Solid Earth Discuss.,
doi:10.5194/se-2015-134-SC10, 2016

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

R. Westaway

robert.westaway@gla.ac.uk

Received and published: 4 March 2016

The latest comment on the Preese Hall saga, by Clarke (2016), raises a number of issues that have not previously been covered in this thread.

The first of these concerns uncertainties in the geometry of the induced seismicity and the related seismogenic fault. Clarke (2016) is correct to state that one expects location of any microearthquake using only a small number of seismograph stations to be subject to considerable uncertainty. However, a key issue, which I attempted to convey both in my recent publication (Westaway, 2016a) and in my previous commentary (Westaway, 2016b), is that in addition to the forms of uncertainty that one expects in any microseismic study, the Clarke et al. (2014) analysis included some pretty fundamental errors. Other studies that have managed to avoid such mistakes, such as my own, are therefore inherently more likely to yield correct results.

Second, the geological structure at Preese Hall-1 and neighbouring boreholes, presented in Fig. 1 of Clarke (2016), differs dramatically from that which has featured in all previous literature on this topic, including the illustrations in my own recent outputs (Westaway, 2015, 2016a, 2016b). He now reports that the Emstites leion (Cravenoceras leion, or E1a1) marine band, which defines the boundary between the Visean and Namurian stages of the Carboniferous, at ∼2500 m depth (MD) in the Preese Hall-1 borehole. This means, essentially, that the part of the sedimentary succession that was previously reported (e.g., in my publications) as the Bowland Shale Formation has been reinterpreted as merely the ‘Upper Bowland Shale’ (i.e., the upper, or Namurian, part of the Bowland Shale Formation). The rocks penetrated at greater depths (previously interpreted as the Pendleside Limestone, Hodder Mudstone, and Clitheroe Limestone formations) have thus been reinterpreted as the upper part of the ‘Lower Bowland Shale’ (i.e., the upper part of the lower, or Visean, part of the Bowland Shale Formation). In this revised scheme, the complexity in the gamma ray and sonic log records, reported by Clarke (2016), indicates alternations between mudstone-dominated and limestone-dominated bedding, as was previously documented, but the limestone thus revealed is internal to the Bowland Shale Formation and not indicative of other formations. If this substantial reinterpretation (the basis of which has not been explained, as far as I am aware) is correct, it means that the deepest frack stages of the Preese Hall-1 well and the associated wellbore deformation were in the upper part of the ‘Lower Bowland Shale’, rather than in the Hodder Mudstone Formation as was previously thought. This change does not affect the conclusions reached in earlier publications (including mine), although it means that the labelling of many figures (including mine) is incorrect. It is nonetheless extraordinary for such an important revision to stratigraphy to be published (apparently in the first instance, as no reference is cited) as part of a commentary on another paper rather than as a publication in its own right.

Third, the excerpt from the 3-D seismic section that was originally published by Clarke et al. (2014) and was re-published by Westaway (2016a, 2016b) with stratigraphic labelling, shows the component of section-parallel bedding dip changing downward from westward, across a zone of deformed bedding, to eastward in the deepest ∼200 m of the Preese Hall-1 well. In contrast, measurements made from the borehole image log, reported by Harper (2011), indicate that the bedding in this depth interval dips WNW at ∼30-40°, steepening downward to ∼70-80°. These two forms of evidence pertaining to the bedding are inconsistent. One possible explanation, tentatively raised by Westaway (2016a) on other grounds, is that Clarke et al. (2014) did not draw the well track on the seismic section in the correct place. However, at no point on this seismic section does the bedding appear steeper than ∼30° in any direction, raising the alternative possibility that the image log has yielded incorrect information. This aspect requires resolution. As Westaway (2016b) noted, this 3-D seismic reflection dataset remains unpublished, except for the excerpt reported by Clarke et al. (2014). In the circumstances it is not helpful for Clarke (2016) to criticise Smythe (2016) for not using this 3-D seismic dataset, to which (like me) he has no access. Given the necessity for the British public and the UK scientific community to develop confidence that potential environmental issues relating to shale gas (such as induced seismicity and wellbore deformation) are understood, timely publication of this and the various other essential datasets, relating to the Preese Hall-1 well, which are not yet in the public domain, is strongly recommended.

