Smythe (doi:10.5194/se-2015-134) Supplement S1

Water well contamination case history: Bradford County, Pennsylvania

Introduction

I propose that this section be incorporated, together with revision of sections 5.3.1 and 5.3.2, as a supplement to my paper, since it goes into considerably more detail than I had provided in my discussion paper. The discussion section below will form the basis for the revised text in the main paper. I thank Dr Engelder for prompting me to think more clearly about this problem.

Let us first define terms in the context of the locality, relative to local ground level:

- *Surface or near-surface* : <100 m, encompassing the unconsolidated sediments up to 60 m thick in the valley, the gas well cellars, the 20 inch conductor casing (probably to about 30 m depth), and the household wells, these last being 60 m deep or less;
- *Shallow to intermediate depth* : 100-500 m of Catskill Formation sandstones, including the 9-5/8 inch surface casing to 300 m; and
- *Deep* : deeper than 500 m, down through the Catskill and the Lock Haven Formation (siltstones) to the bottom of the geology of interest, the Marcellus shale at about 2300 m.

Locations of horizontal wells and homeowner water wells

The relevant horizontal wells drilled from the Welles 1 and Welles 3 were plotted from the well plats (plans). However, the listings of coordinates in these plats are frequently illegible, and the well plans contained within each plat, referenced to local property boundaries, are sketchy. The best-possible well location points were derived by cross-referencing the coordinates given in degree, minute, second format, on the NAD83 datum, with the decimal latitude and longitude (NAD27 datum), on each plat, together with inspection of an overlay of each well plan scan in Global Mapper, a GIS program. The well plans were registered on a digital map of Bradford County property boundaries by triangulation between various points. The projection of the well plans is not stated, so it was assumed to be a Lambert conic conformal with parameters appropriate to Pennsylvania. The wellhead locations, but not the bottom hole coordinates, can be cross-checked against other public sources. The different wellhead locations are consistent to within 5-10 m, which is more than adequate for the present study. The mis-matches are probably due to minor interconversion errors introduced by different map projections and datums.

The six homeowner water wells on Paradise Road (three original and three replacement) were digitised from the inset to figure 1 of Llewellyn et al. (2015; hereinafter LEA). As this is rather small, it was overlain on a Google Earth image, showing buildings and roads, which in turn was overlaid on the USGS quadrant topographical map for Wyalusing. The fit of the inset was checked and adjusted by cross-checking the contours in the inset map against values from the DCNR DEM as used by LEA. The locations of the three replacement wells, obtained from PADEP files, are inaccurate, so these locations were not used. The resulting well locations are probably within ±10 m horizontally and ±3 m vertically of their true location, which is accurate enough for the analysis in question.

Surface or shallow to intermediate depth contamination pathways

This section concerns the possible transport of organic unresolved complex mixtures (UCMs) and the target compound linked to shale gas-related contamination (2-n-Butoxyethanol, 2-BE) in the near surface (LEA). It does not concern the methane path.

There is an impoundment pond situated 500 m NE of W1 and 700 m west of W3 (Figure S1), seen on the USGS topographic map and identified from Google Earth Pro by its characteristic black liner. This pond presumably serves all five Welles Farm wells (denoted by W1, etc.) in the locality. It is about 130 Ha (320 acres) in area, and if built to hold a 3 m depth of produced water the total capacity is of the order of 40,000 m^3. It lies on the path of the more easterly fracture zone identified by LEA; its eastermost edge is about 90 m west of Sugar Run North Branch (SRNB).

A leak out of a pit at W1 occurred on 7 August 2009, and on 2 September the same two wells (W1-3H and W1-5H) were cited by PADEP for discharge of contaminated fluids to ground. Well W1-3H was also cited on 29 September 2011 for *"failure to control residual waste to prevent water pollution"*, but this latter event postdates, and therefore cannot be related to, the homeowner well contamination. The 2009 pit leak could either be due to a spill on the W1 pad, or to a leak from the main impoundment pond. Both these scenarios are considered next.

