TOWN AND COUNTRY PLANNING (APPEALS) (SCOTLAND) REGULATIONS 2013

APPEAL UNDER SECTION 47(2) OF THE TOWN AND COUNTRY PLANNING (SCOTLAND) ACT 1997 BY DART ENERGY (FORTH VALLEY) LTD CONCERNING COAL BED METHANE PRODUCTION, INCLUDING DRILLING, WELL SITE ESTABLISHMENT AT 14 LOCATIONS AND ASSOCIATED INFRASTRUCTURE AT LETHAM MOSS, FALKIRK, AND POWDRAKE ROAD, NEAR AIRTH, PLEAN

(REFERENCES PPA-240-2032 AND PPA-390-2029)

REBUTTAL BY PROFESSOR DAVID K. SMYTHE

ON BEHALF OF

CONCERNED COMMUNITIES OF FALKIRK

(AND SUPPORTERS)

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1 INTRODUCTION

1.1 Precognitions commented upon

1.1.1 This rebuttal deals with the following four Dart precognitions:

- Geology (author: Mr David Goold)
- Hydrogeology (author: Richard Graham)
- Fugitive methane (author: Dr Christopher Cuff)
- Drilling and wells (author: Mr Andrew Sloan)

1.1.2 I shall discuss these precognitions primarily under the headings used in my own precognition, but also under new headings where required.

1.2 Comments by Mr David Goold on my previous submission (CCoF 13)

1.2.1 Mr Goold devotes nine pages to a critique of two documents of mine, which he cites as:

> ***"Smythe D K** (2013a). Dart Energy coal bed methane proposed development at Letham: Review of additional information supplied in support of the hydrogeological assessment.* ***DE(J)72***
>
> ***Smythe D K** (2013b). Written evidence submitted to the House of Lords Economic Affairs Select Committee – The economic impact on UK energy policy of shale gas and oil.* ***DE(J)73"***

1.2.2 First, it should be noted that neither of these two Dart documents has been submitted to the inquiry by Dart; the document numbers quoted above simply do not exist. The document numbers within the DE(J) folder (and its subfolders) supplied by the Appellant start at no. 3 and end at no. 71, with some omissions from the sequence.

1.2.3 Notwithstanding this omission by Dart, I am prepared to respond and rebut here. The first document has been submitted to the Inquiry as CCoF 13. The second document has not been duly submitted by Dart, nor by any other party, therefore I do not feel bound to respond to Mr Goold's comments on it. But as its title implies, the latter document concerned the wider issue of shale gas exploitation in the UK, and only made a single passing reference to Dart under the heading *'Critique of some current unconventional operations'*, as follows:

"Dart Energy PEDL133 - proposed CBM development at Airth, Stirlingshire:

- *Inappropriate geological cross-sections supplied in ES (both outside area of proposal)*
- *Five major faults omitted from these cross-sections*

- *Misleading and very incomplete discussion justifying faults as barriers to fluid flow*
- *Internally inconsistent maps of a major fault (>300 m throw; biggest in whole region)*
- *This fault unaccountably absent over development location, but present either side*
- *Misleading discussion of sealing cap rocks above coal formations*
- *No 3D seismic survey."*

1.2.4 The bullet points above concerning Dart's work all stand, in my view, and are fully covered in my present response below to the first document quoted above by Mr Goold.

1.2.5 I understand, and even sympathise with, some of the comments made by Mr Goold on my earlier submission (CCoF 13). This initial document of mine was written *pro bono* over the space of four days in August 2013, in response to an urgent request by CCoF. Prior to that request I had very little detailed knowledge of the Appellant's (and its predecessors') activities at Airth. Therefore it is not surprising that the document was based on what I freely conceded at the time was an incomplete dataset in my possession. I also had a few misunderstandings (since corrected), for example, about the existence of underground 'galleries' - an inappropriately used term taken from mining practice.

1.2.6 However, this August 2013 submission has been superseded by my current precognition of February 2014. It therefore follows that much of what Mr Goold finds worthy of criticism, being based solely on my August 2013 paper, is now irrelevant. I shall discuss and rebut the remaining relevant parts of Mr Goold's critique under the appropriate headings below, in addition to rebuttal, where necessary, of parts of Mr Goold's precognition that do not directly refer to me.

2 GEOLOGY AND HYDROGEOLOGY OF THE LETHAM SITE

2.1 The structural geology database

2.1.1 Mr Goold lists an extensive range of data sources (section 3.1) used by the Appellant. It is noteworthy that the companies involved in data collection and/or archiving over the last three decades or so with a view to CBM extraction appear to be as follows:

- National Coal Board (historical deep mine data)
- ? Coal Authority (privatised successor to NCB in 1994)
- Hillfarm Coal Ltd (c. 1993-1996)
- Coal Bed Methane Ltd (1996 - 2004)
- Composite Energy (2004 on; interest acquired by Dart in 2011)
- Dart Energy

2.1.2 I do not know whether the Coal Authority had any CBM interests. The first private limited company with a CBM interest in the PDA seems to have been Hillfarm Coal, operator at Airth from 1993 (see, for example CCoF 68; DECC 2010). Mr Goold suggests that the vast majority of the database is freely available, but this is not the case. Two examples suffice. The DECC report states, with reference to the Airth CBM pilot field operated by Composite:

> *"No public domain information is available on the gas content, permeability or water and gas production of these wells at this time."* [the epoch being 2010]

2.1.3 The second example concerns the 2D seismic database, about which Mr Goold states:

> *"Complete 2D seismic coverage available in the public domain for the area of PEDL 133 (total of 534km) of which 400km has been reprocessed and reinterpreted since 2010 (data source: British Geological Survey and DECC, via the UK Onshore Geophysical Library)."*

2.1.4 Not all the seismic data shown on Mr Goold's figure 5 (document DE(I).43) are in the public domain, as I have pointed out in my precognition (para. 2.4 15). Nor are the reprocessed versions available.

2.1.5 Mr Goold considers (para. 3.10.1) that:

> *"Seismic coverage of 400km over an area the size of PEDL 133 would be considered to be good to excellent for any CBM project (for coverage see Figure 5) and, in my experience, is a situation without precedent amongst UK and European CBM developments."*

2.1.6 I disagree. Firstly, we should not be interested in whether or not this coverage compares favourably with other CBM projects; what matters is whether the coverage is adequate for the project in question. Figure 1 shows Dart's 2D seismic database (blue lines) in relation to the PDA (buff lines) and faults as mapped by the BGS at the surface (red lines).