Fourth, Clarke (2016) criticizes the Smythe (2016) interpretation that the 2011 seismogenic fault cut across the Preese Hall-1 borehole, accounting for the observed wellbore deformation. However, as previously discussed (Westaway, 2016b), this struck me as pretty much the most useful aspect of the Smythe (2016) contribution, since it confirms – in general terms – my own stated view; the principal problem with it being that it was based on an incorrect geometry of the fault, having been confounded by some of the mistakes in the original Clarke et al. (2014) publication. From de Pater and Baisch (2011) and Harper (2011), the wellbore deformation was concentrated

between depths of ∼8500 and ∼8650 feet (MD) (∼2591-2637 m MD), equivalent to ∼2540-2590 m (TVD). This is close to what was previously interpreted as the top of the Hodder Mudstone Formation, just below the base of the Pendleside Limestone Formation, and is now regarded as near the top of the Lower Bowland Shale, not far below the aforementioned Emstites leion marine band. De Pater and Baisch (2011) reported that the bedding in this vicinity dips WNW at ∼30° and the wellbore deformation involved strike-parallel shearing, at an azimuth of ∼N30°E, but due to the ambiguity inherent in such measurements (using a multi-fingered caliper tool) had no means of resolving whether the sense of shear was top-to-the-NNE or top-to-the-SSW. This part of the stratigraphic succession consists of interbedded mudstones and limestones; the correlation between the gamma ray log and the wellbore deformation indicates that slip occurred on bedding planes at changes in lithology (cf. de Pater and Baisch, 2011; Harper, 2011). Clarke (2016) is correct to note this interpretation of bedding plane slip, but it does not mean that the slip was not caused by the induced seismicity; the Dusseault et al. (2001) reference cited by Clarke (2016) indeed includes examples of bedding plane slip caused by seismicity. Figure 1 indicates schematically in cross-section how this bedding plane slip might have linked to the coseismic faulting; the inferred geometry resembles a conventional ‘horsetail splay’ (e.g., Sylvester, 1988) or ‘contractional imbricate fan’ (e.g., Woodcock and Fischer, 1986) fault termination. From consideration of the magnitude (2.3) and, thus, seismic moment, of the largest Preese Hall induced earthquake, a coseismic displacement of ∼10 mm can be estimated (cf. Westaway and Younger, 2014); it is envisaged that, beyond the up-dip limit of this fault, this shear displacement would have been partitioned across the various planes of weakness within the deformed zone. One reason why this wellbore deformation has not hitherto been associated with the induced seismicity was that Clarke et al. (2014) located the seismicity so far from the wellbore. This argument was superseded by the realisation of the mistakes in their paper and the resulting adjustment of the position of the seismogenic fault much closer to the wellbore (Westaway, 2016a). Another reason has been because de Pater and Baisch (2011) were unable to identify a clear conceptual link between the seismogenic fault and the wellbore deformation. Since such a link is now evident (Fig. 1), this issue warrants further attention. In the meantime, I note in passing that Clarke's (2016) comment that 'all of the evidence collected to date supports the observation that the wellbore was within 300 m of a fault but does not intersect it' is not in fact correct. On the contrary, it would appear that the wellbore intersected the 'horsetail splay' or 'contractional imbricate fan' at the up-dip termination of this fault (Fig. 1); by most definitions this is regarded as part of the fault.

.

References

Clarke, H., 2016. Reply to "Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald Basins, UK" by D.K. Smythe. Interactive Discussion item SC9, 7 pp. Available online: http://www.solid-earth-discuss.net/se-2015-134/#discussion (accessed 3 March 2016)

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.

de Pater, C.J., Baisch, S., 2011. Geomechanical study of Bowland Shale seismicity: synthesis report. Cuadrilla Resources Ltd., Lichfield, 71 pp. Available online: http://www.rijksoverheid.nl/bestanden/documenten-en-publicaties/rapporten/2011/11/04/rapport-geomechanical-study-of-bowland-shale-seismicity/rapport-geomechanical-study-of-bowland-shale-seismicity.pdf (accessed 3 March 2016)

Dusseault, M.B., Bruno, M.S., Barrera, J., 2001. Casing shear: causes, cases, cures. SPE paper 72060. SPE Drilling & Completion Journal, 16 (2), 98-107.

Fisher, K., Warpinski, N., 2012. Hydraulic-fracture-height growth: Real data. SPE paper 145949. SPE Productions & Operations Journal, 27 (1), 8–19.

Harper, T.R., 2011. Well Preese HallâĂŘ1: The mechanism of induced seismicity. Geosphere Ltd., Beaworthy, Devon, 67 pp. Available online: http://www.cuadrillaresources.com/wp-content/uploads/2012/06/Geosphere-Final-Report.pdf (accessed 3 March 2016)

Smythe, D.K., 2016. Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald basins, UK. Solid Earth Discussion; doi: 10.5194/se-2015-134, 45 pp.

Sylvester, A.G., 1988. Strike-slip faults. GSA Bulletin, 100, 1666-1703.

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., 2016a. 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., 2016b. Comment on "Hydraulic fracturing in thick shale basins: problems in identifying faults in the Bowland and Weald basins, UK" by D.K. Smythe. Interactive Discussion item SC2, 8 pp. Available online: http://www.solid-earth-discuss.net/se-2015-134/#discussion (accessed 3 March 2016)

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.