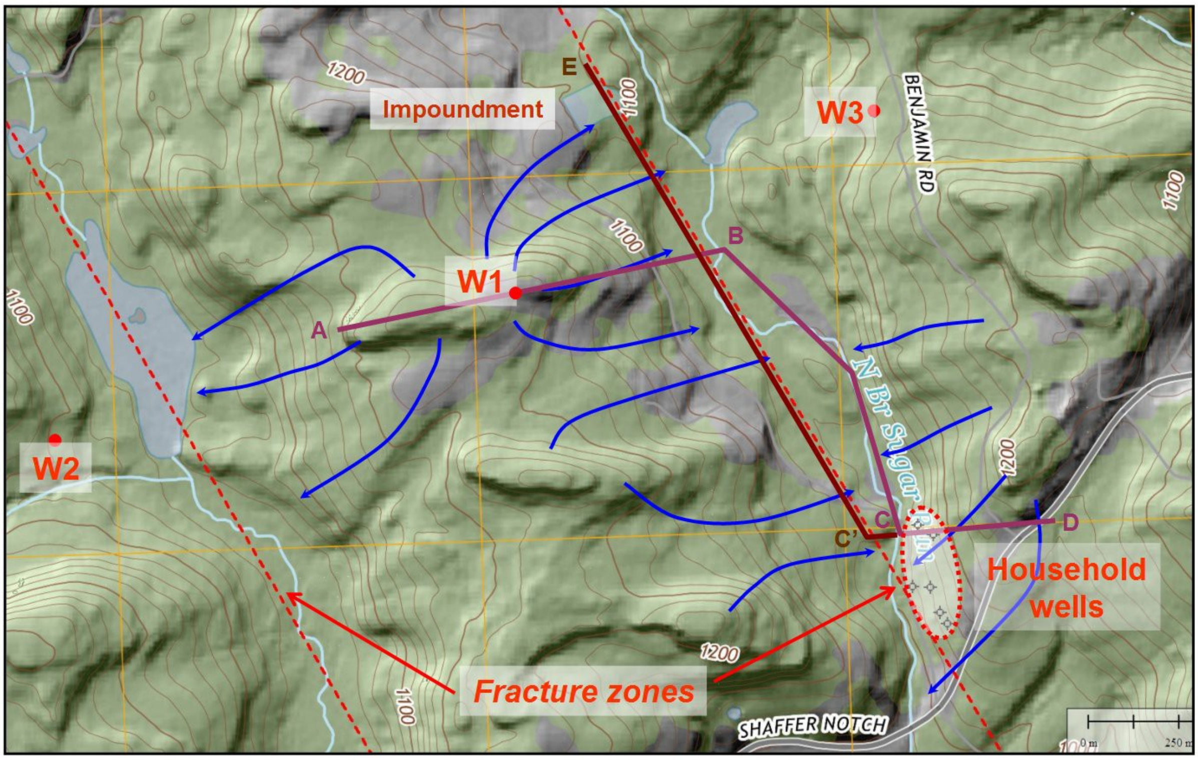

Figure S1. Topographic map of the Paradise Road area, Terry Township, Bradford County. Blue arrows show runoff directions for meteoric water. Chesapeake wells W1-W3 belong to the Welles Farm series of five wells. The six contaminated household wells are located within the ellipse. Profiles ABCD and EC'D are shown in Figures S2 and S3, respectively.

Figure S2 shows the profile ABCD of the shallow geology, assuming that the pit leak referred to an event on the W1 pad. The blue arrows indicate schematic subterranean recharge/discharge water flow vectors. The Catskill Formation acts as a series of confining layers; therefore it is unlikely that a spill from W1 would be able to penetrate to any significant depth west of SRNB, carried along by the meteoric water. On reaching SRNB the contamination would run down the river to the south. It is highly unlikely that from there it could penetrate downwards and eastwards to get to the base of the household wells.

Figure S3 shows profile EC'D running south from the impoundment pond, along the fracture zone. It is possible that contamination could have penetrated downwards, of the order of 100-150 m, and southwards along the fault zone, and then migrated upwards with the meteoric water flow. This scenario also applies to the possible case of a long-term undetected leak of the impoundment *via* a faulty liner directly into the subsurface. Such a leak could go undetected unless it were large enough for a drop in water level to be noticed.

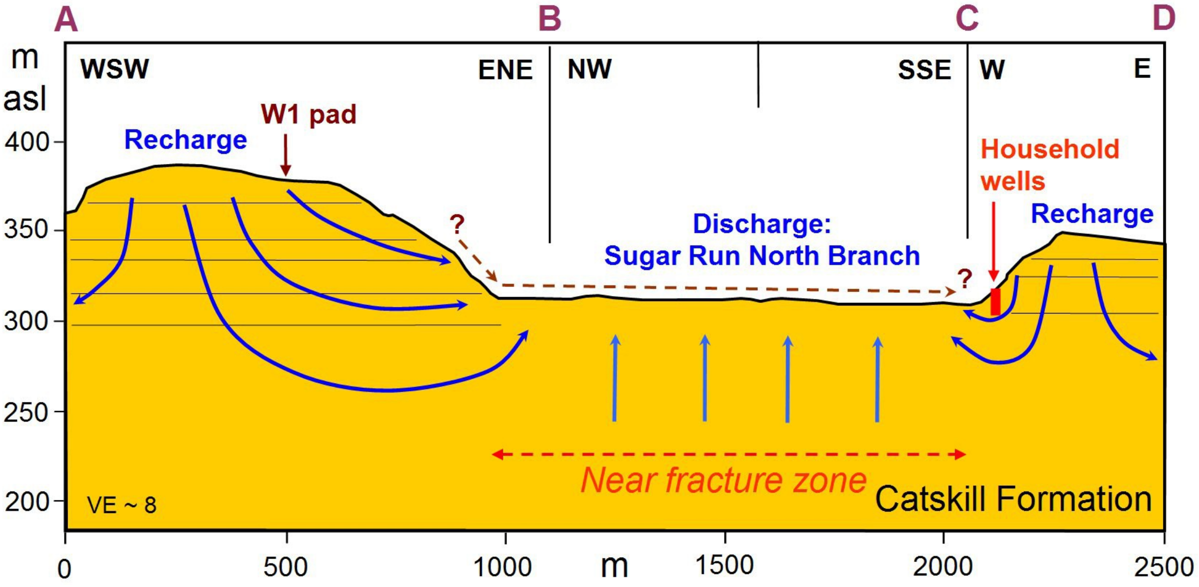

Figure S2. Hypothetical transport pattern of a spill at the surface of the W1 pad. Brown dashed arrows show transport along the discharge zone of Sugar Run North Branch, below which the near-surface groundwater flow must be upwards. Thin horizontal lines indicate schematic Catskill Formation layering acting as confining layers.