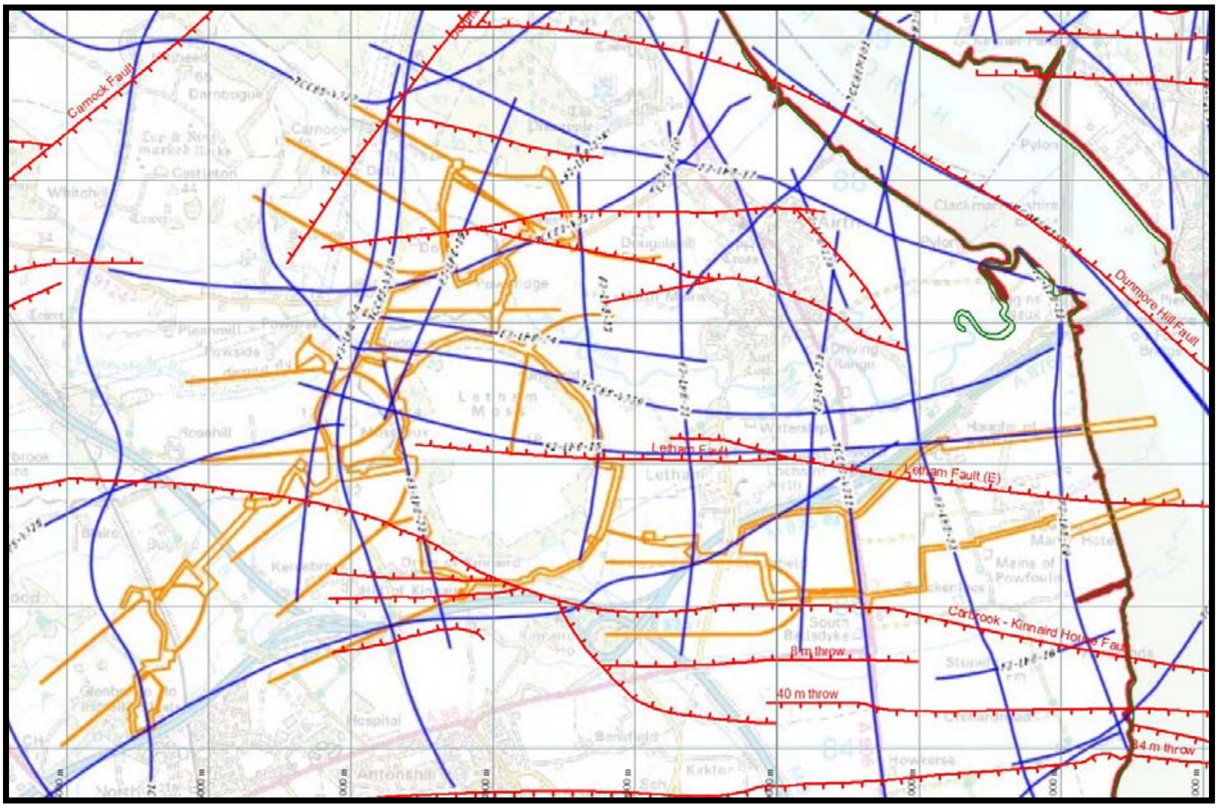

Fig. 1. Dart seismic database in relation to the PDA and surface-mapped faults.

2.1.7 Figure 1 shows that the linear density of faults at the surface is greater than the density of seismic lines. Given that we need to be able to characterise how these faults behave at depth - how one merges into another; how they grow in amplitude and die out laterally; their shape and genesis (strike-slip, normal, growth) and so on - the linear density of the existing blue grid is several times too sparse for the purpose.

2.1.8 For example, the whole SW corner of the proposed development originating at Airth-13 and Airth-14 is crossed by just one N-S seismic line (see figure 10 of my precognition). This is completely inadequate, given the faulting identification problem discussed in paras. 2.2.11 - 2.2.14 below.

2.1.9 At the NW corner of the PDA the three proposed laterals directed NW are controlled by two parallel N-S seismic lines - but these two are only about 130 m apart in the area of interest, so in effect count as one line. Again, this is inadequate imaging coverage.

2.1.10 An adequate 2D seismic imaging network would comprise mainly N-S lines at a 250 m spacing, with tie lines running E-W at a 500 m spacing. The N-S direction is chosen to run across the dominant E-W geological structural trend. The existing grid is of the order of five times too sparse compared to this. But even then, the presence of oblique and cross-faults shows that the structure is more complicated than simply flat layers with E-W faulting. In short, we need 3D seismic coverage, which I have previously advocated.

2.1.11 Mr Goold has listed in section 4.2 several reasons why the data that I asked for in August 2013 cannot be provided. Firstly, he says that such a degree of detailed data supply lies *"outwith the scope of documents normally supplied for planning applications for oil and gas developments"*, and that Dart complies with DECC regulations by supplying DECC with information. But the Applicant's present proposed development is no ordinary 'oil and gas' development. It is entirely novel to the UK, and, as such it is very much a protoype or flagship project of a new kind of *unconventional* hydrocarbon exploitation. I am not interested in whether or not such CBM projects are considered 'mature' in other countries such as the USA or Australia. The essential point is that it is new to the UK, where we have unique geology and (for example) our own problems of high population density. My view is expanded on in section 3.2 below.

2.1.12 Therefore it is incumbent upon the Applicant, in my view, to provide far more information than it has done to date concerning its geological database. Dart's interpretations need to be open to independent scrutiny; this requires access to the 'raw' data. It is also incumbent upon Dart to find ways round the perceived third-party data confidentiality problems. To hide behind the convenient label 'Commercial in Confidence' is, in my view, an inadequate excuse.

2.1.13 Mr Goold criticises my own incomplete database holding (section 4.3). But my lack of certain data as of August 2013 has since been rectified. Although I do not hold a database as thorough or complete as Dart's, I have more than sufficient accurate information and data to be able to scrutinise Dart's geological understanding and interpretation at certain critical points. It is not my job to obtain all of Dart's database and then to do its interpretation job for it. I simply need to have enough information (which I now hold) to make informed judgments on where errors in the Applicant's geological interpretation could lead to environmental problems. These criticisms have been aired in detail in my precognition, and will be discussed again below in the light of the Appellant's precognitions.

2.2 Faulting within the potential development area (PDA)

2.2.1 Mr Goold gives over a whole section of his precognition to fault avoidance. He accepts, as do I, that avoidance of faults is crucial. But his reasons are different from mine - he believes that:

> *"faults can provide a risk to successful commercial development by limiting production (creating flow barriers) and should be avoided" [para. 3.1.3]*

2.2.2 In contrast, regarding the potential danger to receptors, he states in the same paragraph:

> *"Dart believes that faulting at any scale does not present a credible pathway for <u>significant or rapid migration of fluids or natural gas</u> to receptors at the surface or within the subsurface"* [my underlining].

2.2.3 This argument is founded, he states, upon *"ten years of drilling and production by Dart and its previous operator"* (i.e. Composite Energy). He states that supporting documentation is to be found in the precognitions of Mr Graham and Dr Cuff.

On the subject of faulting Dr Cuff states:

> *"The scale of faulting at Airth is:*
>
> *(i) Major: Detectable at 2D seismic resolution ± 10m.*
>
> *(ii) Minor: Even below 3D seismic resolution.*
>
> *(iii) Micro: Grade down to fractures, fissures, etc."* [para. 3.3.2.5]

2.2.4 This categorisation is somewhat inaccurate. The minimum detectable throw of a fault in the rocks of the PDA is of the order of 25-30 m with the 2D seismic of the type used, not the ~10 m claimed by Dr Cuff. This figure is based on the standard 'quarter wavelength' criterion using appropriate frequencies and velocities. On the other hand, a 3D survey, yielding a digital volume of 'voxels' (like pixels on a computer screen, but in 3D) can reveal much more detail in addition to its inherently greater imaging accuracy. The fault resolution limit of the 3D equivalent of the 30-year old 2D surveys used by Dart would be more like 5 m. A semi-high resolution survey, with up to double the frequency bandwidth (if this were technically possible) could bring the resolution down to 2-3 m.

2.2.5 But Mr Goold takes a pessimistic view of using such 3D technology:

> *"...the suggestion is that faults with throws of <5m will have to be resolved to demonstrate that small scale faults are not introducing pathways between permeable and impermeable formations. Since such faulting cannot be reliably resolved in modern 3D onshore seismic, it would not lead to a more definitive position on theoretical pathways for migration of fluids."* [para. 4.3.8.4]

2.2.6 Mr Graham says much the same thing:

> *"As a geophysicist Professor Smythe will be familiar with the imaging resolution afforded by 3D seismic data and that even a high resolution survey would not be able to resolve faults to less than 5 metres, i.e. the vertical scale of the coal beds. If Professor Smythe accepts that a minor fault throw as little as one metre displacement is capable of juxtaposing layers of different permeability against one another acting to break horizontal permeable pathways, it is apparent that 3D seismic can not add significantly to the conceptual interpretation of this field."* [para. 5.3.7]

2.2.7 Both persons seem to be saying here that if the best possible imaging cannot produce better than a 5 m resolution, we should not even bother trying to use it. They are correct in saying that there may be potential pathways requiring an even lower resolution (although Mr Goold calls them 'theoretical'), but they fail to realise (or cannot accept) that even such a less-than-perfect 3D image of the PDA would go a long way to resolving current inconsistencies.

2.2.8 The problem with fault geometry is that it is fractal, which means it is self-similar over a wide range of scales (e.g. Turcotte 1997). This has been demonstrated by measurements of coal basin fault geology, among others. To illustrate the concept: if the faulting over the whole of PEDL133 has a particular kind of pattern, for example the mix of large and small faults and their directions (at the scale of 10 km by 10 km of the licence) then in a 1 km square block the faulting will still have the same relative patterns, but at a ten times smaller scale. We can progressively reduce this to 100 m by 100 m, then even smaller, and so on. This fractal geometry is a continuum, or spectrum, and not a hard-and-fast division into discrete classes, as suggested in the quotation above from Dr Cuff.

