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)

PRECOGNITION BY PROFESSOR DAVID K. SMYTHE

ON BEHALF OF

CONCERNED COMMUNITIES OF FALKIRK

(AND SUPPORTERS)

Printing note: If printed, this document must be printed in colour throughout.

TABLE OF CONTENTS

LIST OF FIGURES

1 INTRODUCTION

1.1 Relevant personal details from my CV

1.1.1 I am Emeritus Professor of Geophysics in the University of Glasgow. Although I am now a French resident I remain a British citizen, and take an active interest in UK, French and foreign affairs, as well as in various facets of scientific research.

1.1.2 Prior to my taking up the Chair of Geophysics at the University of Glasgow in 1988 I was employed by the British Geological Survey (BGS) in Edinburgh, from 1973 to 1987. I was a research scientist, rising to the post of Principal Scientific Officer. My professional qualifications are: BSc Geology (Glasgow 1970), PhD Geophysics (Glasgow 1987), Chartered Geologist.

1.1.3 In the 1990s I was closely involved in the search for a UK underground nuclear waste repository. I served on the BNFL Geological Review Panel from 1990 to 1991. I was invited to join the panel by one of its members, Professor John Lloyd, a hydrogeologist from the University of Birmingham. I served on this panel to support BNFL's case for a Sellafield site for a Potential Repository Zone (PRZ), at the time when Nirex was investigating both Dounreay and Sellafield. I resigned from the panel after the case for Sellafield had been successfully made.

1.1.4 I was closely involved with Nirex at this epoch, and conducted for Nirex an experimental 3D seismic reflection survey, which took place in 1994. The survey encompassed the volume of the proposed rock characterisation facility (RCF) – a deep underground laboratory planned as a precursor to actual waste disposal. This was a double world 'first' – the first ever 3D seismic survey of such a site, and the first academic group to use this method, which at the time was just emerging as an essential tool of the oil exploration industry.

1.1.5 I have published 44 papers in the peer-reviewed literature, and written many other research reports and presentations. I am familiar with the geology of the Midland Valley (the central belt of Scotland) through teaching and undergraduate field excursions. One of my papers concerns the dykes of the Midland Valley (vertical sheets of igneous rock), which pass through the area of the planning appeal and extend into the North Sea.

1.1.6 Since my retirement from the university in 1998 I have carried out private research, acted as a consultant to the oil industry, and maintained an interest in the geological problems raised by nuclear waste disposal, shale gas exploration and coal-bed methane exploration.

2. GEOLOGY AND HYDROGEOLOGY OF THE LETHAM SITE

2.1 Relevant aspects of Dart's development proposals

2.1.1 Dart has a licence from DECC to explore within the area of PEDL133. I shall only be concerned with the sub-area within this licence block (hereinafter referred to as the proposed development area, or PDA), where Dart proposes to drill a number of wells (Fig. 1). Underground connecting tunnels or bores will be constructed, and lateral, or horizontal wells will be bored out from the vertical wells. All these operations will take place at a depth of around 800 - 900 m below mean sea level.