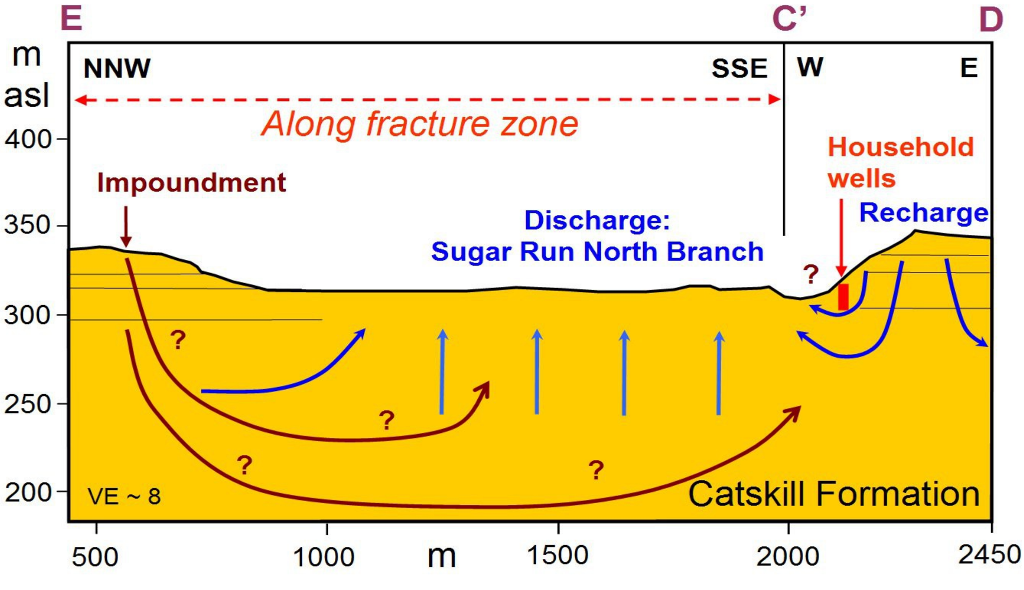

Figure S3. Hypothetical pattern of contamination flow path (brown lines) from the Welles Farm impoundment pond situated on the fault identified by LEA.

The alternative pathway proposed by LEA, that of travel up through the geology by a step and stair progression southwards from the leaking wells at pads W3, W4 and W5, remains possible, but is inconsistent with the lack of contamination observed at background well B1 (Fig. S4).

Deep contamination pathways

This section concerns the fugitive methane. The relevant wells are plotted in Figure S4. Two horizontal wells were drilled from each of the well pads W1 and W3, respectively. One well from each pad one well goes NW and the other SE. There was a planned well, W1-2H, going directly NNW from the W1 pad, but was never drilled.