2.2.9 I would accept, for example, that a fault with a linear dimension of 10 m (in height or width) and with a likely maximum throw of 20 cm is unlikely to be significant when penetrated by the drill, but I would not say the same for a fault of one order of magnitude bigger (100 m in size, throw of 2 m). But the onus is on the Appellant firstly, to prove that faults (or fault patterns) below a certain scale are insignificant for the problem of fugitive migration, *and then* to prove that it has satisfactorily characterised all the faults bigger than this limiting scale.

2.2.10 Mr Goold's precognition has two sections on faults; 'Dart's current structural understanding of Airth' and 'Geological model iterations' (3.11 and 3.12 respectively). He cites a new two-part geological structure map for the top of the Lower Bannockburn Main Coal horizon (his figures 3a and 3b; Dart inquiry document DE(J)1, drawings 5 and 6).

2.2.11 In parallel with Mr Goold's precognition, my own precogition included a detailed critique of Dart's geological interpretation (my paras. 2.4.9 to 2.4.23 and figures 7 to 12) demonstrating that Dart's structural map, dated late October 2013 (revised G20 submissions), was geologically untenable. Here I showed that the apparent dying-out of two important faults in the PDA, the Carbrook to the west and the Kinnaird House to the east, according to Dart, was inconsistent with subsurface and surface data. The BGS has mapped the two faults as being one continuous E-W structure right across the area. The throw at the surface, in the zone of interest, is 120 m. By local and even regional standards this is a major fault. I showed that the subsurface data also match the BGS view of a continuous fault; therefore the Dart interpretation is seriously in error, as it has a major fault just disappearing abruptly and then re-appearing as one goes from east to west, or vice-versa.

2.2.12 Now Dart has revised its interpretation, with Mr Goold presenting the two-part map dated 30 January 2014. The problem is illustrated in Figure 2, which covers the same area as my precognition figure 10. The surface location of the fault, as mapped by the BGS, is shown in red, with tick-marks on the downthrown side. A spot value of throw of 120 m is indicated in the centre, estimated easily by the considerable apparent lateral displacement of surface outcrops. But Dart's G20 interpretation showed the fault dying out (0 m throw) at the two places labelled in Figure 2. The new version now has its two separate faults connected, as indicated by the bracket, and as I pointed out should be the case.

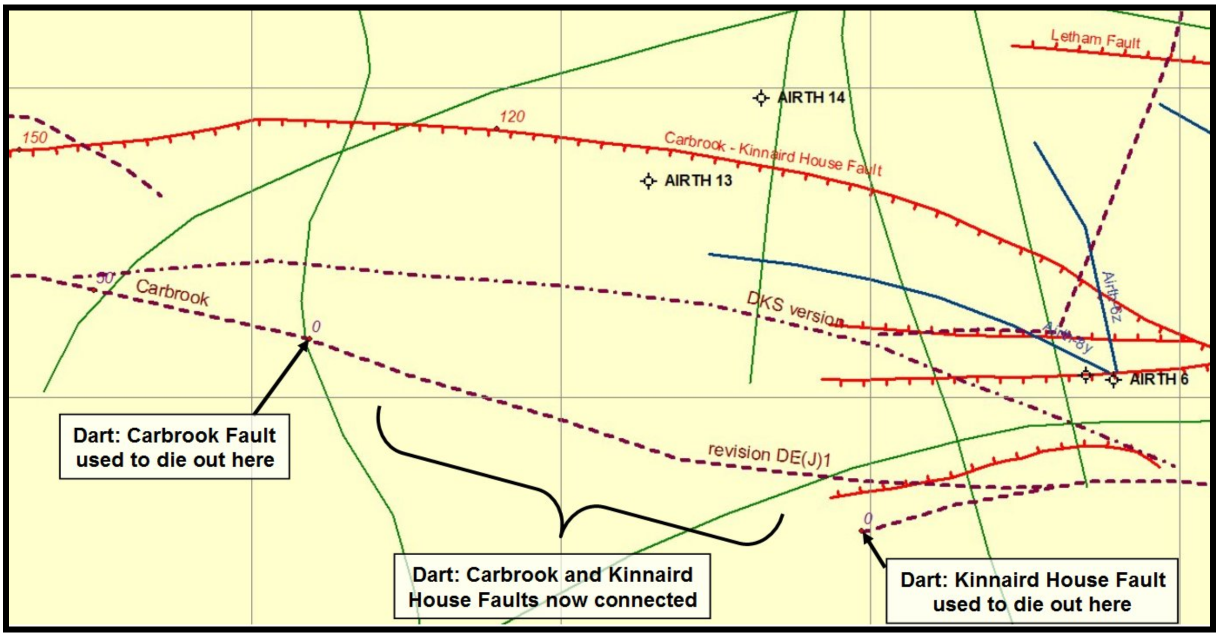

Fig. 2. Three interpretations of the Carbrook - Kinnaird House Fault at the depth of the coal horizons to be developed. These are (1) two separate faults (Dart, October 2013), (2) a continuous fault (Dart, January 2014, document DE(J)1), and (3) a more reasonably positioned continuous fault labelled 'DKS version'.

2.2.13 Although Dart's last-minute re-interpretation is an improvement, it is still a minimal alteration. It is more consistent with the seismic data to re-draw (or to draw, in my case) the subsurface trace of the fault to keep it parallel to its surface expression. I have shown this by the dash-dot line. This difference between my version and Dart's new version is not trivial, as it still implies a difference in depth to the coal horizons of perhaps 50 m in the 'zone of dispute'. So in my view Dart's latest interpretation, although a great improvement, remains seriously in error.

2.2.14 Mr Goold discusses Dart's re-interpretation in his para. 3.12.1, and invites comparison between old and new by means of his figures 3a and 3 b (new) and figure 8 (old). He goes on to provide what sounds suspiciously like an excuse:

> *"During iterative geological remodelling, which will continue during the drilling phase itself, it is conceivable that certain well trajectories might require to be altered from the initially proposed plan to reflect the geology encountered. This is normal for petroleum developments and is accommodated on a per well basis by regulators and licensing authorities (e.g. SEPA, DECC and CA)."*

2.2.15 I find this unacceptable. It is tantamount to admitting that likely major errors exist in Dart's understanding of the geology, and will be iteratively corrected as horizontal well drilling proceeds. But the 'errors' will only be discovered by a lateral drill losing the coal horizon that it is supposed to be tracking, and penetrating other layers - in the case quoted above, possibly stratigraphically 50 m higher or lower than the target coal.

2.2.16 Once again Mr Goold asserts that the development is a *"normal"* petroleum development, and that such iterative re-interpretations are normal. But in my view, for Dart to proceed with drilling based on its current database and understanding would be irresponsible. The radical changes in interpretation by Dart over the space of the last few months, as outlined above, show that Dart's current understanding of the geology can hardly be considered as final, or even converging towards a consistent picture. In any case, in a 'normal' petroleum field development, the operator would only commit to an extensive programme of horizontal drilling after having obtained a 3D seismic image. In short, Dart's development application is premature.

2.2.17 Mr Goold has criticised (para. 4.3.4) my speculation (in my August 2013 review) of a possible re-interpretation of the Letham Fault which, in passing, he claims I name incorrectly by omitting Moss from the name; I am following the BGS nomenclature, e.g. of Hinxman *et al.* (1917). Note that I have withdrawn my August 2013 suggested re-interpretation, and it therefore does not appear in my precognition.

2.2.18 Mr Goold also takes me to task (para. 4.3.5) for criticising both the location and the accuracy of the two cross-sections supplied by Dart. His criticism is based on my August 2013 review. I expanded upon this criticism in my precognition, section 2.4.1. It concerns, in particular, the Dart N-S cross-section, located in my precognition figure 5. He makes no attempt to respond to the inaccuracy of the cross-section , but merely asserts that its location is *"fit for purpose"*. As I pointed out in my precognition (paras. 2.4.2 - 2.4.4 and figures 5, 6), Dart acknowledged the errors in the cross-section, but, instead of correcting them, Dart simply removed the vertical scale and added a disclaimer. Mr Goold defends this irresponsible approach in his precognition. Far from being 'fit for purpose', I contend that to present the only N-S cross-section through the PDA made available by Dart in a form in which important faults are knowingly omitted is misleading. The importance of the faults is demonstrated in my precognition figure 6, which shows the faulted circular basin structure.

