Clarke et al., 2014, fault plane) to fit what he wants the solution to be. Both Westaway (2016) and Smythe (2016) have nonetheless recognized an essential point, that the fracking that resulted in the largest induced earthquake occurred within the zone of wellbore deformation, where the seismogenic fault intersects the wellbore, making the cause and effect connection between the two indisputable, this point having not hitherto been apparent. However, the detailed geometry of flow of fracking fluid within this fault and the induced fracture network, and the physical cause of the observed time delays between fracking and seismicity, remain to be resolved; Smythe's (2016) analysis has not added anything here beyond details already published, for example by Davies et al. (2013) and Westaway (2015, 2016), none of which references he has cited.

A similar selective approach is evident in the citation of other references by Smythe (2016): for example, he praises the paper by Myers (2012) which deduces rapid upward migration of fracking fluid and the resulting possibility of contamination of shallow aquifers, when many workers (e.g., Saiers and Barth, 2012; Cohen et al., 2013; Cai and Ofterdinger, 2014) have pointed out that Myers (2012) did not construct his numerical model appropriately, casting doubt on his conclusions. Conversely, Smythe (2016) criticises the study by Cai and Ofterdinger (2014), which shows that the creation of induced fracture networks of plausible dimensions will result in no significant contamination of groundwater at shallow depths.

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Discussion paper

Cai and Ofterdinger (2014) also considered a ‘worst case scenario’ of a 1 mm wide open fracture reaching to shallow depths, to represent the possibility of an induced fracture network intersecting a large, pre-existing fault, for which contamination was shown to take ∼100 years to reach shallow depths. Smythe (2016) describes this analysis as ‘flawed’ and ‘unrealistic’, presumably because he is aware that major faults consist of ‘damage zones’ that are many metres wide (rather than being open apertures of width 1 mm) through which he thinks groundwater will flow much faster than Cai and Ofterdinger (2014) calculated. However, Cai and Ofterdinger (2014) assigned this aperture a hydraulic conductivity of 0.73 m sˆ-1 which means, for the specified width, a transmissivity of 7.3 x 10ˆ-4 mˆ2 sˆ-1. A subsequent worldwide inventory analysis of drillcore transecting faults, by Ishii (2015) (another reference that Smythe, 2016, does not cite), including data from Sellafield in northwest England, reports an upper bound to fault transmissivity of ∼10ˆ-4 mˆ2 sˆ-1. Rather than being a ridiculously low value, the higher upper bound to transmissivity considered by Cai and Ofterdinger (2014) thus appears to be an exaggeration; these authors were indeed aware of this possibility, since they noted that much of the cross-section of fault ‘damage zones’ is occupied by rock fragments and carbonate precipitates, so does not provide a conduit for groundwater flow. The true timescale for contamination from fracking fluid to reach shallow aquifers used for water supply is thus likely to be much longer than the ‘worst case scenario’ estimate by Cai and Ofterdinger (2014), especially if steps are taken to avoid fracking near faults, which might be based on estimation of dimensions of induced fracture networks and/or geophysical logging to reveal the faults (see below).

Smythe (2016) is also highly critical of the Fisher and Warpinski (2012) paper, which demonstrates that the vertical extents of the induced fracture networks produced by fracking have a limit of ∼600 m. Smythe (2016) queries these authors’ choice of case study localities, when Fisher and Warpinski (2012) clearly state that they chose the four localities with the most data, and questions the fact that the underlying dataset is proprietary. However, partial disclosure of ‘anonymized’ proprietary datasets is common in Earth Science, when the only alternative would be non-disclosure, which would benefit no-one. For example, the BGS / DECC assessments of the shale resource in Britain (Andrews, 2013, 2014; Monaghan, 2014) make extensive use of confidential borehole datasets, which have been reported to BGS (a legal requirement in the UK) on condition that essential details are not made public. Fisher and Warpinski (2012) also showed from first principles, using fracture-mechanical theory by England and Green (1963), how the observed limit to induced fracture growth follows from the practical limit to the volume of water available per frack job. Westaway and Younger (2014) and Westaway (2015) have subsequently showed that this theory accounts for the upper bound to the size (expressed as magnitude or seismic moment) of induced earthquakes caused by fracking (cf. McGarr, 2014). As Westaway (2015) has pointed out, the current regulatory limit for water volume used per frack job (introduced by the Environment Agency for England and supported by the Scottish Environmental Protection Agency for Scotland) of 750 m3 imposes an effective limit of induced fracture growth of ~250 m; the ~600 m limit observed in North America (Fisher and Warpinski, 2012) arises because in U.S. and Canadian jurisdictions developers routinely use much larger volumes of water per frack job, this being one aspect where regulation is relatively tight in the UK (rather than being hopelessly lax as Smythe, 2016, has claimed; see, also, below). In summary, rather than being 'severely flawed', as Smythe (2016) has claimed, the Fisher and Warpinski (2012) study is of fundamental importance; it indeed represents a milestone in understanding the physics of fracking.