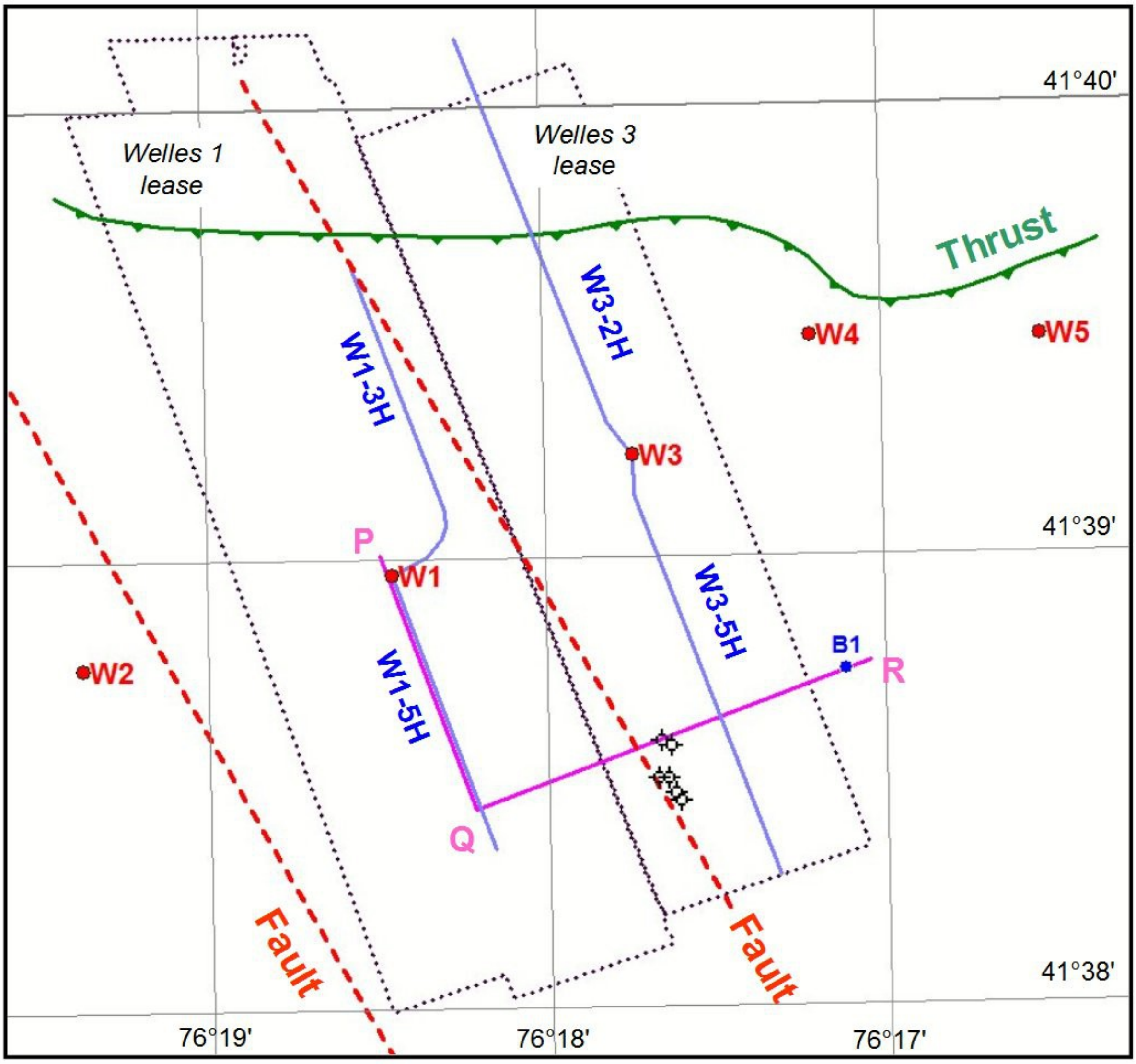

Figure S4. Horizontal wells (blue) drilled from pads W1 and W3 within their respective lease areas (dotted lines). B1 is a background water well showing no contamination. Paradise Road homeowner water wells shown by black cross/circle symbol. Cross-section PQR is shown in Figure S5. Lambert conformal conic projection, central meridian 78°W, standard parallels 33° and 45°N, datum WGS84.

Its place was taken by W1-3H, which starts out in a north-easterly direction before deviating NNW, keeping to the east side of Paradise Road at depth. This may have been to avoid certain properties lying to the west side of the road. The lease units for W1 and W3 are shown by dotted outlines. The fracture zones postulated by LEA have been positioned exactly as the straight lines shown by them, even though there may be a good case for having them follow more precisely the slightly sinuous topographic lows from which they were identified.

I am confining my attention to the two horizontal wells drilled from pad W1, because they were the only two that were fracked before the methane leaks and water contamination were observed by the water well homeowners. Although the NNW-directed horizontal well W1-3H may actually intersect the fault zone (Fig. S4), the other leg running SSE (W1-5H) is of greater interest.

Figure S5 shows a true-scale dog-leg cross-section (PQR in Figure S4), running along horizontal well W1-5H to the south-south-east, then eastwards along strike through the water well locality on Paradise Road. Note that the Welles Farm wells are two-string wells, air-and-mist drilled to the kick-off point (Ashley 2009).

LEA note that there were gas shows in the vertical portion of both W1 wells (small black arrows in Figure S5), but these must have been recorded before the 5-½ inch production casing was run and set in the 8-½ inch hole. A maximum annular pressure of 4 psi was recorded in W1-5H, date unknown (LEA figure S10). LEA's table S1 notes a 0 psi annular pressure on 2 April 2010, after the fracking of the well, which had begun on 1 February 2010, was completed. Therefore the casing and the cement must be considered sound.

The radius of the well deviation landing in the Marcellus Shale is 240 m (Ashley 2009). The generally upward growth of hydraulically-induced fractures (fracks) is depicted schematically in Fig. S5 by the maze of lines extending up to about 300 m above the perforated production casing. This height is appropriate for the upward growth of fracks in Bradford County (Fisher and Warpinski 2012). The fracks are presumed to extend eastwards to about the edge of the lease area, which lies 200-300 m west of the water wells, and 165 m west of the marked position of the fault at the surface. These limits are not precise, because the frack limit could extend beyond the lease area, or else may not have extended fully to its eastern edge; in addition, the fault zone may not follow precisely the straight line marked by LEA, nor is it necessarily vertical.

The small black arrows in Figure S5 are taken from LEA figure S10. However, this latter figure has a vertical scale problem for the W1 wells, because it indicates an approximate kickoff point (KOP) at 2300 m below ground surface, whereas the KOP must be much shallower, as shown in Figure S5. The Marcellus Shale is at 1700-1800 m below sea level (2100-2200 m below ground level) at the W1 pad, not 2400 m below ground level implied by LEA's figure S9. In addition, the surface casing of W1-5H is only about 164 m in length, not the approximate 300 m length shown by LEA. The thrust fault intersection is at about 250 m below sea level.