2.2.19 Mr Goold argues (at 4.3.6, in response to my August 2013 review) that my view of faults persisting to depth is over-simplified, citing two reasons:

1. Rapid lateral and vertical variation in fault throw due to depositional conditions (i.e. growth faults),

2. Fault geometry, where two separate faults at the surface meet at depth in a fork-like structure.

2.2.20 Neither of these two complicating factors in fault geometry is an excuse for omitting faults, as Dart has done. I concur in principle with the first reason cited above, because the BGS memoir to accompany Falkirk sheet 31E says so. The memoir is listed as Dart document DE(I)35, but has not been submitted, presumably because it is in copyright. To aid the inquiry I have scanned the frontispiece map and pages 58-59 dealing with folding and faulting. This is submitted by CCoF. The BGS has added several caveats (see the BGS memoir, pp. 58-59). Firstly, there is an approximate 'line of variation' trending east-west from Falkirk to Bo'ness, north of which there is an abrupt increase in thickness. However, this change is not to be associated with any single fault. There is also thickening of formations into the centre of the N-S trending Clackmannan Syncline (this is located in the frontispiece map, figure 1 of the memoir), within which the PDA is to be found. Thus these changes are more regional and gradual than Mr Goold implies, and apply only to the Namurian strata; that is, the Limestone Coal Formation (within which the target CBM coals occur), the Upper Limestone Formation and the lower two-thirds of the Passage Formation. By Westphalian time (deposition of the later Passage Formation and the Coal Measures) the differential subsidence had ceased.

2.2.21 The second reason cited above by Mr Goold has been fully accounted for by me where appropriate, as seen by my seismic interpretations in figures 9 and 11 of my precognition. Turning back to my provisional re-interpretation of Dart's N-S cross-section (my precognition, figure 6), it can be seen that the three missing faults to the south of Airth-6, which I have re-inserted, all have *southerly* downthrows. The most northerly of these three faults, just left of the 'Base Coal Measures' label is the Carbrook - Kinnaird House Fault discussed above. Due to their southerly downthrow it is unlikely, according to the BGS view, that these were growth faults. The first fault to the north (just to the right of the label) is the Letham Fault. This fault, and the next one to the north, may well show evidence of growth faulting.

2.2.22 None of the above affects in any way my conclusion that Dart's N-S cross-section is misleading, and that my figure 6 is a much more realistic interpretation of both the folding and faulting.

2.2.23 Therefore Mr Goold's assertion that:

> *"Professor Smythe's assertion that the throw on faults indicated on Geological Survey maps is valid to depths of at least 1km is a gross oversimplification which does not take into account fault geometry and sedimentology."* [para. 4.3.6.2]

is invalid, not only qualitatively as I have explained above, but also quantitatively; a given fault throw measured from surface data in the PDA will be valid, probably to within ±20% or better when extrapolated downwards to about a kilometre depth. If two parallel faults at the surface connect up at depth then the total displacement of the single combined fault can be estimated by summing the two separate values of throw for the faults higher up. So if the surface faults have the same sense of throw (say, both to the south) then the two throw values are simply added. If the faults of a pair have opposing senses of throw then the summed throw will tend to cancel out. All this is elementary geology, called 'section balancing', and based on the principle that geological layers cannot simply disappear or abruptly change thickness (or attitude) across faults without good reason.

2.2.24 In conclusion, I have not misinterpreted the faulting as asserted by Mr Goold, due to the *"paucity of data"* (para. 4.3.7.3) that I have collected (note that this comment is out of date, based as it is on what data I had available in August 2013). On the contrary, I have more than enough data to be able to analyse Dart's work. I stand by my view that Dart has a limited understanding of the geological structure of the PDA; in particular, there is insufficient understanding for Dart to be permitted at present to proceed with the development.

2.3 Faults as potential conduits or barriers

2.3.1 Mr Goold relies on the precognitions of Mr Graham and Dr Cuff for his statement:

> *"Dart believes that faulting at any scale does not present a credible pathway for significant or rapid migration of fluids or natural gas to receptors at the surface or within the subsurface."* [para. 3.1.3]

2.3.2 He states further down:

> *"Comprehensive counter arguments to Professor Smythe's are presented in other submissions to the Inquiry (notably by Mr Graham and Dr Cuff)."* [para. 4.4.2]

2.3.3 Mr Graham lists seven points which in his view limit or inhibit the development of permeability in faults that would result in *"significant fluid flow"* (para. 5.3.6).

2.3.4 His first point concerns the bulk permeability of the Carboniferous strata, which he describes as *"limited"*. In section 3.3 he emphasises the cyclic or repetitive nature of the Carboniferous strata, such that the permeability is strongly anisotropic. This means that the horizontal permeability (along the layers rather than across them) can be ten times higher than the vertical permeability. At the same time he admits that the coal seams, because of fracturing, have a very high permeability. He also concedes that the Passage Formation has high permeabilty, and is classed as a high productivity aquifer. But none of these arguments counter the possibility of fluid flow proceeding <u>along</u> the layers and then <u>up</u> the faults, like the rows and ladders in a Snakes and Ladders board.

2.3.5 Mr Graham's second and third points concern faults. The second point mentions what he terms as *"unambiguous conceptual evidence"* that compartmentalisation by faults inhibits transfer of fluid between fault blocks (and, presumably, up the fault plane itself). I discuss and dismiss this supposed compartmentalisation concept in section 2.7 below. His third point is:

> *"Vertical displacement of ductile strata of low strength , i.e. shales and seatearths, with corresponding poor development and resistance to discontinuities"* [para. 5.3.6]

2.3.6 This point is somewhat obscure; he may mean that the ductile strata like seat-earths get smeared out along fault planes, to lower the bulk permeability of the fault zone; on the other hand he may be intending to mean that the prevalence of such strata within the Carboniferous geological column somehow prevents vertical discontinuities from forming. If the latter is what is intended, this might work on the scale of centimetres, but would be ineffective in preventing the formation of larger fractures (as the evidence shows - the faults exist).

2.3.7 Mr Graham's points four and five discuss the pressure gradient or other forces available to drive fugitive methane upwards. He, in company with Mr Goold (paras. 4.4 and 4.4.2.2), questions how fluid could be driven upwards along faults or through the bulk rock itself when the pressure gradient created by the dewatering means that fluid is drawn into the coal seams (the locus of lowest pressure). Dr Cuff asserts that:

*"The upward flow from the target beds to the overlying units as a direct result of the project drilling is **negligible given that CBM depressurises the coal aquifer and creates a hydraulic gradient towards the target beds."*** [his emboldening; para. 3.3.1.3].

2.3.8 This is a valid point made by the three authors - but it is valid only in the simplest, idealised case of constant flow conditions. I concur with the view expressed in Dr Shawn Salmon's precognition (para. 2.3.11) that transient pressure conditions, due to blocking of a lateral, or after cessation of a dewatering episode, could lead to fugitive emissions, if the pathways exist. These pathways do exist, in the form of faults.

2.3.9 Mr Graham's points six and seven refer back to Mr Goold's evidence and discuss tectonic stress. I deal with this under section 2.9 below.

2.4 Permeability, hydraulic conductivity and vertical flow - solid rock

2.4.1 Mr Goold devotes five pages (pp. 7-11) to an explanation of permeability within the target coal formations, but nowhere does he discuss the permeability (or hydraulic conductivity) of the Carboniferous succession in general, nor that of fault zones.

2.4.2 Mr Graham generalises about the permeability of the Carboniferous, emphasising its anisotropy, as discussed in 2.2.4 above. He mentions the sole value of hydraulic conductivity actually measured from core in a commercial well some 5 km NE of the PDA. I have already pointed out (precognition, para. 4.3) that this is hardly an adequate basis for estimating the hydraulic conductivity of the 800-900 m of Carboniferous above the target coals in the PDA.

2.4.3 Neither Mr Goold nor Mr Graham discuss the geology and hydrogeology of fault zones. Mr Goold, without going into any detail, takes issue with my summary view of faults as possible or likely migration routes. His opinions are discussed in section 2.6 below.

2.5 Permeability, hydraulic conductivity and vertical flow - superficial deposits

2.5.1 The Appellant and I concur that there are no significant groundwater resources within the Quaternary superficial deposits in the PDA. The relevance of these deposits lies in their potential barrier properties. Dr Cuff asserts that:

"3.3.2.7 There is no evidence that faults continue to the ground level surface although many terminate on rockhead with fairly limited unconsolidated cover."

implying that the Quaternary unconsolidated cover sediments somehow provide a barrier to any upward flow through the faults.

