Reply to Dr Rob Westaway (SC2)

I am responding to Dr Westaway's comments using his own headings. This is an interim reply, since interactive comments close on 1 April 2016, and the Preese Hall fault problem deserves more detailed consideration following the release of the CMI log image by Mr Kingdon (SC15) on 29 March 2016.

Introduction

Dr Westaway's introductory comments begin in an antagonistic manner, particularly as in his initial comment SC1 dated 3 February 2016 he tried to present, in the guise of a standard Harvard-type citation, 'Seamark 2014'. This 'paper' was nothing less than a smear piece published in the UK tabloid press quoting some precipitate and abusive comments made about me by another UK academic. That version of his comment was removed by the editor at my request, as it fell well below the standards required of the journal discussion. However, once the discussion turns to the science, particularly of Preese Hall, it appears that Dr Westaway and I do share a lot of common ground.

Geometry of the Preese Hall induced seismicity

Dr Westaway starts this important topic with a reading list:

> *"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"*

Westaway and Younger (2014) deals with the limitations of the 'traffic-light system of earthquake monitoring using local magnitude M_L. Although I have some sympathy with the authors' views, I did not discuss this paper, because it is peripheral to the main problem. The commentary (Younger and Westaway (2014) on my submissions to Lancashire County Council is nominally in the public domain, as all submissions to LCC should have been, but I only became aware of its contents in summer 2015. As the new frontispiece intimates, it is now somewhat of historic interest, as the authors' more recent work has superseded their views expressed in that report.

I could hardly have cited his latest paper (Westaway 2016) in a paper submitted on 22 December 2015, when his own paper only went online on 7 January 2016. However, I am grateful for the chance to discuss it here. He and I evidently share some common ground.

Like Dr Westaway, I too was confused by the mismatch of the illustration of the focal plane solutions (Clarke et al. 2014, fig. 4) with the geometry of the fault orientation. This is given by Clarke et al. in supplementary publication B as "*strike, dip and rake of 40°; 70°; -150° (resp. 299°;*

62º; -23º)". However, the second triplet of figures matches the illustration well if one assumes that white quadrants represent compression.

The uncertainty in the fault planes is stated to be about 20º. Clarke et al. concluded that all three earthquake studies have very similar locations and mechanisms, being no more than 170 m apart (supplementary publication A). For that reason I accepted their hypocentral location.

Westaway accuses me of basing my interpretation on "*uncritical acceptance of the accuracy of this Clarke et al. (2014) hypocentre*". I do not intend to enter the hypocentral location discussion here, suffice to say that the seismological data are rather poor. For some arrivals there is even doubt about the polarity as well as the onset time. Dr Verdon (comment SC8) shares my misgivings.

In my view the most important data (for which, unfortunately, we only get a tiny sample) are the 3D seismic data and its interpretation. We do not even need a hypocentral location to identify a fault or fault zone. I reproduce here the line drawing I prepared for my response to Huw Clarke (Figure 1 below), but this time with the oblique view of the time slice at 2930 m visible.