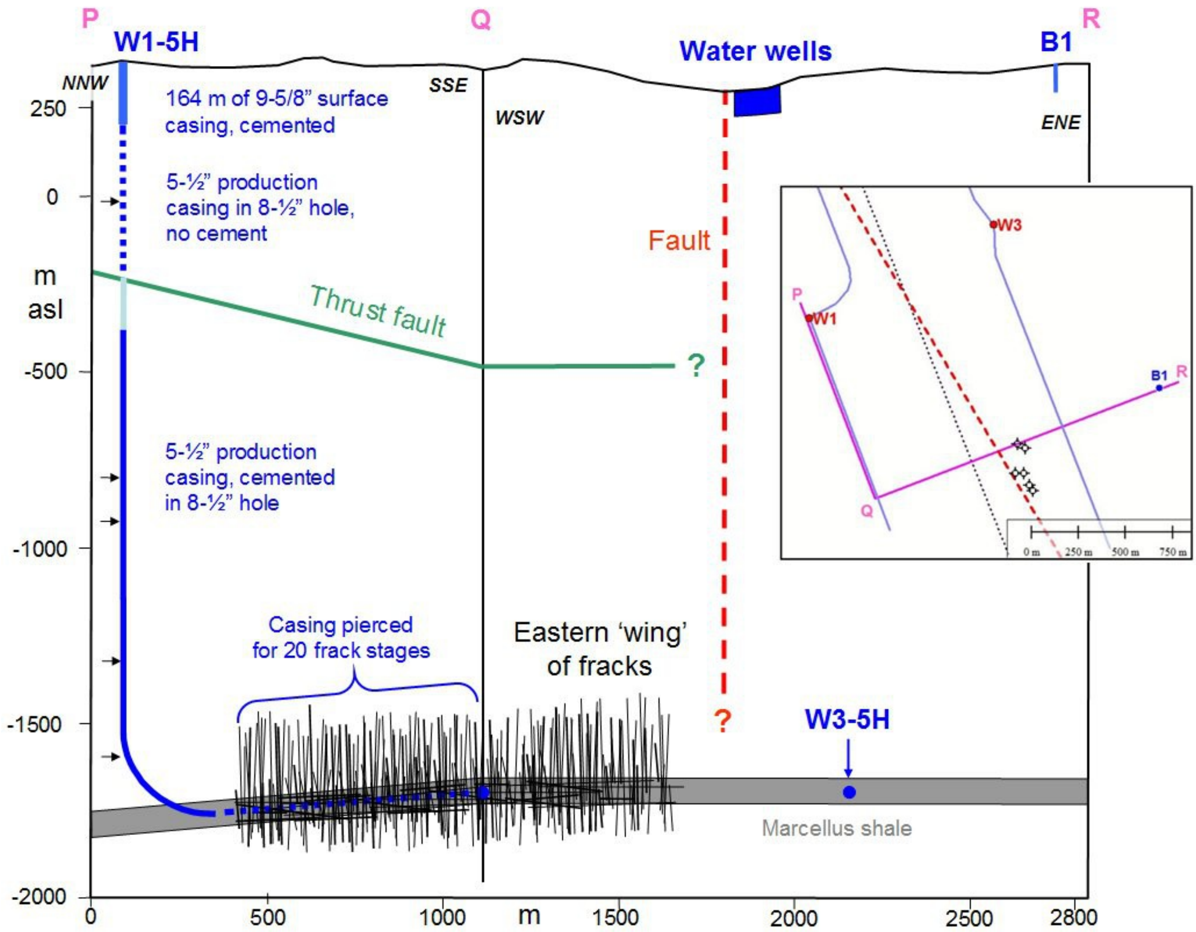

Figure S5. Section PQR located in Fig. S4, true scale, along line of W1-5H then east through homeowner water wells (blue block) and unimpacted background well B1. Small black arrows are gas shows identified before the production casing was run. Light blue vertical section illustrates partial cement bonding just below the thrust fault intersection. The inset shows the location map with horizontal wells in blue.

A 'proactive' cement squeeze job was carried out at 81 m below sea level on 13 November 2010. This may correspond to the topmost gas show depicted by LEA, above the thrust in the uncemented portion of the production casing.

The original well permit shows W1-5H terminating about 180 m SE of point Q (Fig. S4 and inset to Fig. S5). However, the well must have been extended to the SE limit of the permit (Fig. S4), because 1571 m of well was perforated for 20 stages of fracking. This length cannot be fitted within the 1207 m of horizontal well including the deviation quadrant from vertical of about 240 m horizontal component.

Correlations of methane contamination over time and distance

Gas bubbling in the Susquehanna river at Sugar Run was first reported on 2 September 2010, at around the same time that remedial activities were in progress to repair faulty cement jobs at W3, W4 and W5. LEA observed that *"gas bubbling ceased following gas well remedial activities conducted at the Welles 3, 4, and 5 well pads"*. This statement may be correct for the impacted wells at Sugar Run, but field data sheets by PADEP inspectors (made available by publicfiles.org) show that although the methane in the wells had diminished to near-zero, there was still bubbling in the Susquehanna near to the Potupack residence as late as 25 October 2011.

The dissolved methane data (LEA fig. 2) are taken from their tables S2 and S5, and reproduced herein as Figure S6, but plotted with a logarithmic ordinate scale to separate more clearly the data points vertically. This figure is similar to LEA's figure 2, but with different events added. It should be noted that in their graph (but not in the legend) the symbols for well 3 and well 4 have been interchanged; well 3 readings are erroneously shown by green squares and well 4 by green triangles, whereas it should have been the converse. The timescale in Figure S6 runs from 22 January 2010 to 26 April 2013.