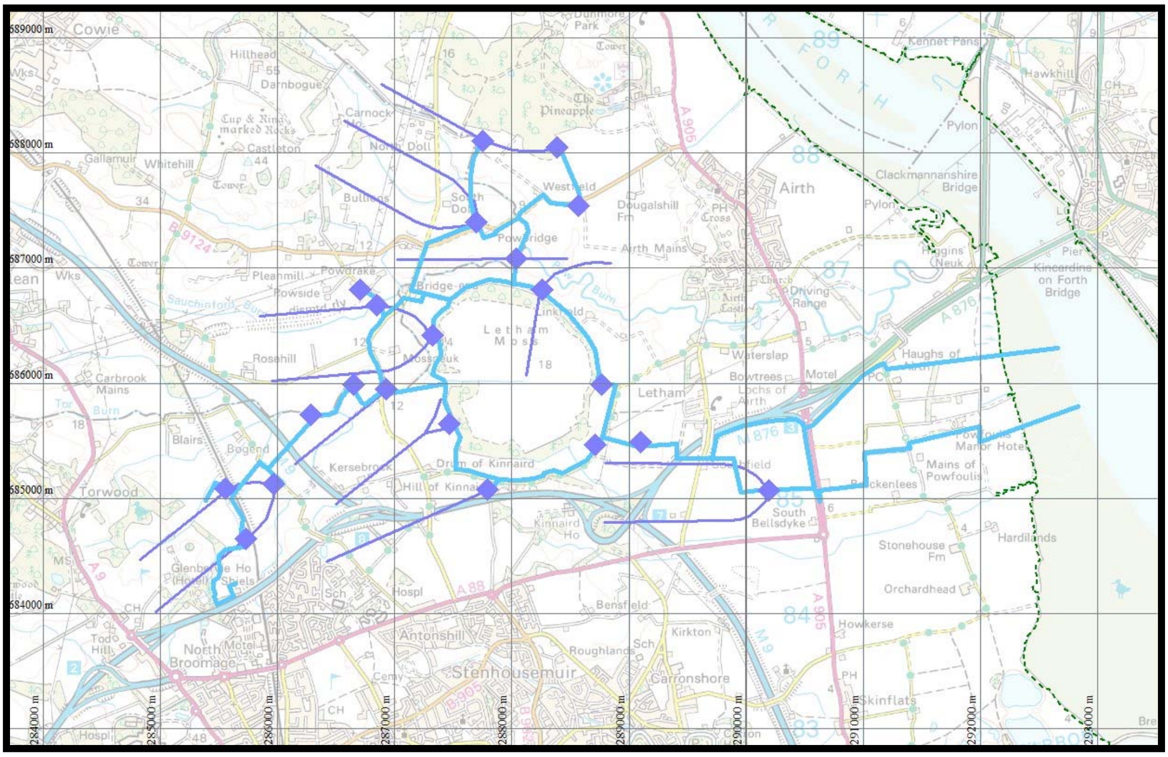

Fig. 1. Dart Energy underground works (the proposed development area, or PDA): light blue – services corridor; dark blue – lateral well trajectory; blue diamonds – existing and planned vertical wells and shafts. Existing horizontal wells are omitted.

2.1.2 There are four coal horizons to be exploited for methane within the Limestone Coal Group (Carboniferous). For each lateral well line shown in plan view in Figure 1, four actual horizontal bores will be constructed one above the other, one for each coal horizon. Methane will be abstracted by dewatering these coal horizons. This releases the methane adsorbed onto the coal. According to Dart, no stimulation, such as hydraulic fracturation ('fracking') or acid treatment, is necessary.

2.1.3 Because no fracking will be used, there will be no problem of earthquake triggering, according to Dart.

2.1.4 The original planning submission and later documents singularly fail to disclose adequately the current state of drilling, background geological knowledge to date, and details of drilling methodology to be employed. I would expect to find (*inter alia*) within the submissions:

- Composite well logs for every existing well,
- A brief history of why each existing well was drilled,
- Fence diagrams linking the wells,
- Seismic data used (if any), both raw and interpreted,
- Contour maps of the PDA showing structure of certain key horizons,
- Details as to how the horizontal wells will be constructed.

2.1.5 For example, in the original application (Appendix 8.1) the logs for 8 shallow water boreholes are reproduced, but the only log supplied for a deep borehole is Airth-6 (G20 submission, Appendix 3). There are stock extracts from industry manuals and brochures for the drilling rigs, generators, and so on (e.g. Appendix 3), but what is missing is an account of how the horizontal wells will be drilled so as to confine the borehole path within each coal seam. Such information is crucial for making a safety case within an environmental statement, particularly as such technology is new to the UK.

