Response to Professor Paul Younger (SC20) and Professor Andrew Aplin (RC1) on Fylde groundwater salinity

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Introduction

The scientific issue here is whether or not the confined aquifer of the Sherwood Sandstone Group (SSG) below the Mercia Mudstone Group (MMG) in the Fylde west of the Woodsfold Fault is saline or not.

Alleged non-citation of previous research

Professor Younger writes:

> "*Smythe then proceeds to "examine the Fylde evidence" – though, breathtakingly, this examination does not engage with a single one of the many hydrogeological studies of the Fylde Aquifer published over the decades (including Allen et al. 1997; Barker and Worthington 1973a, 1973b; Brereton and Skinner 1974; Lovelock 1977; Oakes and Skinner 1975; Seymour et al. 2006; Tellam and Barker 2006; and Worthington 1977).*"

I shall first summarise in turn the relevance of the nine papers cited above by Professor Younger.

Allen et al. 1997. I downloaded this paper on 16 Mar 2015, and cited it in my submission to Nottinghamshire County Council (Smythe 2015). It is also present as an orphan reference in my SED paper (but there is no discussion of it), because I had removed several paragraphs from an earlier draft in an effort to reduce the length of the paper. I shall re-insert these paragraphs discussing Cai and Ofterdinger (2014) in my new paper, and quote them here in Appendix A for the record.

Brereton and Skinner 1974. I do not have access to this paper, but it is discussed in Sage and Lloyd (1978) and Tellam and Barker (2006), both of which I have consulted. All three papers confine their attention to the SSG aquifer at outcrop east of the Woodsfold Fault (Fig. 1).

Barker and Worthington 1973a, 1973b; Worthington 1977. I have now downloaded the first two of these papers, to confirm their non-relevance to the issue; the last I had downloaded on 4 February 2014. All three papers discuss the physical properties of the SSG. Figure 1 in each shows that all the samples come from the outcrop east of the Woodsfold Fault. These papers are cited in

Tellam and Barker (2006). The green dashed line (Fig. 1) encompasses all the boreholes discussed by Worthington (1977).

