Response to Daniel Birdsell and co-authors

Mr Birdsell has commented under several headings, as follows:

1 Misunderstandings in the literature

1.1 Fisher and Warpinski 2012

1.2 Llewellyn et al. 2015

2 Numerical modelling

I thank him (and his colleagues, on behalf of whom I presume he is writing, since he uses the first person plural) for his comments, and respond below to his sections 1.1 and 2 above. I have considerably revised my analysis of Llewellyn et al. (2015), submitted separately, and trust that this revision will satisfy his concerns cited under 1.2 above. Concerning Llewellyn et al., he might also wish to read my response to Dr Engelder, again, submitted separately.

Misunderstanding of Fisher and Warpinski

Fisher and Warpinski (2012) wrote:

> *"Faults have been suggested as mechanisms for enhancing fracture growth, but this ignores the basic understanding of faults* ***in hydrocarbon reservoirs****. If there is an open path to the near surface through an existing fault, throughout geologic time, all of the hydrocarbons would have escaped and there would be no reason for exploiting the resource."* [my emphasis].
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> *"While faults can offer somewhat better conductive paths, it is not likely that they are conductive over sizeable fractions of the depth because any* ***oil or gas in the reservoir*** *would have escaped through such conduits and there would not be any hydrocarbon exploitation success in that area."* [my emphasis].

I criticised these statements, writing: *"... if faults were conduits they would have leaked all the gas away by now. This is clearly false; the whole point of fracking is to release gas which is trapped and therefore unable to migrate."*

Mr Birdsell has commented on my statement above as follows:

> *"If highly permeable faults did exist, the hydrocarbons would have leaked out of the*

> *reservoir during the millions of years since the hydrocarbons were generated. Smythe has misunderstood the qualitative argument that the presence of hydrocarbons indicates that either there are no faults near* ***the shale reservoir****, or that if there are faults, they do not conduct fluids at a high rate."* [my emphasis].

The confusion has arisen because Fisher and Warpinski describe (correctly) the behaviour of faults in hydrocarbon *reservoirs*, as I have emphasised in the two quotations. Conventionally, a reservoir rock will be a sandstone or limestone, but never a shale. A shale, conventionally, is a source rock or a seal, unless it is (unconventionally) fracked, at which point it becomes both the source and the reservoir. Hydrocarbons are generated within a source rock under appropriate P-T conditions, and will migrate, albeit slowly (i.e. over geological time) upwards into potential reservoirs. Hydrocarbon generation is usually a dynamic process, with ongoing generation and migration, if the 'kitchen' (the source rock at the right depth) is active. The process can even be visualised now with high-quality (offshore) 3D seismic (Aminzadeh et al. 2013). What Fisher and Warpinski say does not apply to very low permeability rocks like shale, because they are not *reservoirs* until they have been fracked.

Take the Marcellus as an example. If a hypothetical permeable fault cuts the Marcellus, only the rock in the immediate vicinity will be drained of hydrocarbons, not the entire layer. Proof of this is the fact that hydrocarbons remain trapped today in the Marcellus, even though the 'cooking' took place some 350 million years ago when it was buried to 4-5 km. If the Marcellus had sufficient permeability for faults to drain it, then all the hydrocarbons would have long ago migrated upwards - a distance of a mere 50 to 100 m - into the overlying Mahantango, even in the absence of faults.

My understanding of shale source rocks is that the gas is mostly trapped by being adsorbed onto microscopic surfaces, and only a small proportion is present as free gas in pore space. Fracking physically transforms this source/seal rock into a reservoir, desorbing the gas, and only then can permeable faults, if present, start to drain the shale.

I largely agree with Mr Birdsell's later discussion about rates of flow and the likelihood of high gas concentration remaining near a permeable fault, but I disagree with his interpretation of Fisher and Warpinski's *"general concept ...* [that] *if there is a high concentration of gas in a source rock, there probably is not a highly permeable fault nearby."* That is not what they said; they twice mentioned faulting in the context of *reservoirs* (cf. the two quotations from Fisher and Warpinski cited above). Therefore I stand by my claim that Fisher and Warpinski miscontrue the importance of faults in having the potential to drain an unfracked shale.

Numerical modelling

I apologise to Mr Birdsell for omitting a proper discussion of his 2015 paper in my review of the development of numerical modelling of flow up faults. I had downloaded it on 29 November 2015, and referred to it in the context of Llewellyn et al. (2015), but had not then given the attention it deserves before submitting my initial discussion paper a month later. I shall add his paper to my organogram and discuss its important contribution in a new section within section 5.2.

References

Aminzadeh, F., Berge, T. B., and Connolly, D. L., 2013. Hydrocarbon seepage: from source to surface, Geophysical Developments Series no. 16, Society of Exploration Geophysicists and American Association of Petroleum Geologists, Tulsa, Oklahoma, 244 pp.

Birdsell, D. T., Rajaram, H., Dempsey, D. and Viswanathan, H. S., 2015 Hydraulic fracturing fluid migration in the subsurface: A review and expanded modeling results, Water Resources Research, 51(9), 7159–7188.

Fisher, K. and Warpinski, N., 2012. Hydraulic-fracture-height growth: real data. Society of Petroleum Engineers Annual Conference Paper SPE 145949, Denver 2011. SPE Production & Operations, February 2012, pp 8-19.

Llewellyn, G.T., Dorman, F., Westland, J.L. Yoxtheimer, D., Grieve, P. Sowers, T. Humston-Fulmer, E. and Brantley, S., 2015. Evaluating a groundwater supply contamination incident attributed to Marcellus Shale gas development. Proc. Natl. Acad. Sci. PNAS Early Edition, www.pnas.org/cgi/doi/10.1073/pnas.1420279112, 2015.