There are a number of new observations worth making. Firstly, W1-3H and W1-5H were fracked (20 stages each) starting on 1 February 2010, but production did not start until around 18 August 2011. The latter date is estimated from PADEP production figures, for which the first recorded gas production periods are given as 134 days (W1-3H) and 132 days (W1-5H) for the half-year July-December 2011. So the two wells must have been shut in for over 18 months.

The start of problems with the homeowner wells may have been the observation of sediment in the water of well 3, noticed in early May 2010, although the main impacts started on or just before 13 July, when two homeowners notified PADEP. These two dates are shown by the red arrows in Fig. S6.

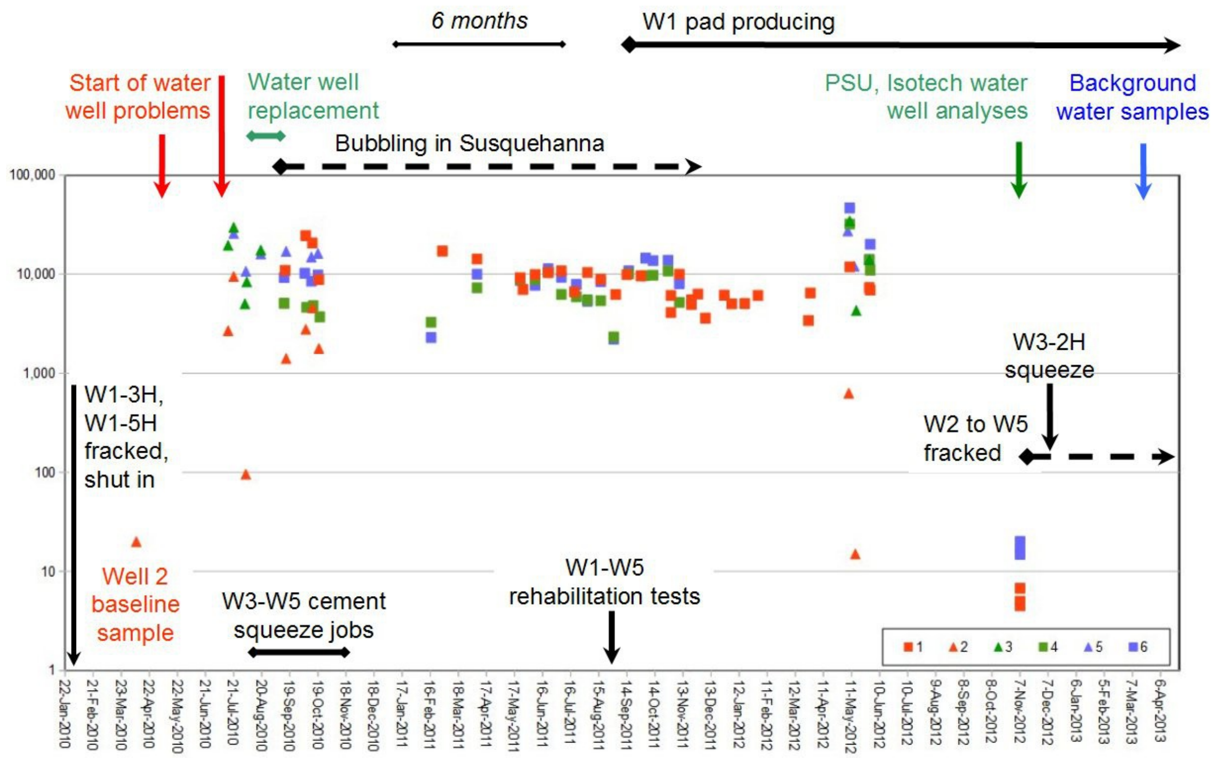

Figure S6. Methane concentration (µg/l) vs. time in the six Paradise Road homeowner wells (denoted by the symbols shown in the inset) in relation to various gas well and methane analysis events.

The remediation of the wells on pads W3 to W5, by perforation and cement squeezes behind the 5½ inch production casing, was carried out between 11 August and 18 November 2010. During this period between 4 and 12 intervals were remediated in each well, except at W1, where one interval at each of W1-3H and W1-5H was also treated as a *"proactive measure due to the proximity to a citizen complaint"*, even though no abnormal pressures had been noted at these two wellheads. Two further squeeze jobs were done on W3-2H on 25 April 2012 and on 10 December 2012 (vertical black arrow in Fig. S6). The latter job may have been connected with fracking of that well, since fracking of the W2 to W5 wells had started on 11 November 2012 and ran until 15 September 2013 (horizontal dashed arrow in Fig. S6).

All the wells W1-W5 successfully passed rehabilitation tests starting on 2 September 2011, so the leaking well problems may be considered to have been cured by this time.

Bubbling in the Susquehanna River at Sugar Run was first notified to PADEP on 2 September 2010, but continued until at least 25 October 2011 (dashed black arrow in Fig. S6).