2.2 Dart's G20 responses on the geological structure and hydrogeology

2.2.1 Dart presented a set of maps showing old coal-mine workings over the entire area of PEDL133, and two geological cross-sections, dated May 2013, in its original G20 submission to the councils. The location of the two cross-sections is shown in Figure 2. The east-west cross section is 4 km north of Letham Moss (which can be considered as the centroid of the proposed operations) and 1500 m north of the most northerly lateral. It nearly intersects the Inch of Ferryton-1 oil well. The north-south cross-section runs some 200 m west of Airth-4, Airth-11 and one of the proposed vertical wells, but only intersects four linear features (lateral wells or underground tunnels) of the proposed development (see Figure 1 above). It is wrongly labelled; B' should be in the south and B in the north, not the reverse as shown.

2.2.2 In its revised G20 submissions (DE 35, Appendix 2) Dart has reproduced again the two original cross-sections, instead of drawing new cross-sections through the PDA. The wrong sense of labelling of profile BB' discussed in the preceding paragraph has been corrected. But the missing fault problem has not been corrected. This last problem is discussed below.

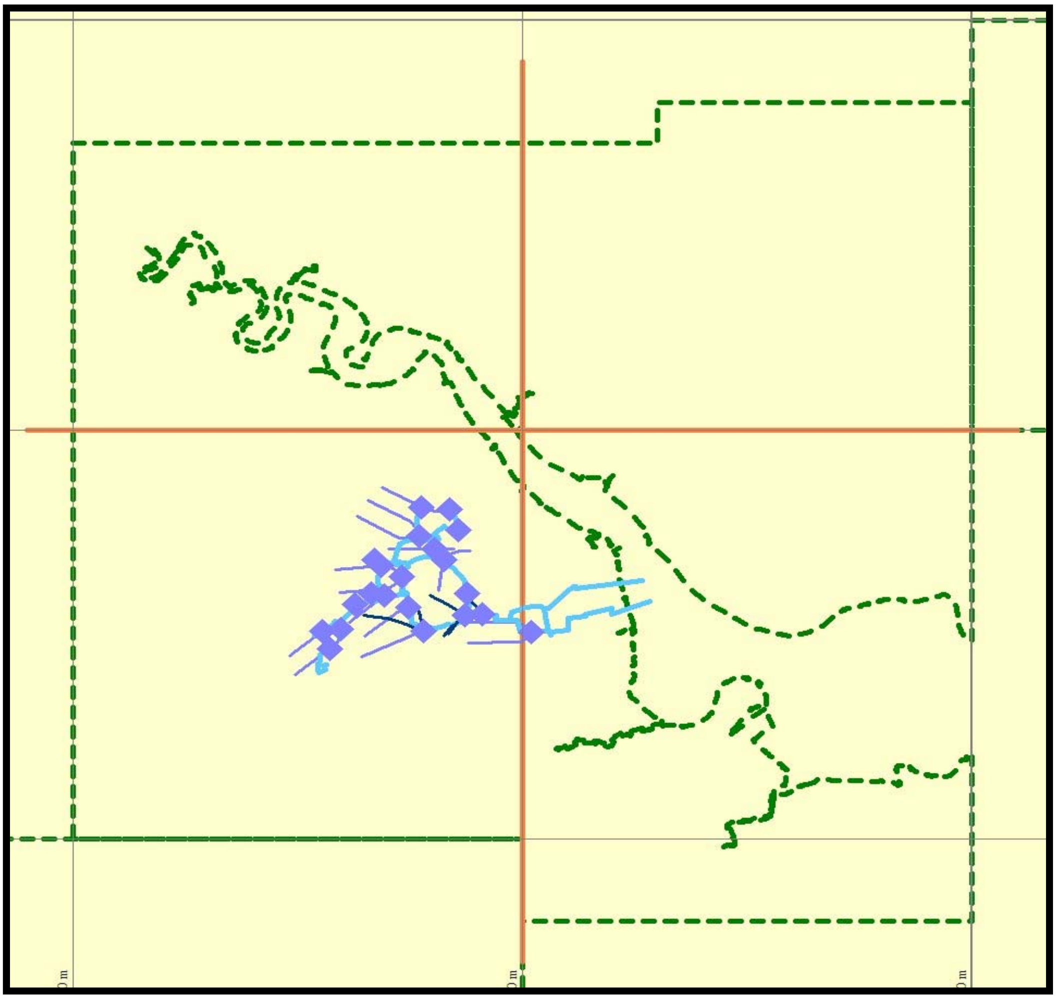

Fig. 2. PEDL133 (green dashed area) and location of two geological cross-sections shown in orange; AA' (E-W) and BB' (N-S). Blue shapes show the PDA as in Figure 1.

2.2.3 Dart has responded to AMEC's request concerning dewatering volumes by explaining that the 'horizontal zone of influence' of each lateral is around 250 m (half of the lateral spacing), and that the 'vertical zone of influence' is minimal, because *"based on the evidence below that the strata are of low permeability, there is no hydraulic continuity across the almost 0.5 km thickness of strata."* [para. 3.6].

2.2.4 In a succeeding section (Permeability of Geology overlying Target Coal Seams), Dart quotes measurements made on a 10 m long core from the Inch of Ferryton 1 well, drilled by Tricentrol in 1986. The core is from the Limestone Coal Formation, the same formation as the target coals. A calculation is then presented by extrapolation, to infer that the transit time of downdrawn water from the Passage Formation (classified as a Secondary A aquifer) to the uppermost target coal band would be of the order of seven years.

2.3 The structural geology database

2.3.1 Based upon the information supplied in the original application, the G20 documents, and Inquiry submissions, I show below that there are serious flaws in Dart's understanding of the geological structure of the proposed development area. I am not in a position to say whether Dart has withheld detailed information which it would have been better to have published, or whether it simply does not possess that information.