2.5.2 Comparison of the BGS solid and superficial geology maps, both in hard copy and using the BGS online mapping tool, shows that the Quaternary deposits cover 95% of the solid rock in the PDA. They comprise tidal flat deposits over more than 50% of the area, raised tidal flat deposits in the west, and smaller areas of Devensian till, together with the peat of Letham Moss in the centre of the area.

2.5.3 Mr Graham has summarised the relevant properties of the Quaternary in section 3.4, but in a rather over-generalised way. For example, the supporting document cited (DE(I).152) is a BGS report on Carboniferous (i.e. solid rock) aquifers of the whole Midland Valley. This report contains a single paragraph, on page 6, summarising the superficial deposits, as follows:

> *"Much of the Carboniferous aquifer outcrop is overlain by superficial deposits, except for the areas of highest ground. The main deposit type is glacial till, which tends to be clay-rich and compacted. On higher ground some extensive areas of peat have developed. The largest of the active river valleys, which typically acted as conduits for post-glacial meltwater, are infilled with glaciofluvial sand and gravel, overlain by alluvium. Raised marine deposits are important in many modern coastal areas, and extend inland along the Forth, Clyde and Tay estuaries, where they can be tens of metres thick. They include both granular and clay-rich deposits."*

2.5.4 Mr Graham's contribution under this head therefore adds no specific detail, except to say that 26 historical boreholes in *"the study area"* apparently corroborate the generalisation quoted above. But it is not clear from this statement whether Mr Graham's study area means the whole Midland Valley, the PEDL133 licence, or the PDA.

2.5.5 The thicknesses, lithologies and permeabilities of the Quaternary have been studied and mapped by the BGS within the so-called study area, including the PDA (CCoF 66: Dochartaigh *et al.* 2005). The three classes of permeability (high, medium and low) are shown in Figure 3. The Quaternary thickness is shown in Figure 4.

2.5.6 The PDA lies within zones of Quaternary with low or medium permeability (Fig. 3). The Quaternary thickness over the PDA varies from about 1 m to 30 m, with the exception of the more southerly outfall pipe to the River Forth. Approximately half of the underground works of the PDA underlie a cover of superficial clay less than 10 m thick.

2.5.7 Unindurated clays can have extremely low permeabilities, but unfortunately the range of variation in permeability of intact clays and glacial till is of the order of ten million (Hobbs *et al.* 2002). We do not know at which end of this very broad spectrum the superficial deposits in question lie. But for the implied purpose of protecting receptors from possible upward flow through bedrock faults, the known thickness of Quaternary, of the order of 10 m, is completely inadequate as a protective layer, even if it is of low permeability. In conclusion, **any upward flow along faults or other natural geological features will not be stopped by the superficial cover.**

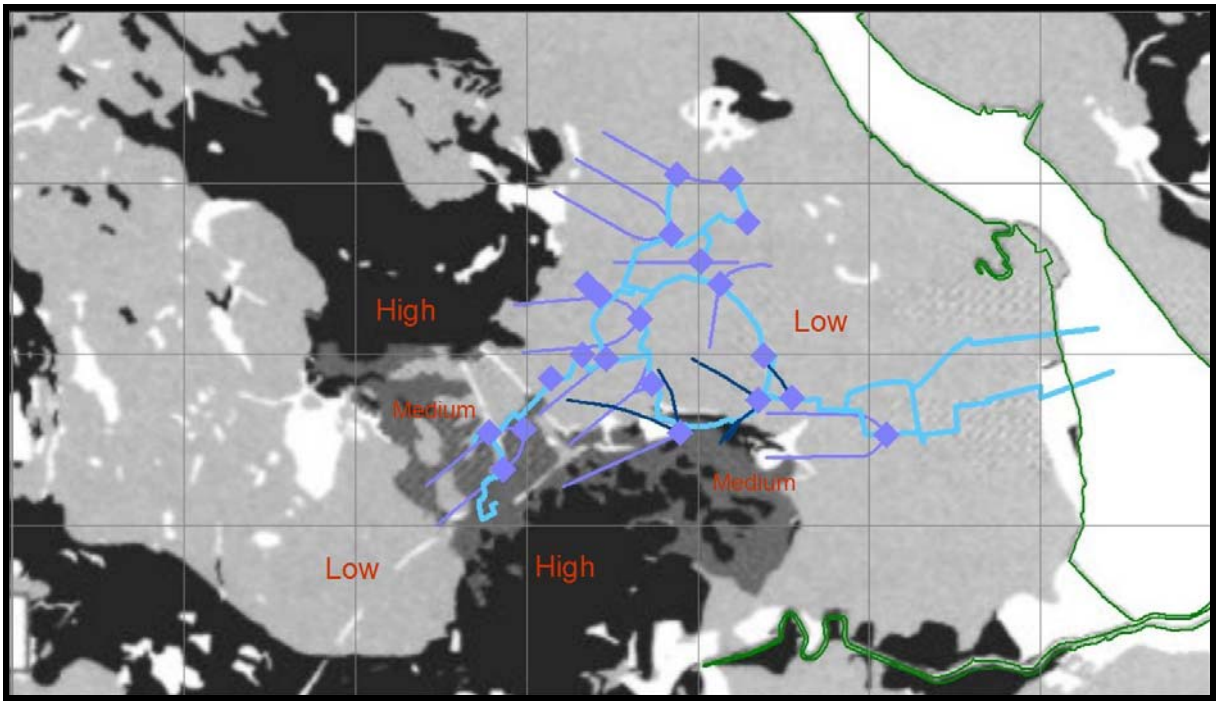

Fig. 3. Quaternary permeabilities in the PDA. High - dark grey; medium - mid grey; low - light grey.

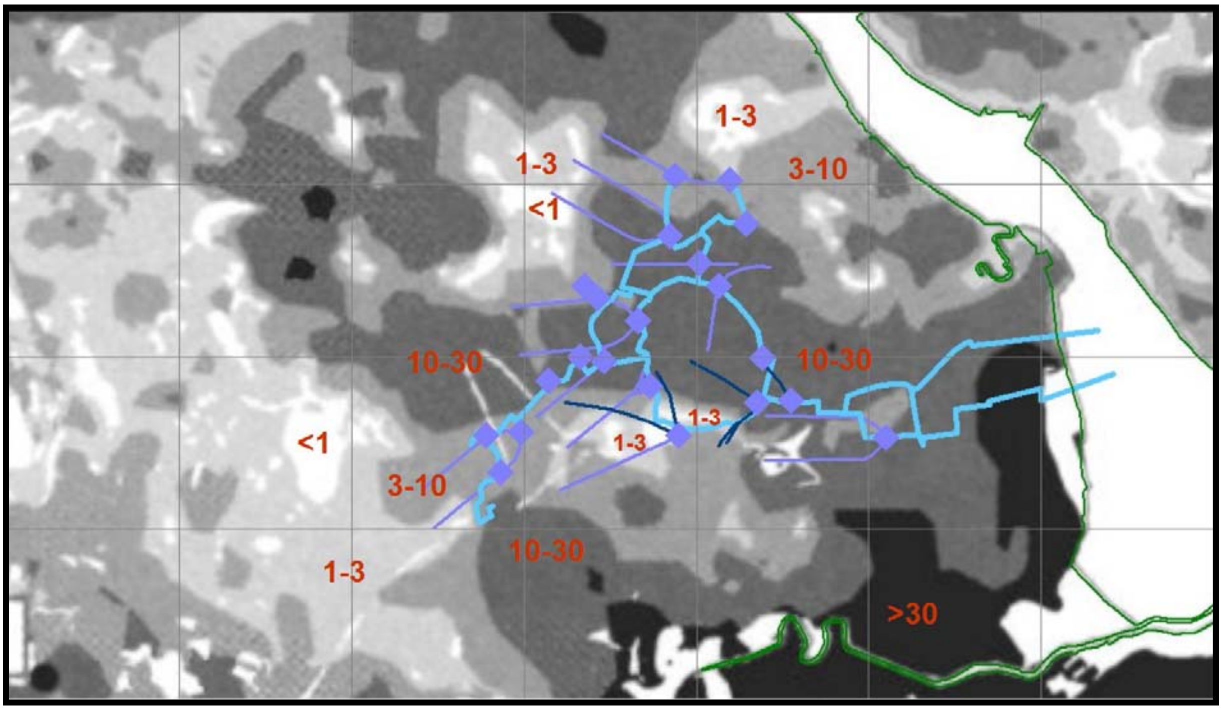

Fig. 4. Quaternary thickness in the PDA, in metres. Greater than 30 m - dark grey, with three progressively lighter shades as labelled in red. White - less than 1 m.