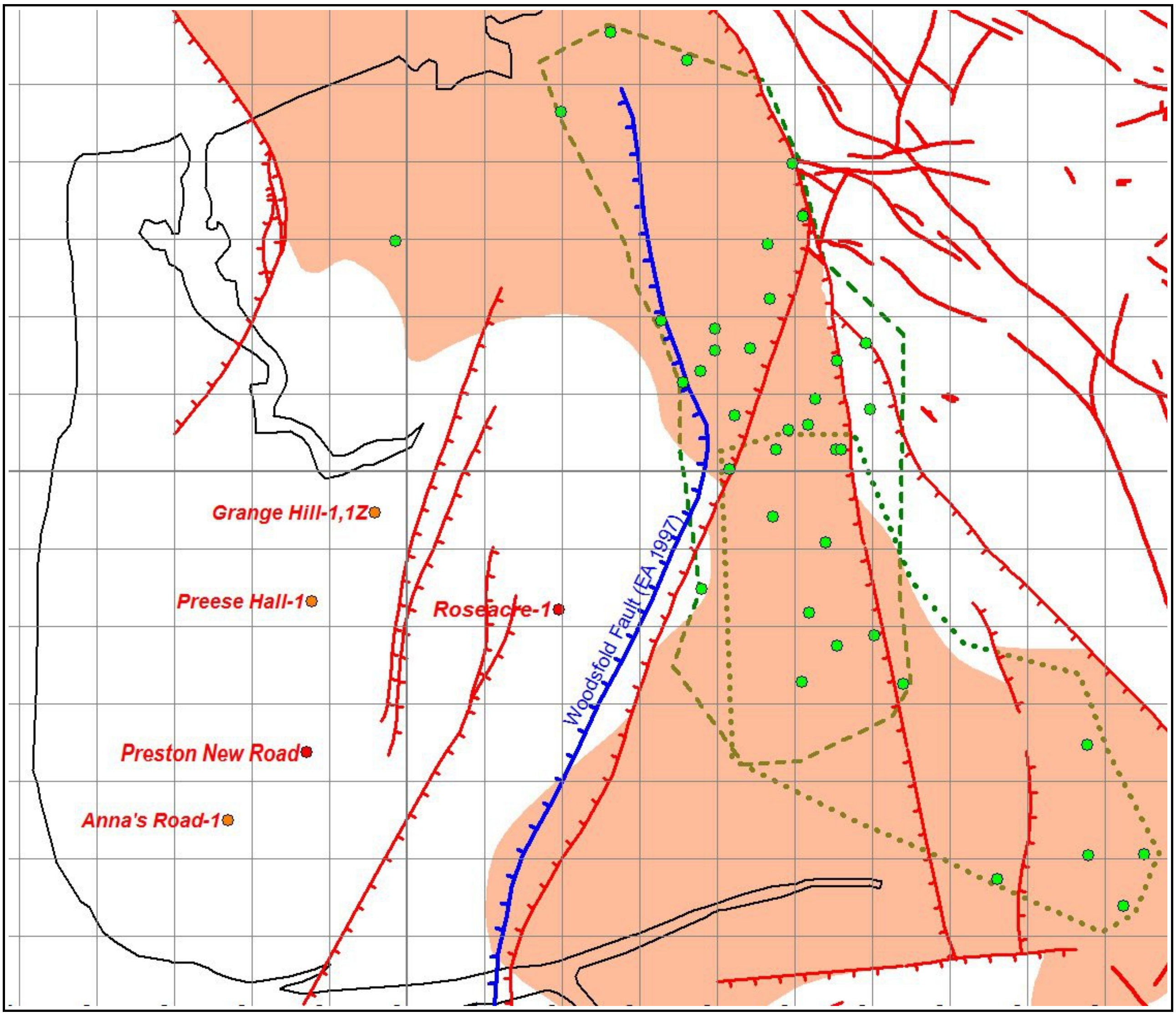

Fig. 1. Outcrop of the Sherwood Sandstone Group (tan shading) in the Fylde. Two versions of the Woodsfold Fault are shown; the EA 1997 in blue and the earlier BGS map version just to the east in red. Other faults (red lines, teeth on downthrown side where known) are from the BGS sheets. Green dotted line encompasses all the boreholes discussed by Seymour et al. (2006); green dashed line those by Worthington (1977). Light green dots are the observation boreholes used in the Fylde conjunctive groundwater studies (Mott MacDonald 1997, 2009). Orange dots – existing Cuadrilla wells; red dots – proposed Cuadrilla wells. National Grid displayed at 2 km interval.

Lovelock 1977. I do not currently have access to this BGS bulletin, but it is presumably a version of the author's thesis (Lovelock 1972), which I downloaded on 2 August 2013 from the UCL website (http://discovery.ucl.ac.uk/1381922/). Field samples of the SSG (known then in the Fylde area as the Bunter Sandstone) were collected from outcrop between Preston and Garstang (i.e.east of the Woodsfold Fault, Lovelock 1972, fig. 14), but no core was studied from boreholes in the Fylde area (Lovelock, op. cit. table 1). Once again, the thesis has no relevance to the issue discussed here.

Oakes and Skinner 1975. I do not have this is a forty-year old reference (slightly mis-cited by Professor Younger), to early mathematical modelling of the Fylde reservoir, but it can hardly be relevant, since I have consulted the much more extensive study which superseded the 1975 model (Mott MacDonald 1997), together with its update and conversion (Mott MacDonald 2009); all downloaded on 6 August 2015.

In Mott MacDonald (1997) the Oakes and Skinner study, referred to by them as Water Research Centre (1975), states:

> *"In the early 1970's, the first extensive pumping tests of the aquifer were undertaken by the former Fylde Water Board and Lancashire River Authority. The data collected during these tests were used in the development of a groundwater model of the Fylde aquifer (Water Research Centre (WRC), 1975)."*

Seymour et al. 2006. I downloaded this on 4 February 2014, and discussed it in my Roseacre Wood objection submission (Smythe 2014), p.26:

> *"The ES states:*
>
> *"In the Fylde area the north-south trending faults are reported to act as barriers or partial barriers to flow in the Sherwood Sandstone" [para. 115, p.302]*
>
> *This statement is supported by reference to Seymour et al. 2006. But it is misleading. The Seymour et al. study divides the Fylde into three areas. In the northern and central areas the predicted hydrogeological model matches well the observed data without modification. These are the two area nearest to the Cuadrilla drillsite. For the third, southerly, area it was found that the numerous N-S faults (5 faults within an E-W distance of 1.5 km according to the cross section of figure 4b of Seymour et al.) did affect the flow in the observation borehole T74. A match of predicted to observed flow was achieved by lowering the flow across the faults to 0.2 m/day within the Sherwood Sandstone Group aquifer, and by setting the regional hydraulic conductivity to 3 m/day, the regional value. So the N-S faults here act as partial barriers,* ***but***

not as seals." [emboldening in original].