2.3.2 My own geological database is slightly incomplete, in that I do not possess copies of the BGS descriptive memoirs for Alloa or Airdrie. I do have a copy of the BGS Alloa solid geology map, Sheet 39, published in 1974, and two versions of the Airdrie solid geology sheet 31 (the earlier one-inch series, at a scale of 1:63360, published in 1924, and the newer eastern half, Falkirk Sheet 31E at 1:50,000, published in 1997). The boundary between the two sheets (Alloa to the north, Airdrie/Falkirk to the south) runs through the PDA. Access to the printed copies of the maps is important, as is discussed in the next paragraphs.

2.3.3 I have access to the online BGS digital map database. This is available in two flavours:

- 'Digimap' - a coloured image of the 1:50K solid and/or superficial geology,
- Digital outlines and areas for incorporation into graphic mapping packages.

2.3.4 The fault-lines in the latter database do not indicate a sense of throw. The Digimap faults have tick-marks to indicate the downthrow side, but approximately 50% of these are wrong. This serious error is due to the erroneous assumption that the progression of vertices marking the fault, from beginning to end, have always been digitised such that the downthrow side is on the right. This problem is national, not just local to the present review. So all faults shown on the Digimap images either have to be checked against the paper copy of the solid geology map, or else can often be corrected by inspection.

2.3.5 I have corrected the throw sense of faults within the current area, but those of which I am unsure I have left without a tick mark.

2.3.6 There are slight discrepancies between the faults shown on the Airdrie paper solid geology sheet, which dates from 1924, and the current BGS digital database. The latter matches the more modern printed Falkirk Sheet 31E, apart from the sense of throw of some faults, discussed above.

2.3.7 Dart has used the 2D seismic profiles which cover the PDA. There are about a dozen lines running approximately north-south, and five or six running roughly east-west. They all date from the early 1980s. Two of these lines, overlain by a geological interpretation, have been made available by Dart for the Inquiry.

2.3.8 The Dart maps showing the old mineworkings (G20 Appendix 5) cover the entire licence, and are therefore not very clear at the scale of the PDA. Nevertheless, they appear to show that there are no deep workings within the PDA. There are, however, a number of old mine shafts which I have plotted from another source (Fig. 3).