2.6 Hydraulic conductivity of faults

2.6.1 A crucial issue for the inquiry is whether or not the faults in the PDA, once correctly mapped, conduct fluids easily or not; another way of putting it is to assess what the oil industry calls the *fault seal risk*.

2.6.2 Mr Goold calls my view, that the default industry position is that faults do not act as seals, is *"naïve"*. He goes on to quote his own 30 years of industry experience, and to point out that a very common method by which oil or gas is trapped is the 'fault seal trap'. Nowhere does he go into any detail of my review of the literature on hydraulic conductivities of faults, which was discussed in my August 2013 review and is largely reproduced without alteration in my precognition.

2.6.3 I agree with Mr Goold that fault seal traps are very common. The well-known UK consulting company Badleys, for example, even quantifies it:

(http://www.badleys.co.uk/consulting-fault-seal-analysis.php):

> *"Finding and mapping traps and risking fault seals is an everyday task in the oil industry. About 75% of all hydrocarbon-bearing traps are fault-related."* [my underlining]

2.6.4 Section 2.7 of my August 2013 initial report for CCoF is essentially the same as in my precognition. Therefore Mr Goold's limited comments on the former may be applied to the latter.

2.6.5 I took the phrase about the default industry view on fault hydraulic conductivity from a petroleum textbook. A better way to summarise the industry view would be to say that fault seal traps are inherently risky. That is why there is a whole service industry, and dozens of academic and industry research groups, working on the problem of 'risking' potential oil seal traps. The aim is to quantify the probability that a particular fault will actually form an effective seal; if it is probably a seal (say more than a 50% chance) then the potential trap might be worth drilling. To reverse Mr Goold's view, it would be 'naïve' for any explorationist to drill a potential oil or gas 'fault seal' accumulation on the *assumption* that the fault or faults are sealing.

2.6.6 I therefore reiterate the view expressed in my precognition (Para. 2.7.3) that **taking the gamble of fault seal risk may be permissible in conventional hydrocarbon exploration, where the worst outcome is a 'dry hole', but it is unacceptable to play this game when the potential environmental consequences may be profound.**

2.7 Compartmentalisation by faults

2.7.1 Mr Goold once mentions compartmentalisation by faults; this is a common geological feature known from the experience of the hydrocarbon reservoir production industry (para. 4.4.2.4). He then adds that migration through faults:

"happens necessarily through geological time compared with the lifespan of a CBM well and possibly in response to other geological processes such as tectonic movement and basin subsidence and uplift"

2.7.2 He is implying here that the hydraulic conductivity of faults is relatively very small (so that *"geological"* time is apparently needed for it to be significant in comparison to migration through bulk unfaulted rock), and/or that tectonic movements either temporarily alter the conductivity, or else the hydraulic head alters (again perhaps temporarily) to speed up the flow. He is trying (by the use of the phrase 'geological time') to dissociate artificially the hydrogeological properties of a fault zone from hydrogeological properties in general. This is invalid. A fault zone has certain hydrogeological properties here and now, just as the bulk rock or coal seam does. One cannot separate the fluid flow through all these media into 'geological' time spans as opposed to here-and-now timespans, for example the period required to dewater a coal seam.

2.7.3 Mr Graham also mentions compartmentalisation by faults, quoting the BGS in support once (para. 3.6.3) and the British Geological Society (sic) as his source (para. 5.3.6). He provides no further details as to why such compartmentalisation is important.

2.7.4 Dr Cuff mentions compartmentalisation *"by later extensional faulting"*. He also adds that the coals may have been altered locally by intrusive volcanic rocks (para. 7.3.3). However, there are no intrusives within the PDA to cause such an effect.

2.7.5 I have already shown that there is no evidence for compartmentalisation at the scale of the PDA, and, further, that the relevant BGS report only mentions such a phenomenon once. The BGS is clearly applying it over a scale far larger than the PDA or even PEDL133 (my precognition, section 2.8).

2.7.6 In conclusion, compartmentalisation of blocks of geology by faults has to be considered by studying at the physical characteristics of the faults concerned. **At present Dart is merely asserting, with no evidence, that it happens in the PDA.**

2.8 Hydrocarbon seepages and volcanism-induced pathways

2.8.1 Neither of these two important problems have been given any consideration in the Appellant's precognitions.

2.9 Earthquake risk and tectonic stress

2.9.1 Dr Cuff refers (section 3.3) to potential methods for fugitive gases including methane, including:

"Through seismic activity. This refers to the potential for fugitive emissions resulting from earthquake induced damage." [para. 3.3.3.1]

2.9.2 There are two related issues here; firstly, could the projected works initiate or trigger earthquakes, and secondly, could earthquakes, however triggered, result in fugitive emissions? I concluded that the first risk is low, provided that no hydraulic fracturing is conducted. I concur with Dr Shawn Salmon's precognition view:

> *"I considered that the data and modelling results, by themselves, did not preclude the use of fracking, but the Appellant's assurances* [that fracking will not be used] *should be taken at face value, and be reflected in the wording of any future planning permission and the accompanying conditions."* [AMEC precognition para. 2.3.18]

2.9.3 Dr Cuff refers to the second issue:

> *"Information regarding the seismicity of the UK (refer British Geological Survey sources), integrated into a risk assessment analysis, has been carried out by Dart. ... Interpretation of the British Geological Survey (BGS) Peak Ground Acceleration data indicates that the risk associated with earthquakes at the site is **negligible**, with a return period of ~2,500 years."* [para. 3.4; author's emboldening]

2.9.4 This statement appears to be based on probabilistic ground motion modelling by the BGS (Musson and Sargeant 2007), although the reference is missing from Dr Cuff's precognition. The BGS predictions of national hazard maps were based on the historical catalogue of moment magnitudes (Mw) greater than 4.5. The results of the study are expressed as peak ground acceleration (PGA) values. Specifically, it is the horizontal component of the bedrock acceleration that is measured. The predictions were carried out using Monte Carlo techniques. The measurement unit of PGA is g, the acceleration due to Earth's gravity. For example, if you are accelerated upwards by 1 g you will be (momentarily) weightless and your feet will leave the ground. The hazard map for a 2500 year return period shows that the Midland Valley (away from a 'bullseye' centred on Comrie, which is exceptional) falls into the zone of 0.02 to 0.04 times g. This corresponds roughly to an intensity scale; see: http://en.wikipedia.org/wiki/Peak_ground_acceleration in which the perceived shaking is categorised as 'light' and the potential damage as 'none'.

2.9.5 The analysis above refers to relatively large earthquakes (by UK standards) and to the evidently very small hazard that they will cause in our zone of interest. It does not apply to smaller earthquakes, which I now discuss.

2.9.6 Several earthquakes, of which the largest had a local magnitude (M_L) of 2.3, occurred during fracking by Cuadrilla near Blackpool in 2011. An expert report commissioned by DECC (Green *et al.* 2012) concluded that they were triggered by the fracking 'treatment'. The report concluded that, based on coal-mining induced earthquakes, the maximum magnitude that would be experienced in the UK would be around 3.0 M_L. The report further stated that the fault which slipped, causing the largest earthquake, was 'critically stressed'. This means that it had stored energy ready to be released. Such a critical state of stress is common in the Earth's upper crust. The report adds:

> *"it is not possible to state categorically that no further earthquakes will be experienced given a similar treatment in a nearby well. There is no evidence to suggest that the causative fault is unique and knowledge of faulting in the basin is poor, so it is quite possible that there are many such faults throughout the basin. ... and numerous observations of mining induced earthquakes throughout the UK show*

that brittle failure can occur at shallow depths (c 1 km) in similar rocks. This means that the probability of further earthquakes, if similar treatments were repeated, may be higher than suggested, though this is difficult to quantify without detailed data to analyse."

2.9.7 The steel casing (liner tubing) of the vertical Preese Hall-1 well was deformed into an oval cross-section (flattened by more than 1 cm) over about 60 m of the hole, due to the largest earthquake.

2.9.8 What relevance does this recent Lancashire fracking and earthquake triggering history have for Airth? Firstly, it is possible that any intrusive underground activity, including coal-mining or coal seam dewatering, may be sufficient to trigger earthquakes in a critically stressed volume of the upper crust. We do not know for certain that the Midland Valley is <u>not</u> critically stressed; the conservative assumption is that it is critically stressed. There is evidence of earthquakes in the locality since 1970, when the online BGS catalogue began; see: http://mapapps.bgs.ac.uk/geologyofbritain/home.html?mode=earthquakes. Figure 5 shows the three earthquakes that have been recorded since 1970 within the PEDL133 licence.