Tellam and Barker 2006. I downloaded this UK-wide review of the hydrogeological properties of the SSG on 4 February 2014. The Fylde is only mentioned in passing, either in the context of discussing geophysical survey techniques, or in summarising previous work on regional flow systems where faulting may be important, citing Seymour et al. (2006).

Discussion of the 'missing' citations

All nine of the citations that Professor Younger accuses me of neglecting are either irrelevant and/or outdated. I was previously aware of five of them; I have downloaded two more to confirm their irrelevance, as suspected, and the two remaining, over 40 years old, have been superseded by later work. **None of the work cited by Professor Younger has any bearing on the hydrogeology of the western Fylde, west of the Woodsfold Fault (Fig. 1).** They all concern the SSG aquifer at outcrop. To demonstrate this I have plotted on Figure 1 two green-bordered polygons, each showing the areas encompassed by the boreholes studied in Worthington (1977) – dashed line, and Seymour et al. (2006) – dotted line.

Unlike Professor Younger, I do not believe in citing works which have no relevance to the question at hand. That is why I did not cite these papers.

It is noteworthy that, despite his blunderbuss approach to citations, Professor Younger fails to cite either Mott MacDonald (1997) or its update (Mott MacDonald 2009). These are much more detailed studies, but once again, these hydrogeological modelling studies have no direct relevance to the confined SSG aquifer west of the Woodsfold Fault. However, they do reveal the Environment Agency's thinking on the transmissivity of faults. This is discussed below.

In conclusion, Professor Younger has erected a facade of emphatic assertions, buttressed by numerous citations; but when one examines his story it has no more substance than a cowboy township erected for a spaghetti western – there is nothing behind it. Is Professor Younger seeking to deceive the reader (which I do not believe) or is he lazily recycling half-remembered and mostly obsolete references from his youth? In short, it demonstrates poor scholarship in his own area of expertise – groundwater.

Discussion

In his second comment (SC20) ProfessorYounger has not responded to my criticism (AC8) of his first comment (SC6) under the heading 'Potable groundwater below the Mercia Mudstone Group (MMG)'. I showed that his assertion concerning the impossibility of fresh water in the confined SSG aquifer is wrong, both in logic and in the (unspecified) examples he cites.

The groundwater modelling of Mott MacDonald (1997) and its update (Mott MacDonald 2009) for the Environment Agency concern only the unconfined SSG aquifer at outcrop; although the finite-element modelling grid does locally extend west of the Woodsfold Fault by up to 3 km, the elements here are purely for boundary condition control. In the modelling a number of observation boreholes are used to constrain the modelling. These are shown as green dots in Figure 1. Note that they all, with one exception, lie east of the Woodsfold Fault. So once again, the modelling tells us nothing about the confined aquifer west of the Woodsfold Fault.

Mott MacDonald (1997) states:

> *"*[1] *Flow to the west, across the Woodsfold Fault to the Kirkham Basin is considered to be very low. There is no detailed piezometric evidence to suggest otherwise.* [2] *In addition, the overlying Mercia Mudstone has a very low vertical permeability and thus there is unlikely to be any significant vertical exchange of water between the Sherwood Sandstone and Mercia Mudstone.* [3] *Consequently, there is unlikely to be any significant lateral flow from the Fylde aquifer to the west since there is no obvious point for this inflow to discharge to.* [4] *This boundary was, therefore, defined as a no flow boundary."* [numbering added].

So from [1], the EA asserts, based on no solid evidence, that the flow across the Woodsfold Fault will be low. Next, it assumes [2] that there will be little or no vertical flow – but this assumption ignores the presence of faults cutting the MMG. These could be transmissive pathways, particularly when one considers the stress regime in the uppermost 300 m below ground level.

The EA cannot find a discharge [3] for the flow, if present, but this again ignores the presence of faults, plus the many springs and sources in the area. Lastly, since the Woodsfold Fault is *defined* as a no-flow boundary [4], the lack of westward flow in the model cannot be used as an argument to prove that there is no westward flow.

Neither Professor Younger nor Professor Aplin have commented on the false inference drawn by the EA, based on samples from the Kirkham well taken at MMG depths, that the confined aquifer west of the Woodsfold Fault is saline. The former draws instead on misleading and erroneous analogies with other similar settings, as I have already pointed out (SC6). The latter dismisses all this as "*some rather random salinity data*" (RC1). What does Professor Aplin mean by 'rather random'? Is it that the EA has chosen borehole data at random? Have I, on the other hand, chosen the Kirkham well at random? If he wishes to debate seriously the evidence for the level of salinity in this aquifer he needs greater precision in his argument.