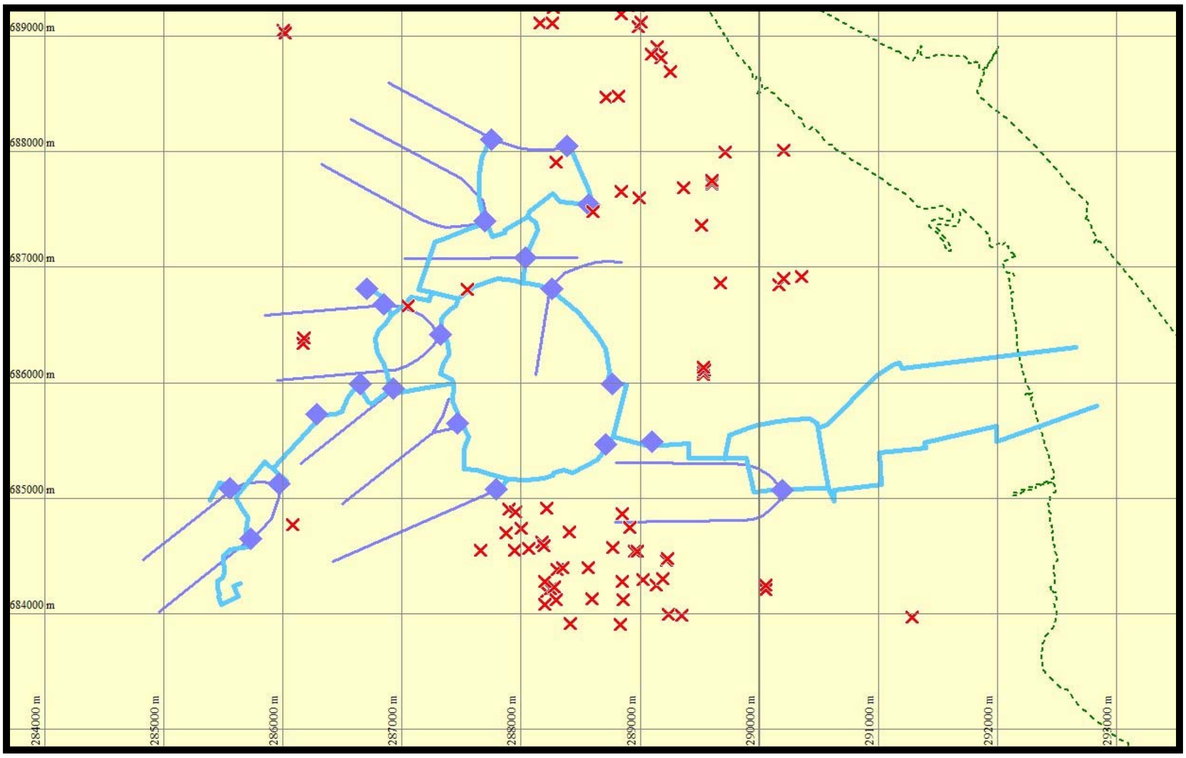

Fig. 3. Old mine shafts (red crosses) within the PDA.

2.3.9 It is very probable that these were dug to target the Productive Coal Measures (now called the Lower Coal Measures Formation) which outcrops over most of the PDA. It is unlikely that they would have penetrated as deep as the Limestone Coal Formation, which is evidently too deep to have been exploited in the past. It can be assumed that these old mineworkings are probably less than 50 m deep below the surface, i.e. the thickness of the productive formation. If any of them penetrate to the Passage Formation (formerly called the Millstone Grit), which is depicted in yellow on all the BGS maps, then they will provide fast-track migration paths to the Quaternary deposits (a Primary Aquifer) and the surface for any fugitive methane or other fluids.

2.3.10 The two cross-sections supplied by Dart are of very limited use, due to their inappropriate location relative to the PDA, as mentioned above. Figure 2 illustrates this.