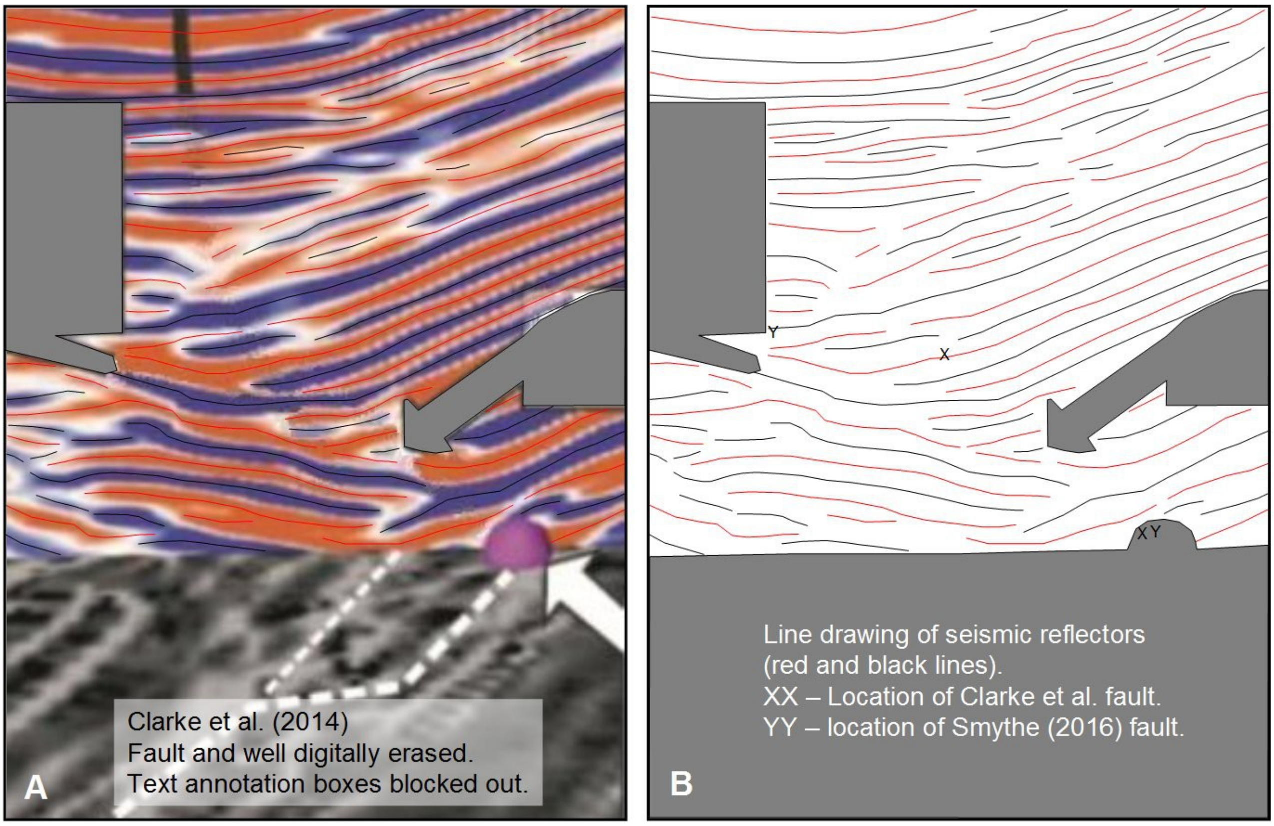

Figure 1. A. Clarke et al. (2014, fig. 4) sample of east-west 3D seismic through the Preese Hall-1 well. The grey-shaded lower part is an oblique view of the seismic timeslice at 2930 m depth, with a bifurcating fault picked by them shown as a dashed line.

B. Line drawing of reflectors with alternative fault positions noted. The semicircle on the lowermost blocked-out area is the upper half of the hypocentral location.

Figure 2 is an attempt to portray the 2930 m depth timeslice on a map. The bifurcating fault shown on the timeslice (white dashed lines) follows a light event on the timeslice. The interpreted fault (Clarke et al. 2014, fig. 1) seems to be picked (red line) through the middle of what could be interpreted as being more of a complex fault zone than the discrete line mapped by Clarke et al.