Woodcock, N.H., Fischer, M., 1986. Strike-slip duplexes. Journal of Structural Geology, 8, 725-735.

.

Figure 1. Schematic representation, not to scale, but representing vertical and horizontal distances of up to several hundred metres, of the geometry of faulting associated with the induced seismicity and related wellbore deformation at Preese Hall in 2011. This is a vertical cross-section oriented WNW-ESE depicting the Preese Hall-1 well track (brown), on which a tick marks the part of the casing that was perforated for frack stage 2 that led to the induced seismicity. Vertical blue line marks the geometry of the resulting induced fracture network, which developed in the plane perpendicular to the minimum principal stress and was thus vertical, with an azimuth circa N7°E S7°W (Westaway, 2016a). The induced fracture network is assumed to have developed mainly upwards, rather than downwards, from its point of initiation, as is expected if the pressure of the fracking fluid was only slightly above the minimum necessary for fracture initiation (e.g., Fisher and Warpinski, 2012; Westaway and Younger, 2014). Thick red line indicates the orientation of the fault that slipped in the induced seismicity, which had a focal mechanism with strike 030°, dip 75° and rake 20° according to Westaway (2016a). The predominant sense of slip on this fault plane was thus left-lateral, indicated with dot and cross symbols to denote motions in and out of the section plane, together with a minor component of normal slip, indicated by paired arrows. According to Westaway (2016a), the patch of fault that slipped was south of the section plane, where the fault (oriented perpendicular to this section) intersected the induced fracture network (oriented oblique to the section). From Westaway and Younger (2014), the magnitude and seismic moment of the largest induced earthquake indicate slip on a patch of fault with dimensions of ∼100 m, with up to ∼10 mm of slip. Curved black lines indicate schematically the ‘horsetail splay’ or ‘contractional imbricate fan’ at the up-dip termination of the fault, which is inferred on the basis of the ‘bedding plane slip’ that caused the deformation to the Preese Hall-1 wellbore. Given the ∼30° WNW dip of the bedding in this vicinity, according to de Pater and Baisch (2011) and Harper (2011), based on the borehole image log, this bedding is subperpendicular to the neighbouring steeply ESE-dipping part of the fault. The strike-slip component of motion on the steep part of the fault is thus accommodated by top-to-the-NNE bedding plane slip,

again represented by dot and cross symbols, whereas its normal component of slip is accommodated by contraction, perpendicular to the bedding planes, represented by chevron symbols. This schematic model provides a potential resolution, for the first time, to a significant conundrum relating to this instance of induced seismicity: once the induced fracture network had propagated upwards into the zone of weakness where the ‘bedding plane slip’ occurred, why did the pressure of the fracking fluid not simply force open these bedding planes and the fluid then leak along them into the adjoining steep part of the fault? The answer is that this effect of fluid pressure would have facilitated a component of dip slip on this steep part of the fault in the opposite sense to that observed – reverse slip on the steep, ESE-dipping part of the fault being compatible with tensile opening of the weak bedding planes – and so would have been opposed by the local stress field. In order to induce seismicity, the high-pressure fracking fluid had to enter the steep part of the fault directly, not via bedding planes, which was only possible at the intersection between the fault and the induced fracture network to the south of the borehole. Hence, the seismicity occurred in this more southerly location. This proposed configuration is also consistent, to first order, with the geometry of the fault as imaged on the 3-D seismic section (Fig. 4 of Westaway, 2016a; Fig. 1(b) of Westaway, 2016b), which indicates that the overall ∼100 m of normal slip on its steep ESE-dipping part is accommodated by ∼100 m of contraction in what was formerly regarded as the Hodder Mudstone Formation but is now considered to be the upper part of the ‘Lower Bowland Shale’ (although this seismic section does not show the 30° dip of the bedding apparent on the borehole image log). In detail, the geometry of the deformation is more complicated than is depicted here, because the bedding is not precisely perpendicular to the steep part of the fault, the two make an angle of ∼105° (∼75°+30°), so normal slip on the steep part of the fault will be accommodated by contraction and distributed simple shear across the bedding, rather than just contraction.

Interactive comment on Solid Earth Discuss., doi:10.5194/se-2015-134, 2016.

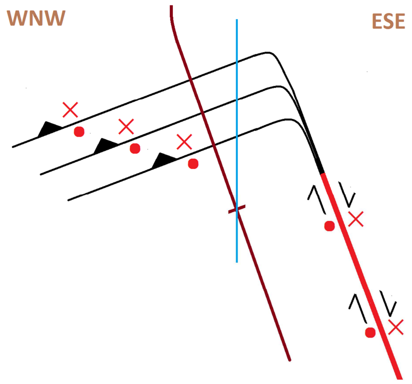

Fig. 1. Please refer to the main document for this Figure caption.