2.3.11 Section BB' passes 2.3 km east of Airth-6, and a geological column of the well is featured at the side. A much more useful section would have been one running directly through both Airth-6 and Inch of Ferryton-1. Construction of such a cross-section is not difficult; it could be carried out correctly by an Honours undergraduate student in geology, and would take only a couple of hours. I see no rational reason why this has not been carried out by Dart.

2.4 Faulting within the PDA

2.4.1 The throws (vertical displacements) of some faults are indicated on the old edition of the Airdrie solid geology sheet, measured in fathoms. I have multiplied the figures by two to get an approximate throw in metres. These figures presumably refer to the maximum throw in the central portion of the fault, and if the fault extends horizontally for several kilometres, the throw figure can be presumed to be valid vertically down to at least a kilometre, i.e. at least as deep as the target zone.

2.4.2 Section BB' (G20, Appendix 2) is misleading, as it excludes several of these normal faults, trending east-west, within the PDA (Fig. 4). Two of these have throws of 34 m and 50 m, respectively, at the location of the cross-section. The latter fault lies at the southern margin of the PDA at the section location, and runs westwards right through the PDA. Another E-W fault about 1 km south of the PDA has a throw of 40 m.

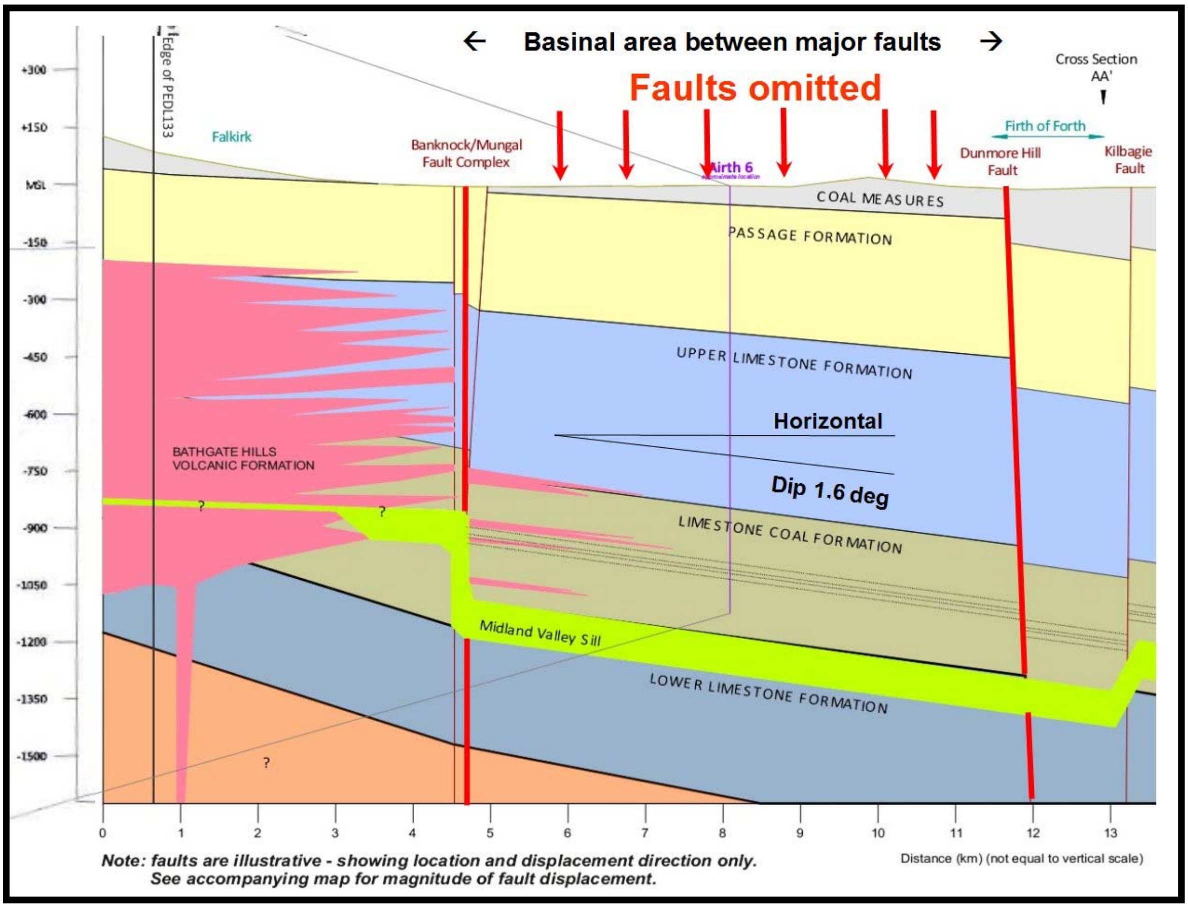

Fig. 4. Southern half of cross-section BB', as revised by Dart, October 2013, south on left. The locations of six faults (vertical red arrows) have been superimposed from the BGS maps. These should have been shown on the cross-section.

2.4.3 Dart had the opportunity to revise the cross-sections AA'and BB' presented in the original G20 submission, but has not done so. Section BB' is of particular concern, as it runs through the eastern part of the PDA. According to Dart, the central portion of the cross-section shows geological layers between two large faults, The Banknock-Mungal Fault complex to the south and the Dunmore Hill Fault to the north (Fig. 4). Between these, the layers simply dip (slope) constantly northwards at about 1.6°, according to Dart. I have marked this on Figure 4 by means of a wedge. The revision of section BB', instead of correcting the geology, has comprised merely the removal of the vertical scale on the left, and has added the following text:

> *"Note: faults are illustrative - showing location and displacement direction only. Distance (km) (not equal to vertical scale). See accompanying map for magnitude of fault displacement"* [see Fig. 4].