2.9.9 The Alloa earthquake, of 2.6 M_L, occurred on 3 June 1977. Its epicentre is in the River Forth (so, strictly speaking, it is outwith the PEDL133 licence area which excludes the river), and its nominal depth is zero; that means it was very shallow, but that its depth could not be calculated. It was probably caused by slip on one of the east-west faults shown in Figure 1. The coincident epicentres of the two South Alloa earthquakes appear to lie on the Carnock Fault.

2.9.10 The three earthquake epicentres are only about 5 km from the centre of the Appellant's proposed development area (PDA). **Therefore there is a clear possibility that earthquakes may occur within the PDA, and could even be triggered by drilling or dewatering.** Surface damage resulting from any such earthquake, with a maximum magnitude of less than 3.0, will be negligible, but the underground displacement and distortion could have a significant effect on the boreholes, just as the experience of Cuadrilla near Blackpool has demonstrated. If the energy released by an earthquake of magnitude 2.3 can partially flatten a steel tube, it could feasibly completely crush and close up sections of open (unlined) horizontal boreholes within fissile coal seams. This in turn could lead to disruption or blockages in the dewatering process, with consequent potential upward flux of fugitive methane. This last eventuality has been pointed out in the AMEC precognition (para. 2.3.13).

2.9.11 Mr Goold cites the regional tectonic stress regime as being one of NW-SE aligned compressive stress (para. 2.3.4). This is somewhat inaccurate; the direction in northern Britain is more nearly due north-south. Note that this is at right-angles to the main E-W faults in the PDA. It also refers only to the two horizontal components of the three-dimensional stress tensor.

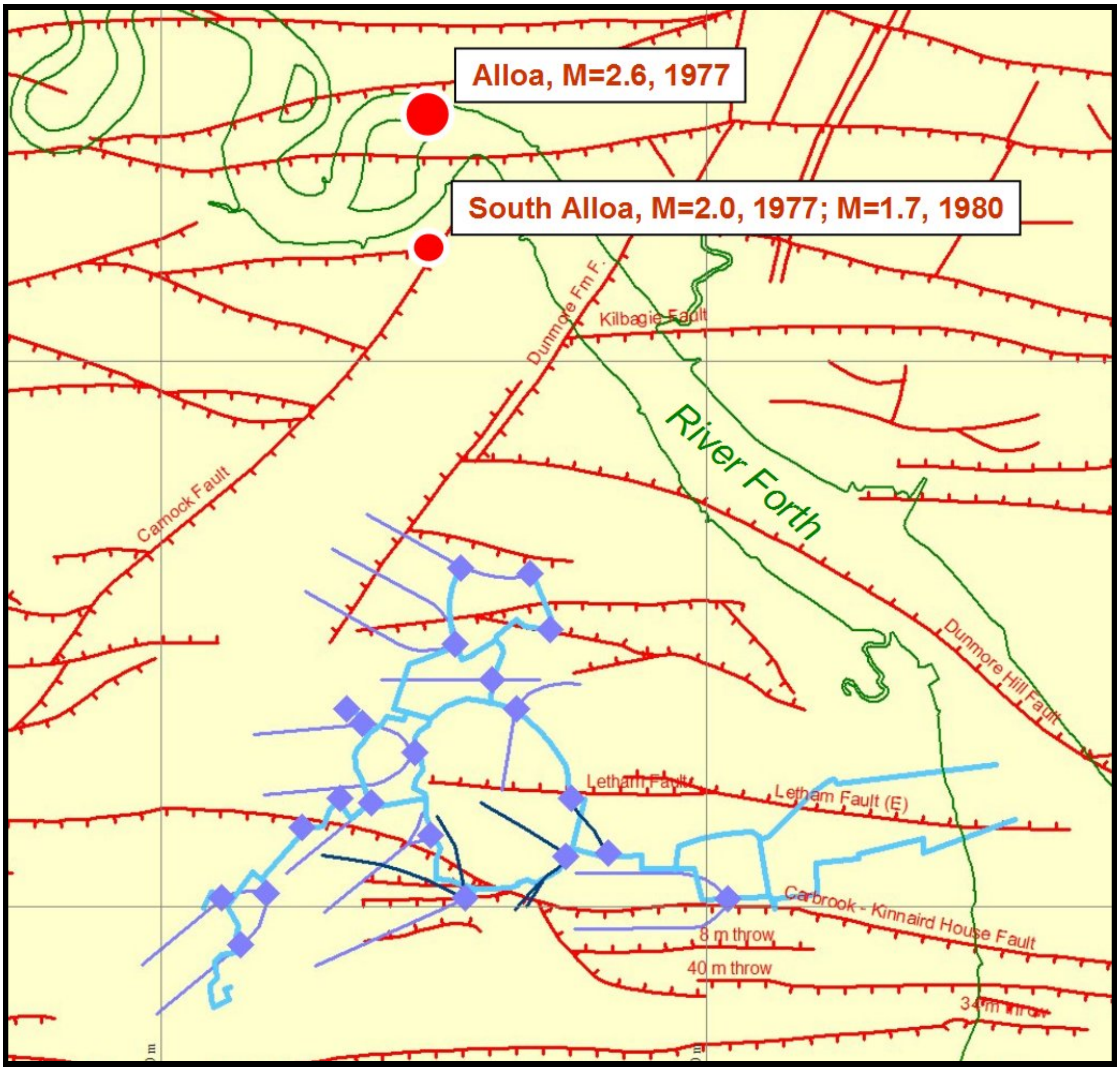

Figure 5. Epicentres of Alloa and South Alloa earthquakes (red circles) recorded between 1970 and the present. Faults at the surface are shown in red, with tick marks on the downthrown side. The proposed development is shown in shades of blue.

2.9.12 It is possible that the upper crust of the PDA is in a state of critical stress, as it is in Lancashire. Let us consider the simplified example of a pre-existing E-W fault, dipping north or south at 45° (this angle is a good approximation to the actual dip of the major faults). At shallow depths, less than about 300 m or so, the N-S horizontal component of stress mentioned above will be the maximum of the three components, considered in 3D. If the fault is somehow triggered, at this shallow depth, the slip will be in a reverse ('thrust') sense. But at deeper depths, say at the 800-900 m where drilling and dewatering is proposed, the sense of slip will be 'normal'; that is, the upper, so-called hanging-wall block, slips down relative to the lower, or footwall block.

2.9.13 The three components of stress (vertical, E-W and N-S) are called <u>lithostatic</u> components, which means the stresses in the bulk rock before we consider any fluid content. Now the values of all three components are reduced by the <u>hydrostatic</u> pressure, which is simply the pore pressure of fluid in the rock. It is a scalar quantity, i.e. it is the same in all directions at any point. We get what is called the effective stress; that is:

Effective stress component = lithostatic stress component - hydrostatic pressure

2.9.14 Obviously it is the hydrostatic pressure that is reduced by dewatering. What happens to the three effective stress components? From the equation above, they all increase by the same amount. You might say that nothing really changes, because the *difference* between maximum and minimum stress components (which is the crucial facture in deciding whether the faults will slip or not) remains the same.

2.9.15 For the benefit of those familiar with elementary rock mechanics, the Mohr circle in a Mohr diagram moves to the right, further away from the failure envelope. The rock, in effect, becomes stronger, which seems to contradict the notion that dewatering might trigger failure (i.e. initiate an earthquake). But this simple picture applies to isotropic rock with no faults. The real world situation we are dealing with includes, in three dimensions, a highly permeable coal layer being dewatered, less- or poorly-permeable strata above and below the coal, and a possibly highly permeable fault damage zone (see my precognition, p. 22, fig. 13) cutting across all the layers. Added to that we have to consider the dynamic stress changes as dewatering starts, stops, or changes its rate.

2.9.16 The previous paragraph is saying, in summary, that dewatering may induce complex and essentially unpredictable local effective stress changes that could trigger an earthquake, especially in the case of the rock being in a critical state - i.e. 'ready to slip'. In short, **dewatering of rock which is critically stressed and contains faults of a suitable orientation could trigger earthquakes.**

2.9.17 A possible consequence of an earthquake being triggered is the phenomenon of 'seismic pumping' whereby significant volumes of fluid are abstracted for a short period during and after the ground motion, as a results of dilatancy changes in the rock, and are usually expelled up fault zones.