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Implications for regulation

As regards the implications for public policy and regulation of fracking and the shale industry in general, I am afraid that I disagree with almost everything Smythe (2016) has written. In most respects the shale industry is being regulated in the UK by applying directly, or building upon, existing regulations covering drilling and other industrial activity, which have in most cases operated uncontroversially for many years and are accepted as conducive to environmental protection. His repeated claims that regulation of shale in the UK is extremely lax can therefore be discounted. For example, Smythe (2016) states as an example of supposed laxity that developers are allowed to drill through faults. However, if there were such a prohibition, datasets on the physical properties of faults, such as that recently analysed by Iichi (2015), would be unobtainable, which would mean that misinformation on this topic would not be open to challenge. Smythe (2016) later suggests that it is essential to be able to detect faults using geophysical techniques, so they can be avoided when fracking, but in the absence of drilling there would be no way to validate such investigations. Smythe (2016) also claims that no method currently exists for detecting faults within shale, but Dohmen et al. (2014) have described one approach, known as 'sacrificial well completion', in which shale well laterals are drilled then logged; if a fault is detected (say, from a gamma ray log), a number of planned frack stages on either side of it are skipped, to reduce the risk of induced fractures intersecting this fault. A similar approach may well prove feasible in Britain, but would of course require calibration for the physical properties of the local shales. Smythe (2016) implies that determination of such 'stand off' distances should be a matter of government regulation, but it is arguably more reasonable to leave this to the judgement of shale operators, who will have to balance losses of revenue from the reduced gas production from the 'skipped' frack stages with the possibility of compensating local residents for the nuisance caused by any induced seismicity (see below) and the costs any other environmental issues that might result.

Most of Smythe's (2016) account conflates reporting on what happened at Preese Hall in 2011 with what will be permitted in the UK in future, when in the meantime a regulatory framework has been put in place. As Westaway (2015, 2016) has already discussed, it is clear that the sequence of actions at Preese Hall was far from ideal; the need to do things differently in future is accepted by all stakeholders in this field. For example, as soon as the induced seismicity started, it should have been realised by applying the series of standard tests established by Davis and Frohlich (1993) that the fracking was the cause, so it should have ceased, pending further investigations, rather than continuing for almost two months until being 'voluntarily' terminated just before the UK government imposed a moratorium. As another example, the in situ stress dataset collected during drilling of Preese Hall-1 might have been analysed before the fracking began, rather than afterwards, and might thus have alerted the operator to the high differential stress in the vicinity and that faults in this vicinity were therefore already near critically stressed, meaning that a clear possibility was apparent that fluid pressure increases associated with fracking might cause induced seismicity. As an alternative, a literature search might have been carried out on the state of stress in Britain, which might have located publications that document measurements indicative of high differential stress (e.g., Cartwright, 1997; Mark and Gadde, 2008). Alternatively, the work of Pine and Batchelor (1984) might have been consulted; this explains why the 1980s' 'hot dry rock' geothermal energy project in Cornwall 'went wrong', as a result of the effect of high differential stress on its geometry of hydraulic fracturing. As a final alternative, they might have read the Westaway et al. (2006) and Westaway (2010) publications that had reported the first discoveries of active faults in Britain and thus provide prima facie evidence of high differential stress at shallow depths. In the light of such information, Cuadrilla might reasonably have decided that the Preese Hall-1 site, which was known to adjoin faults recognized on existing seismic reflection profiles (such as that in Fig. 1(a)), was too 'risky', and might thus have switched their first attempt at fracking to one of their other boreholes in the area.

The one instance of a completely new form of regulation, introduced into the UK since 2011 and praised by Smythe (2016), is the current 'red traffic light' system for 'regulating' induced seismicity, which entails shutting down fracking operations if any earthquake of magnitude >=0.5 occurs. However, as previously discussed (e.g., by Westaway and Younger, 2014), such small earthquakes pose no risk of damage and will probably not even be felt; they might well also be difficult to detect given ambient levels of ground vibration from a wide range of sources in this densely-populated country. Smythe (2016) has argued that shale developers should be made to compensate local residents for 'earthquake damage', but the aforementioned limitation on the magnitude of induced earthquakes, associated with the regulatory limit on the volume of fracking fluid used, means that 'damage' is most unlikely and one is dealing, at worst, with the possibility of 'nuisance' from ground vibrations (Westaway and Younger, 2014). It is reasonable for developers to compensate for such nuisance, if it exceeds a specified threshold, but this threshold should be set based on strength of ground vibration, not earthquake magnitudes, as has been done in the UK for many years for other forms of 'nuisance' ground vibrations such as those arising from quarry blasting (Westaway and Younger, 2014).

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Conclusions

Smythe (2016) is arguably correct to infer that the seismogenic fault plane for the 2011 Preese Hall induced seismicity transected the Preese Hall-1 borehole within the Hodder Mudstone Formation and was responsible for the deformation experienced by this part of the wellbore. However, this is not a new deduction, as I have already published it; moreover, the geometry proposed by Smythe (2016) is incorrect in detail, being based on projection from hypocentral co-ordinates reported by Clarke et al. (2014) which were themselves mislocated. Much of the rest of his paper is based on selective use of the literature; he attacks or omits to cite much of this literature and bases his conclusions on work with known flaws as long as it supports his anti shale gas agenda. His inference that regulation of the shale industry in the UK is lax is absurd; much of this regulatory framework has developed by applying directly, or building upon, existing regulations covering drilling and other industrial activity, which have operated uncontroversially for many years.