Figure S6 shows that there is no systematic decline in methane concentrations after the remediation of the leaky W3-W5 vertical gas well holes, at least until after 31 May 2012. LEA claim that well 1, for which there are the most data points (33), shows a clear decline with time; however, well 4 (22 points) and well 6 (21 points) show the opposite trend. Therefore we have to be cautious in selecting subsets of the data.

The methane concentrations in the six wells were tested for a correlation with distance from the fault. The period analysed was 15 July 2010 to 28 March 2012, during which there was no overall change in methane concentration (although, as pointed out above, individual wells appear to show trends). The methane readings for April and May 2012 were omitted from consideration, since four of them showed anomalously high values which, according to LEA, may have been due to differing collection and measurement protocols. The initial baseline measurement at well 2 taken on 15 July 2010 was also omitted, as was the group of readings taken on 6 November 2012 (LEA table S5). That leaves 86 measurements, with distance from the fault as follows: well 3 – 22 m; well 5 – 54 m; well 6 – 55 m; well 4 - 60 m; well 1 – 112 m; well 2 – 136 m. Background well B1 lies 915 m east of the fault. The variation in methane as a function of distance is shown in Figure S7.

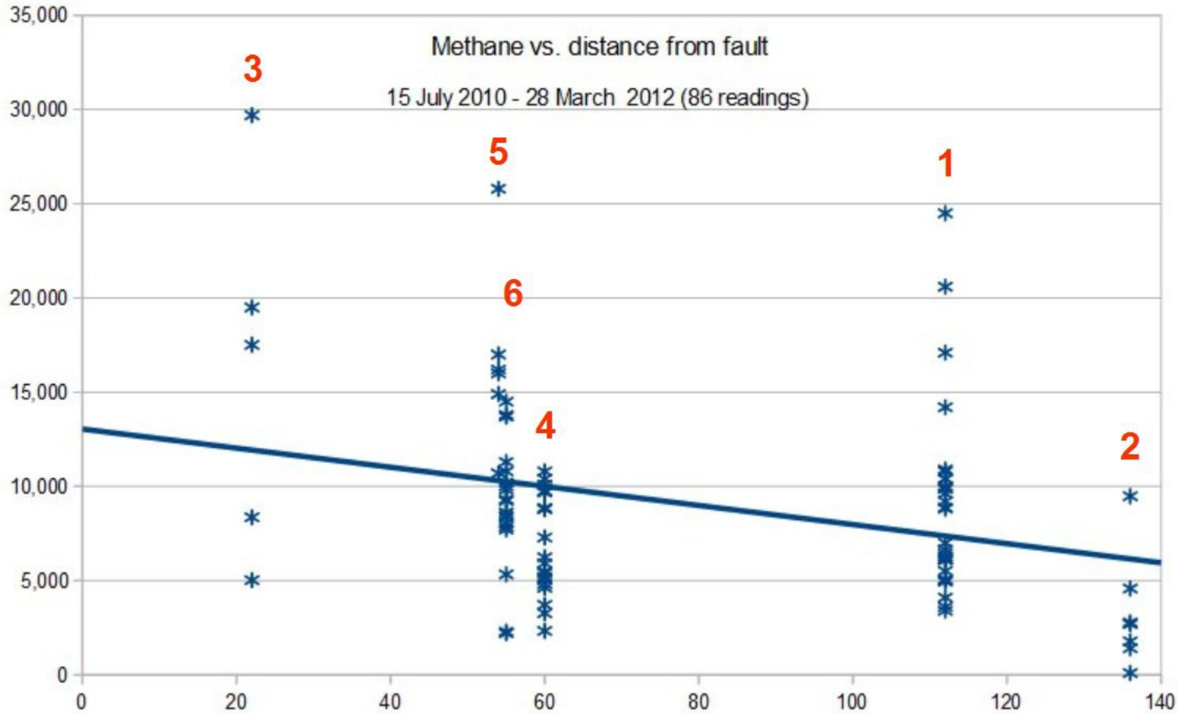

Figure S7. Methane concentration vs. distance from fault for six household wells on Paradise Road (numbered in red). A linear regression line is shown.

The linear regression line shows a decrease with distance from the fault, but the spread of individual readings for each well is evidently very large. We can test the statistical significance of this trend by asking, what is the probability P that the trend is due to random chance and is not a significant decrease with increasing distance? This is a one-tailed probability, which, using the Pearson product moment formula, yields P = 0.005 (calculated online using www.vassarstats.net). We can therefore reject the null hypothesis, of no trend in methane concentration *vs.* distance from the fault, at the 0.5% probability level.

Discussion

The strongest argument proposed by LEA in favour of a gas drilling origin for the water well contamination is their analysis of the foam using a new sensitive method. But they declined to draw a direct link to Marcellus Shale operations (at 2 km depth) because the well water is of near surface origin, plotting in the 'field tile' field of Panno et al. (2006). LEA conclude that migration from faulty wells (specifically, W3, W4 and W5) at intermediate depths, up-dip and along and up shallow fractures, is the most likely explanation. The horizontal component of distance is 1100 – 2400 m and the vertical component about 1000 m, with the source being in the vertical leg of one or more of the six wells. W3-2H is specifically implicated, partly because of high recorded annular pressures.