Conclusions

Neither Professor Younger nor Professor Aplin seem to be capable of grasping the point that the potability, or otherwise, of the groundwater in the confined aquifer west of the Woodsfold Fault is not well constrained, and that the historical evidence of deep boreholes abstracting from the confined SSG suggests that it may well be fresh.

Professor Younger reiterates his serious misunderstandings, combined with misquoting of the literature, including:

- The belief that fluids migrate downwards in a fracked and faulted shale setting, in the face of six independent quantitative modelling studies which suggest the opposite,
- The assertion that the confined aquifer below the western Fylde can only be saline, based on false analogies with similar UK settings,
- The quotation of irrelevant previous work, presumably with the aim of browbeating the editors or other non-specialist readers that he has a superior grasp of the problem than I.

Professor Aplin's review reveals that he too does not grasp the nub of the problem. His report cannot be considered valid or reliable on this point.

It would be constructive if, rather than relying on dogmatic and erroneous assertions, one or both of these two critics would conduct a research project to extend the EA modelling westwards, in parallel with the collection and analysis of waters from the boreholes and natural sources in the area, to test whether or not there is any significant flow into the confined aquifer across the Woodsfold Fault, and whether or not it is potable.

References

Allen, D. J., L. J. Brewerton, L. M. Coleby, B. R. Gibbs, M. A. Lewis, A. M. MacDonald, S. J. Wagstaff, and A. T. Williams 1997. The physical properties of major aquifers in England and Wales, *Br. Geol. Surv. Tech. Rep. WD/97/34*, Environ. Agency R&D Publ. 8, Keyworth, Nottingham.

Barker, R D, and Worthington, P F. 1973a. The hydrological and electrical anisotropy of the Bunter Sandstone of Northwest Lancashire. *Quarterly Journal of Engineering Geology*, 6, 169–175.

Barker, R D, and Worthington, P F. 1973b. Some hydrogeophysical properties of the Bunter Sandstone of northwest England. *Geoexploration*, 11, 151–170.

Brereton, N.R. & Skinner, A.C. 1974. Groundwater flow characteristics in the Triassic Sandstone in the Fylde area of Lancashire. *Water Services,* 78, 275-279.

Cai, Z. and Ofterdinger, U.: Numerical assessment of potential impacts of hydraulically fractured Bowland Shale on overlying aquifers. *Water Resources Research*, 50, 6236–6259, doi:10.1002/2013WR014943, 2014.

Griffiths, K. J., P. Shand, and J. Ingram, 2003. *Baseline Report Series: 8. The Permo-Triassic Sandstones of Manchester and East Cheshire.* British Geological Survey Commissioned Report. Ref. CR/03/265N. BGS, London, UK. 51pp.

Jones, H K, Morris, B L, Cheney, C S, Brewerton, L J, Merrin, P D, Lewis, M A, MacDonald, A M, Coleby, L M, Talbot, J C, McKenzie, A A, Bird, M J, Cunningham, J, and Robinson, V K. 2000. The physical properties of minor aquifers in England and Wales. *British Geological Survey Technical Report*, WD/00/4. 234pp. Environment Agency R&D Publication 68.

Lovelock, P.E.R. 1972. Aquifer properties of the Permo-Triassic sandstones of the United Kingdom. PhD thesis, Department of Geology, University College London, 645 pp.

Lovelock, P.E.R. 1977. *Aquifer properties of the Permo-Triassic sandstones of the United Kingdom.* Bulletin of the Geological Survey of Great Britain, No. 56, 50.

Mott MacDonald 1997. Fylde aquifer/Wyre catchment water resources study final report 38436BA01, 176 pp + 87 figs.

Mott MacDonald 2009. Fylde Model Conversion and Update Final Report 250819/01/C, 78 pp + 41 figs.

Tellam, J.H., and Barker, R.D., 2006, Towards prediction of saturated-zone pollutant movement in groundwaters in fractured permeable-matrix aquifers: the case of the UK Permo-Triassic sandstones. *Geological Society, London, Special Publications*, v. 263:1-48, doi:10.1144/GSL.SP.2006.263.01.01.

Oakes, D. B, and Skinner, A. B. 1975. *Lancashire Conjunctive Use Scheme Groundwater Model. A Mathematical Model of the Triassic Sandstone Aquifer of the Fylde Area.* Technical Report, Water Research Centre, TR12.

