Smythe: Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald Basins, UK

I have chosen here to focus this review on the main aspects of the paper.

The title of the paper is promising, suggesting a focussed and scientific study of issues related to the identification and accurate location of faults in shale-rich sequences; this would have been relevant to discussions surrounding the safe and effective exploitation of shale gas. Indeed, the vertical migration of water, CO_2 and hydrocarbons is a subject of general interest to those interested in the rates and mechanisms by which fluids move in sedimentary basins.

Agreeing to review this paper, I had hoped that it would either be a scientific study or a review of the state of the art. It is neither, in that (a) no new data are presented with which to test a hypothesis and (b) the relevant literature is not reviewed in a helpful, insightful and unbiased way. It turns out that the title of the paper is wholly misleading; one part of it does indeed comment on the difficulties associated with the accurate location of faults using poor quality seismic data, but much is an invective-strewn commentary on other issues, loosely drawn together as a general discussion of potential shale gas exploitation in the UK.

The starting point of the paper is that in terms of risking faults as fluid conduits from target shales to surface, US shale gas experience cannot be extrapolated to the UK (and indeed Europe) since UK basins are extensional (but reactivated) basins, have thick shale sequences and are more likely to have (a) more faults generally and (b) more faults which cut from target shale to surface. This key assertion – which would be interesting if proven - is based on an unpublished desk study and no references are given. So, the underlying premise of the paper is missing.

Section 1.1 reviews “faulting in relation to fracking” (what does this mean – that faults result from hydraulic fracturing?) but primarily questions whether or not a key industry dataset on the locations of induced earthquakes is complete or has had “inconvenient results” omitted”. The author does not present evidence for this and appears not to have looked at the supplementary literature which relates frack fluid volumes to the likely maximum height of hydraulic fractures. Nor does he comment on Hammack et al.’s (2014) field study of the fracture growth and fluid migration in the Marcellus– perhaps a study by the US DoE is less likely to have been redacted? Whilst none of these studies can conclusively prove that induced hydraulic fractures absolutely cannot penetrate from target shale to shallow aquifers, it is essential to present a balanced picture of what the currently amassed data indicate and what their true implications are. In the context of where this paper leads, which is the risk of fluid flow from shale to fault and then along faults, it would have been more useful to review the extent to which microseismic data reflect frack-related changes to shale structure and also how accurately they indicate changes to the small- to large-scale permeability structure of target horizons. Das and Zoback’s (2013) work is also interesting in this respect, since microseismic data do not tell the whole story.

Section 2 is basically irrelevant to the paper and should be removed.

Section 3 discusses the Bowland Basin: its general structure, a very basic introduction to its stratigraphy, a review of available seismic data, its hydrogeology and then a reinterpretation of the location of the fault along which an earthquake was triggered, relative to the position of the wellbore. Much of the background material is unfocussed and thus unhelpful. Going back to the title of the paper, very little information is given about (a) the distributions of faults which can be seen, (b) faults which are likely to be missing on a seismic dataset of a given vintage/quality and (c) those which are can never be seen on seismic. The geophysical community is well aware of the limitations of seismic data and there is a very significant literature on the relation between fault density and length/throw. Both these ideas are relevant to discussions about the safe and effective exploitation of shale resources, but could be condensed into a couple of sentences – or could be expanded into a sound and useful review. The work presented in this paper does neither effectively.

Section 3.2 concerns the hydrogeology of the region. However, it contains almost no hydrogeology (e.g. hydraulic head data, fluid flow measurements), just some rather random salinity data which alone are not relevant to discussions on regional fluid flow or the possibility for upwards fluid flow, which is a central issue in this paper.

The location of the key fault, its proximity to the drilled well and the relation to the induced earthquake is one of the stronger and more focussed parts of the paper (Sections 3.3-3.6). Nevertheless, the subject has been looked at previously and similar material has been published recently by e.g. Westaway (2015). The conclusion that faults can be difficult to observe in thick shale sequences may indeed be valid but does not derive from the analysis in this paper.

Section 4 concerns the identification of faults in the Weald Basin. Key conclusions are that even faults with significant throws may not be visible on old, low quality 2D seismic lines, but that they *can* be interpreted from detailed log and stratigraphic data. Sound - but hardly novel. Section 4.2, which relates to Celtique's drilling application, contains no useful or scientifically relevant material.

Section 5 concerns the potential for faults to act as sub-vertical conduits for fluids – frack fluids, gas or water. This is a topic which has exercised geoscientists for decades, as expressed in standard hydrogeology textbooks and in copious primary literature – which is not reviewed. In this paper, certain modelling studies have been selected to paint an overall picture that contamination of drinking water aquifers is likely as a result of flow along faults – see Table 2. A much more critical approach is needed and to a large extent this has already been covered in papers such as Birdsell et al. (2015), who not only reviewed previous work but also undertook a series of new 3D flow models incorporating robust estimates of permeability and a range of key processes including capillary imbibition. Birdsell et al.'s basic conclusion was that a "permeable pathway" from fracked zone to near-surface was needed in order for any gas/frack fluid to reach e.g. a drinking water aquifer. No surprise there but note that the permeable pathway in Birdsell et al's model extended continuously from fracked unit to surface and had a permeability throughout its length of $8x10^{-11}$ m^2, i.e. that of a sand. What is the evidence that faults through shale-rich sequences have anything like such permeabilities?

Predicting the flow (rate and volume) of gas or frack fluid to and then along a fault requires a set of data which are difficult to obtain. Issues include: shale matrix (relative) permeability; imbibition of water; the permeability of fractured shale; the volume of fractured shale in hydraulic connection to the fault on the appropriate timescale; the permeability of the fault throughout its length (and how it changes if there is slip); the volume of fluid transmitted to the fault; overpressure prior to fracking;

pressure changes as a result of fluid injection. In a thoughtful review, all of this needs to be covered critically; most has been in e.g. Birdsell et al., but not in the current paper – a very fundamental flaw.

Other comments have covered the discussion regarding the drinking water contamination at Bradford County but to use it to support the idea that faults are important leakage routes is disingenuous. The concluding statement in Llewellyn is that "the data released here do not implicate upward flowing fluids along fractures from the target shale as the source of contaminants but rather implicate fluids flowing vertically along gas well boreholes and through intersecting shallow to intermediate flow paths via bedrock fractures". That is, an uncased borehole is implicated for most of the leakage pathway, and it is unclear whether frack fluids derived from the fracking process.

The final section relates to the regulatory regime in the UK. I doubt that this is of broad interest to the readership of Solid Earth Discussions, and I suggest that essentially all of this material is removed; some material comes over as rant, whereas a brief and reasoned comment on how fault properties might be reasonably assessed prior to drilling would be a more useful contribution.

Finally, there are a considerable number of personal and contentious comments regarding the integrity and understanding of both individuals and organisations. None are substantiated and all should be removed.

Andrew Aplin