The weak points of this argument are firstly, that background well B1 was not impacted, even though it lies up-dip of W4 and W5 (Fig. S4), and secondly, that even after remediation of the faulty vertical wellbores, methane was found in the household wells at high levels for about 21 months afterwards, with no suggestion of a diminution over that period; methane bubbling in the Susquehanna River also continued for a minimum of 15 months (Fig. S6).

LEA refer to a *"drilling fluid leak from a pit"* on 7 August 2009, which they presume was on the W1 pad, and *"this could therefore implicate a surface-related release"* (Llewellyn et al. 2015). I have shown above that a leak or spill on the W1 pad is highly unlikely, for simple water flowpath reasons, to lead to persistent household well impacts at Paradise Road, starting one year later (Fig. S2). However, if this reported pit leak in fact refers to the Welles Farm impoundment pond, then it is feasible that a leak could impact the water wells, given that the pond is located directly on the fault identified by LEA (Fig. S3).

Pertinent facts, not previously mentioned above, include:

- The gas in the impacted wells is thermogenic, and almost identical in composition to the annular gas from the W2 to W5 wells (LEA fig. S1).
- The gas in W3 to W5 and household wells 1, 3, 5 and 6 is different from non-impacted

pre-drill private well data (LEA fig. S2).

• The Cl/Br mass ratio and the concentration of Cl in the water from the impacted water wells are both typical of meteoric water, but one order of magnitude higher and one to five orders of magnitude lower, respectively, than Marcellus flowback or Appalachian Basin Brine (LEA fig. 6).

Methane migration from the fracked volume of W1-5H (Fig. S5), passing up the SRNB fault zone (Fig. S4) is clearly a candidate for the water well contamination. In its favour, this scenario has:

- The directness of the pathway.
- A lag of 5-8 months from fracking to the start of the impacts.
- Persistence over time while the well was shut in.
- No negative driving pressure from well production, because the well was shut in (well 'suction' is inactive).
- The lag of 9-11 months between the well starting production and the diminution of methane impact at the household wells.
- A statistically significant (P = 0.005) inverse relationship between methane concentration in a well and distance of the well from the fault.

Birdsell et al. (2015) show that well 'suction' (put simply, the producing well acting as a sink) is an important factor in modelling whether and how effective a generic permeable pathway from shale to aquifer can be. They consider a scenario of a 20-year production stage, but with no suction, i.e. equivalent to a long-term shut-in. In that case, imbibition becomes important.

Against the deep fracked Marcellus Shale scenario there is the evidence of the high Cl/Br mass ratio and the low concentration of Cl in the contaminated well water; in short, the water shows no sign of the expected deep Appalachian Basin Brine (ABB) composition (LEA fig. 6). But we can reconcile the scenario of Marcellus-origin methane migration with the meteoric origin of the well water by considering the timescale involved. Gas migration can occur up a permeable pathway on the order of hours to hundreds of days (Reagan et al. 2015), whereas fluid migration along the same path may take years, decades or centuries (see the review of modelling in Section 5 of my main paper).

The presence of a tiny proportion of deep (Marcellus) water in the household wells is not precluded by the Cl/Br and Cl data; one part in a thousand or in ten thousand of deep ABB-type water mixed with meteoric water will yield the observed conservative tracer values, while at the same time supplying the trace quantities (in the order of parts per million) of UCM and 2-BE observed in the water wells. This last scenario, admittedly speculative, assumes that a very small proportion of ABB is entrained along with the migrating methane.

Conclusions

LEA's proposed migration pathway for methane, from faulty vertical wells W3 to W5 along shallow geological bedding and fractures, may be valid for the Sugar Run contamination, including the bubbling observed in the Susquehanna River. But the pathway seems less probable for explaining the Paradise Road well contamination, because methane concentrations in the latter group of wells persisted long after the originating gas wells had been remediated. This pathway, if valid, also inexplicably avoided impacting upon the B1 background well. In contrast, a direct pathway from fracked Marcellus Shale, up the fault running along Sugar Run North Branch, is feasible, and is supported by a statistically significant inverse relationship between fault to well distance and methane concentration in the well.

It remains only to account for the shallow origin of the household well water, which, although contaminated by thermogenic methane, shows no sign of a deep brine origin. This discrepancy can be explained by the short timescale of the impacts – long enough for methane migration to have occurred, but too short for fluid migration from 2000 m below the impacted wells to have reached the surface.

The UCM and 2-BE contamination of the same water wells could either have been sourced by trace amounts of water brought up by the methane from the fracked zone, or else from putative leaking of the Welles Farm impoundment pond, which lies on the fault some 1500 m to the north of the impacted water wells. Alternative theories of surface spills or contamination from the cement used in the water well construction can be discounted.

This reinterpretation and extension of LEA's results implies that shallow groundwater contamination from fracking of Marcellus Shale is possible, and can occur within a period of a few months following fracking. But it is an unusual event, since it appears to require:

- The existence of a vertical fault or fracture zone, rare in the Appalachian Plateau,

• A fracked horizontal well running sub-parallel to, or intersecting, the fault, and

• An extended period of well shut-in.

Such a combination of requirements, although rare (or even unique) in the Marcellus Shale play, may be much more common in the UK extensional shale basins, in which faults are ubiquitous and hard to avoid.

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