Sage, R.C. And Lloyd, J.W. 1978. Drift deposit influences on the Triassic Sandstone aquifer of NW Lancashire as inferred by hydrochemistry. *Q. Jl Eng Geol.* 11, 209-218

Smythe, D.K. 2014. *Planning application no. LCC/2014/0101 by Cuadrilla Bowland Limited to drill at Roseacre Wood, Lancashire: Objection on grounds of geology and hydrogeology.* 16 September 2014, 47 pp.

Worthington, P F. 1977. Permeation properties of the Bunter Sandstone of Northwest Lancashire. *Journal of Hydrology*, 32, 295–303.

Appendix A

[Draft material removed from the submitted version of the SED paper]

There is an error in the nomenclature of the sedimentary succession, which has been taken from de Pater and Baisch (2011) and which in turn comes from Cuadrilla's interpretation of the Preese Hall-1 well log (Turner, 2012). The error has since been corrected in the released version of the well log.

The two formations immediately below the Mercia Mudstone Group (MMG), for which hydraulic conductivities and other hydrogeological properties are used by Cai and Ofterdinger, are noted as the Sherwood Sandstone Group (SSG) and the St Bees Sandstone (SBS). The one-dimensional 3000 m–thick layer-cake hydrogeological model used by Cai and Ofterdinger has an effective grouping of elevation and hydraulic conductivity as follows, from top to bottom, increasing downwards from ground level at 0 m to the top of the Bowland Shale, as shown in Table 1:

Table 1. Hydraulic conductivity values used by Cai and Ofterdinger

Group/Formation	Depth (m)	Thickness (m)	K_h (m s^{-1})	K_h (µm s^{-1})
Mercia Mudstone Group	0-200	200	1.0 10^{-7}	100
Sherwood Sandstone Group	200-400	200	1.2 10^{-5}	10,000
St Bees Sandstone Formation	400-1000	600	8.1 10^{-7}	810
Manchester Marl Formation	1000-1100	100	1.0 10^{-8}	10
Collyhurst Sandstone	1100-1250	150	7.9 10^{-5}	79,000
Lower Coal Measures	1250-1300	50	1.7 10^{-9}	1.7
Millstone Grit Group	1300-2000	700	7.9 10^{-8}	79

But the SBS is a formation within the SSG and, furthermore, is not recognized in the Fylde and East Irish Sea Basin. The logging tools were run only below 580 m (1900 ft), within the supposed SBS, so there is no evidence other than drill cuttings for subdividing the arenaceous succession into two parts. The well completion log as depicted by Turner (2012) has been mis-interpreted. This error in the basic basin geology by Cuadrilla, the operator and licensee, would be neither here nor there in itself, but it has led to an inappropriate hydraulic conductivity being assigned to this succession. The SBS is only found in West Cumbria, some 80-100 km to the north, where the physical property measurements were taken (Allen et al., 1997). The two rock formations in the model should therefore have been merged as the single SBS, without the incorrect subdivision, and assigned the physical properties of that group. In the model this group should extend from 2000 to 2800 m elevation, and not just the uppermost 200 m, as wrongly labelled from the original well log. This is important, because the hydraulic conductivity of the SSG is 15 times higher than that of the SBS.

The sources of the hydraulic conductivity values assumed in the modeling deserve discussion. Firstly, the "*hydrogeological properties*" of the Bowland Shale are taken from Marcellus Shale. This presumably includes the hydraulic conductivity, although the source of the value used is not specified in table 1 of Cai and Ofterdinger. The modelled value of the Millstone Grit (7.9 10^{-8} m s^{-1}, after correcting the misprint in Cai and Ofterdinger's table 1, row 7, column 4) is close to the mean value from drill stem tests in the East Midlands (Jones et al., 2000), but the range of measurements quoted by Jones et al. spans over three orders of magnitude, if one includes the nearest samples taken from outcrop in the West Pennines, some 20 km or more east of the Bowland Basin. The value adopted for the SSG of 1.2 10^{-5} m s^{-1} from core measurements is somewhat lower than the mean from borehole pumping tests in the Fylde (Allen et al., 1997); the latter value of 6.1 10^{-5} m s^{-1}) should preferably have been used as it reflects more accurately the bulk fracture flow rather than the intergranular flow measured in core.

The 100 m of Manchester Marl Formation is the relatively low-permeability formation which is supposed to provide the main barrier to upward flow; however, it is clear from Figure 2 that this barrier is cut by faults which can have a throw greater than the layer thickness.