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Figure 1.

Adaptation of a Powerpoint slide that I presented at the 'Geomechanical and Petrophysical Properties of Mudrocks' meeting at the Geological Society, London, on 17 November 2015. (a) Excerpt from a west-east-trending seismic reflection profile passing ∼400 m north of the Preese Hall-1 wellhead, shot in 1983 and interpreted by de Pater and Baisch (2011), re-published with adaptations as Fig. 3 of Westaway (2016). (b) Excerpt from the 3-D seismic reflection survey that was commissioned by Cuadrilla in 2012, following the 2011 induced seismicity, rendered as a vertical section. This excerpt is part of Fig. 4 of Clarke et al. (2014), but I have shaded it (using information from de Pater and Baisch, 2011), to depict the stratigraphy; it is published as Fig. 4 of Westaway (2016). The red bar in the base shows the interpreted position of the 2011 seismogenic fault, from Westaway (2016), the red circle and brown bar on the figure being the hypocentre and fault plane interpreted by Clarke et al. (2014), which I regard as incorrect. Further details are provided in the Westaway (2016) figure captions. Both parts are ornamented to summarize (in yellow) the Westaway (2016) interpretation that the seismogenic fault plane is steep below the Hodder Mudstone Formation, then flattens upward into this formation, where it runs through the zone of wellbore deformation that is depicted as a white spot on the black Preese Hall-1 well track. It is also tentatively suggested that the same fault might steepen upward and continue upward for some distance, possibly coinciding with one of the faults depicted in part (a), although this cannot be verified in part (b) as Clarke et al. (2014) obliterated this part of the diagram with their excessively large label.

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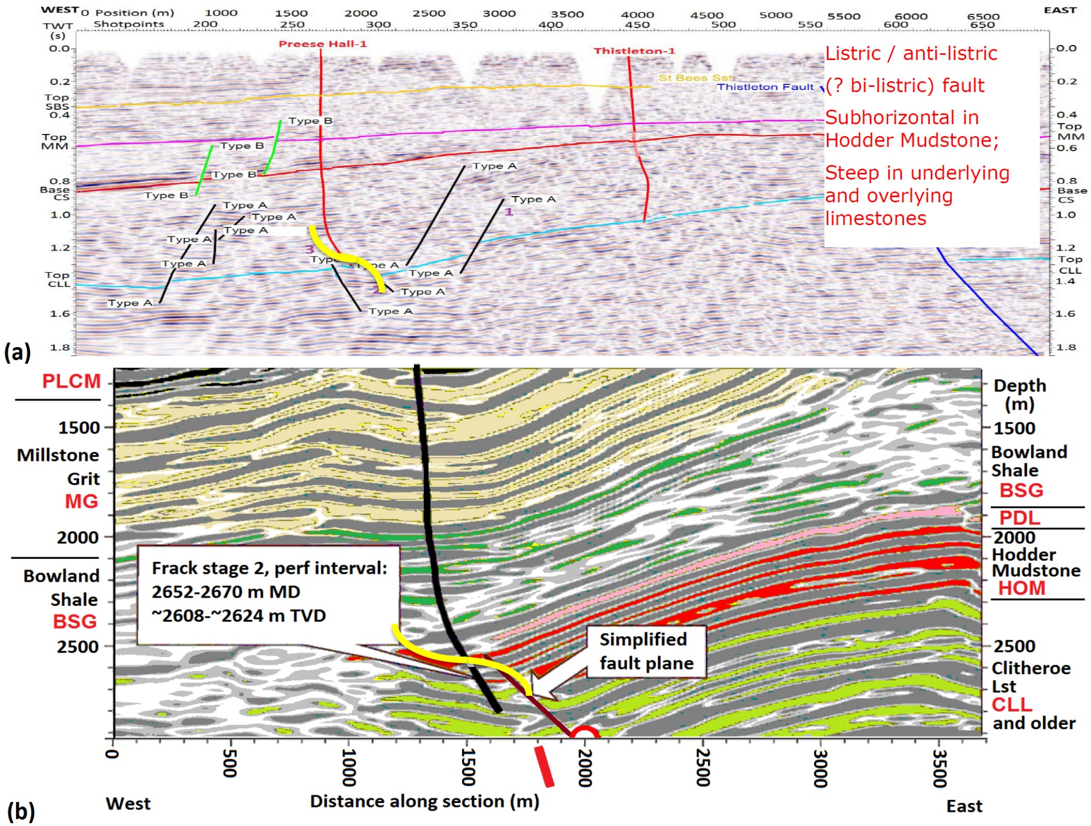

Fig. 1. Please refer to the main document for this Figure caption.

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