3 CBM TECHNOLOGY

3.1 Guiding the drill bit when drilling laterals

3.1.1 In my precognition I raised the question of the the curiously curved lateral (horizontal well) track of Airth-8y (para. 2.4.20 and fig. 12), and speculated that the near-real-time guidance system may have been indicating proximity to a fault. This lateral is shown in Figure 2 above as the blue line extending WNW from Airth-6.

3.1.2 Mr Sloan's precognition explains the 'measurement while drilling' (MWD) tool used by the Appellant to guide the drill bit out of the initial downward vertical direction, to 'land' horizontally in the coal horizon and remain there as the drill bit moves forward. The system uses gamma ray logging, exploiting the fact that gamma ray emissions in coal are an order of magnitude lower in coal than in the shales or mudstones above and below each coal seam.

3.1.3 The gamma ray MWD system is relatively inexpensive, and is designed to work properly only in an unfaulted coal seam. It is unable to cope with the eventuality of the drill bit hitting a fault with a throw (displacement) of about the same magnitude or greater than the thickness of the coal seam being drilled. There exist more sophisticated so-called 'geosteering' systems for guiding the drill bit in real time while drilling horizontally. But these require a pre-existing high-resolution image of the geology, such as might be obtained from a 3D seismic survey, and onto which the position of the drill bit can be plotted and continuously updated.

3.1.4 During the decade or so of test drilling by Dart and its predecessor a lot of information must have been obtained concerning the success (or otherwise) of lateral well drilling in the coal seams. None of this has been made available to the inquiry, apart from the two 100 m sections of gamma ray logs demonstrating the tool approaching the coal seam roof and floor, respectively, plus one more log segment showing the process of landing in the coal seam (Mr Sloan's precognition, figures 1-3).

3.1.5 It is highly unlikely that none of the eight previous lateral drilling attempts (Mr Goold's precognition, para. 4.5.2.2), did not penetrate any fault at all. The Appellant needs to produce logs of all the previous horizontal drilling <u>experiments</u> (for that is what they were) to demonstrate what happened to the well when it penetrated a fault, and the coal seam was lost. There is an important question here of well integrity, not just to demonstrate that future lateral drilling will be secure, but also to prove that there is no risk of fugitive methane and drilling fluids from these 'historical' lateral drilling efforts. We also need to know how successfully (or otherwise) these holes were cemented up; a log of the cementing would be informative. If the cement job was faulty these laterals might be inadvertently reactivated, if and when they turn out to lie within the dewatering zone of influence of the new horizontals.

3.2 Novelty of CBM technology

3.2.1 Mr Goold seeks to establish (section 4.5) that that I am unfamiliar with drilling technology, particularly with the drilling of horizontal wells, and that CBM extraction in the

UK is not a novel technology (para. 4.5.2). Here are some facts. IGas is producing commercial quantities of CBM from two wells at Doe Green, Warrington, *via* several laterals drilled in 2011. I am unaware of any other UK CBM production. So CBM technology can hardly be considered mature in the UK. Figure 6 shows the number of CBM wells drilled annually since 1990, according to DECC.

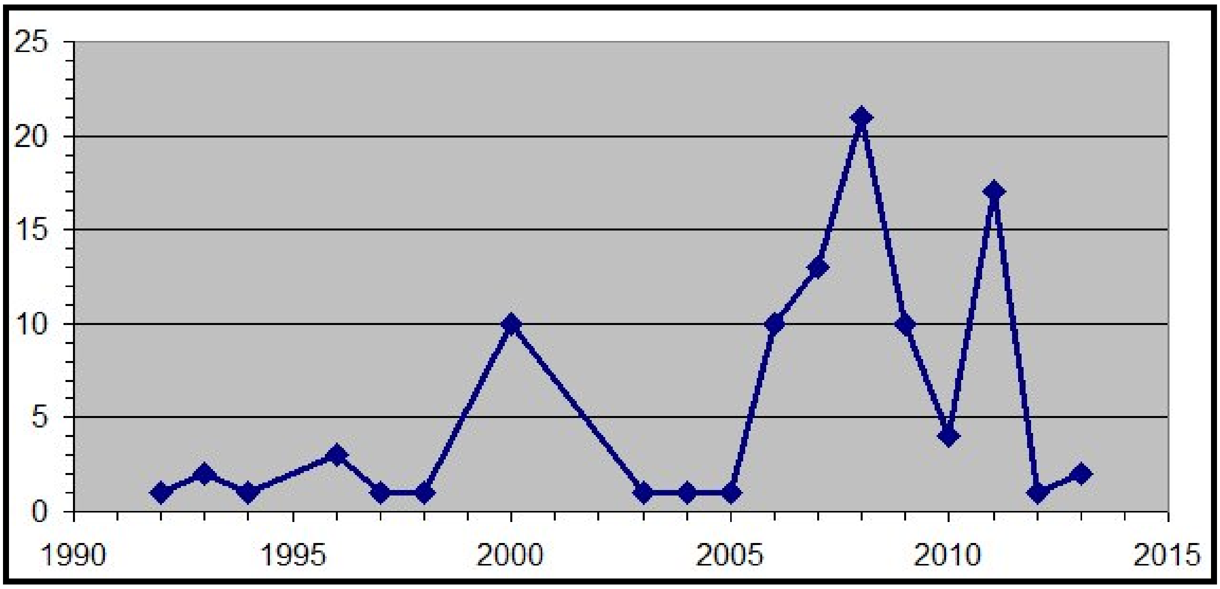

Fig. 6. Annual count of CBM wells in the UK (DECC).

3.2.2 Out of the precisely 100 CBM wells shown in Figure 6, 57 have been deviated from the vertical. These figures are not symptomatic of a mature industry; recall that in the same period half a million horizontal wells have been drilled and fracked in the USA for shale gas exploitation, and **tens of thousands of CBM wells** have been drilled in the Powder River Basin of the USA (see http://en.wikipedia.org/wiki/Coal_bed_methane_extraction).

3.2.3 The derisory UK well count - less than 1% of the Powder River Basin figure - is more a sign of a fledging or experimental 'cottage' industry, albeit using some advanced technology. This is why the inquiry is entitled to examine in a great degree of detail what Dart proposes at Airth. The fact that:

- Four different companies that have operated the same licence area at Airth in the space of twenty years (para. 2.1.1),
- 30-year old 2D reprocessed seismic data is still considered adequate as the basis for the current subsurface geological picture, and
- Just three wells have been drilled since mid-2008,

gives me the strong impression that Airth has progressed by an **underfunded hand-to-mouth succession of projects**.

4 CONCLUSIONS

4.1 My precognition conclusions were, in summary:

1. Dart has a poor understanding of the subsurface geology.
2. A 3D seismic survey is required.
3. Sonic and velocity logging in existing wells is required.
4. There is no reliable and continuous caprock or barrier layer over the PDA.
5. There are inadequate measurements of hydraulic conductivity.
6. There is no evidence that the faults will act as seals.
7. Compartmentalisation of hydrogeology by fault blocks is unfounded.
8. Field and laboratory measurements of hydraulic conductivity are required.
9. 3D computer fluid flow modelling is required.
10. Redesign of lateral layout is required to avoid faults and existing Composite Energy laterals.
11. Volcanic chimney pathways have not been considered.
12. A long-term baseline atmospheric study should be carried out before subsurface works start.
13. DECC and SEPA regulation is currently inadequate.

4.2 I can now add further conclusions, as a result of study of the four Dart precognitions cited in para. 1.1.1 above:

14. There is a risk of earthquake triggering from dewatering.
15. More sophisticated 'measurement while drilling' systems are required.
16. Detailed logs of previous lateral wells are required.
17. CBM is a new, essentially untried *unconventional* hydrocarbon technology in the UK.

4.3 I see no reason, as a result of study of the four precognitions, to alter my conclusions regarding my concerns about the Appellant's existing knowledge, data, and the UK CBM regulatory regime (numbers 1, 4 - 7, 11, 13, 14 and 17). I would like to see new information provided and/or new techniques applied (numbers 2, 3, 8 - 10, 12, 15, and 16), if a new development proposal were to come forward.

4.4 In conclusion, I retain the view expressed in my precognition that the development should be refused.

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