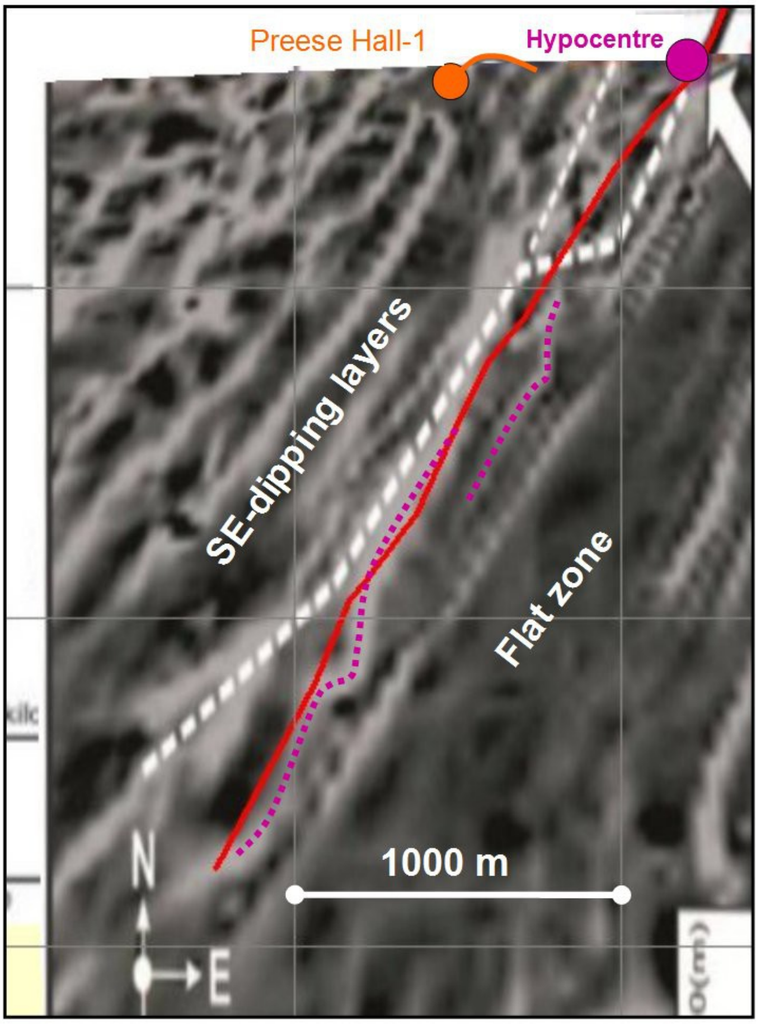

Figure 2. Timeslice of Clarke et al. (2014) anamorphically stretched to fit a map of the Preese Hall-1 locality. The fault interpretation of Clarke et al. (2014, fig.1) from their map is shown in red, and the fault(s) as marked on the timeslice are shown by white dashed lines. Dotted lilac lines are other possible fault structures

In my view the 3D seismic evidence of a fault zone is stronger than any inference from hypocentral locations and focal plane solutions.

The fault zone passes through the lower part of the wellbore, but there is another problem in locating the wellbore on the seismic image. The wellbore deviation shown in Clarke et al. is steeper by a few degrees than the shape implied by the now-released well coordinates, implying that the well as depicted on the 3D seismic image has not been accurately placed. Dr Westaway has just pointed this out independently (SC17). The seismic image cannot be located precisely either to the

OS grid system or to the well top. In short, there are too many unknowns either for myself or for Dr Westaway to attempt to pinpoint precisely where the fault lies.

Another important piece of information is the CMI image spanning the deformed wellbore section. This was only made available by Mr Kingdon of the BGS in his comment (SC15) on 29 March 2016. Clearly the well casing deformation must have been by bedding plane slip, as first recognised by de Pater and Baisch (2011), so the problem now is how to reconcile bedding plane slip over 160 m of the wellbore with the fault zone passing through the well.

Selective referencing

Contrary to what Dr Westaway states, I did not "*praise*" the Myers (2012) paper. I cited (briefly) the various critics (see my organogram, fig. 9), and did, however, point out that although unsuitable for Appalachian geology the model Myers used might have some applicability in a UK setting.

Regulation

I have commented in my response to Dr Verdon on this subject, and also provided in my reply to Professor Younger a lot more new evidence explaining why I am concerned; firstly, about the EA's view on the non-potability of groundwater at 300 m below the Fylde, and secondly, the still poorly-known location of the important Woodsfold Fault, which separates the largest groundwater resource in NW England from the Fylde.

But there is one other point of discussion that Dr Westaway has raised, the subject of regulating drilling through faults. He believes that I consider that this should be prohibited. But I did not imply that; explorationists can hardly avoid faults, and, indeed, often penetrate them unknowingly. Water drillers target shallow faults because they have the best hydaulic conductivity. What I wish to see better regulated in the UK is drilling through or near to faults at or above a shale volume to be fracked. We are in some measure of agreement here, except that I would never entrust a decision to a developer, to decide whether or not to drill or avoid a fault, on the Panglossian premise that the develop will make a sound economic judgment.

References

Clarke, H., Eisner, L., Styles, P., Turner, P., 2014. Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe. Geophysical Research Letters, 41, 8308–8314.

Westaway, R., 2015. Induced Seismicity. In: Kaden, D., Rose, T.L. (eds.), Environmental and Health Issues in Unconventional Oil and Gas Development. Elsevier, Amsterdam, pp. 175-210.

Westaway R., 2016. The importance of characterizing uncertainty in controversial geoscience applications: induced seismicity associated with hydraulic fracturing for shale gas in northwest

England. Proceedings of the Geologists' Association. Doi: 10.1016/j.pgeola.2015.11.011, 17 pp.

Westaway, R., Younger, P.L., 2014. Quantification of potential macroseismic effects of the induced seismicity that might result from hydraulic fracturing for shale gas exploitation in the UK. Quarterly Journal of Engineering Geology and Hydrogeology, 47,333–350.

Younger, P.L., Westaway, R., 2014. 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. Report to Lancashire County Council, 12 pp. + 1 p. preface. University of Glasgow; available online: http://eprints.gla.ac.uk/108343/