2.4.4 In Figure 4 I have restored the missing vertical scale, and adjusted the horizontal and vertical scales anamorphically so that the vertical exaggeration is 5: 1. The *"accompanying map"* in the Appendix does not illustrate the magnitude of fault development, as claimed by the new caption. It would appear that the text has been added as a disclaimer, because Dart was aware that the cross-section was erroneous. In my view this is an unacceptable short-cut to avoid a rational and accurate re-drawing of the geology. All these faults are significant for consideration of the danger of fugitive methane emission and contamination of groundwater resources, and should not have been omitted from the proposals. Much more detailed work is required.

2.4.5 The geology of the Carboniferous rocks in the area of the PDA comprises a circular basin, to a first approximation, upon which the faulting has been superimposed. This is demonstrated in Figure 5, in which I have marked a larger dotted circle to indicate the location of the basin. The inner circle shows the central area of the basin where the youngest rocks crop out (i.e. are found at the surface). The basin is, of course, heavily faulted. On the BGS Alloa solid geology Sheet 39E there is a geological cross-section AA' running in a dog-leg across the Letham Moss area. This section happens to avoid all the faults in the PDA, although the Dunmore Hill Fault to the east is shown below the River Forth. The basin structure is clear on this BGS section.

2.4.6 I have schematically re-interpreted the central part of Dart's cross-section BB' to show what the geology should look like. This is shown in Figure 6. The base of the Coal Measures is shown by the black lines between the various faults; this replaces the over-simplified constant-slope line depicted by Dart (the upper blue dashed line in Figure 6). The same principle will apply to all the geological layers below, including down to the target coals at 900 m or so below sea level, but I have not attempted to show all these.

2.4.7 In addition, Dart has failed to depict the large quartz-dolerite dyke running E-W through the area about 2 km south of the PDA. This should also have been shown in its section BB', where it runs up and along a fault. It is coeval with the Midland Valley Sill, which is shown in the cross-section in light green. It is not apparent why Dart chose to omit this major feature from the cross-section. The relevance of dykes and sills is discussed in section 2.9 below.

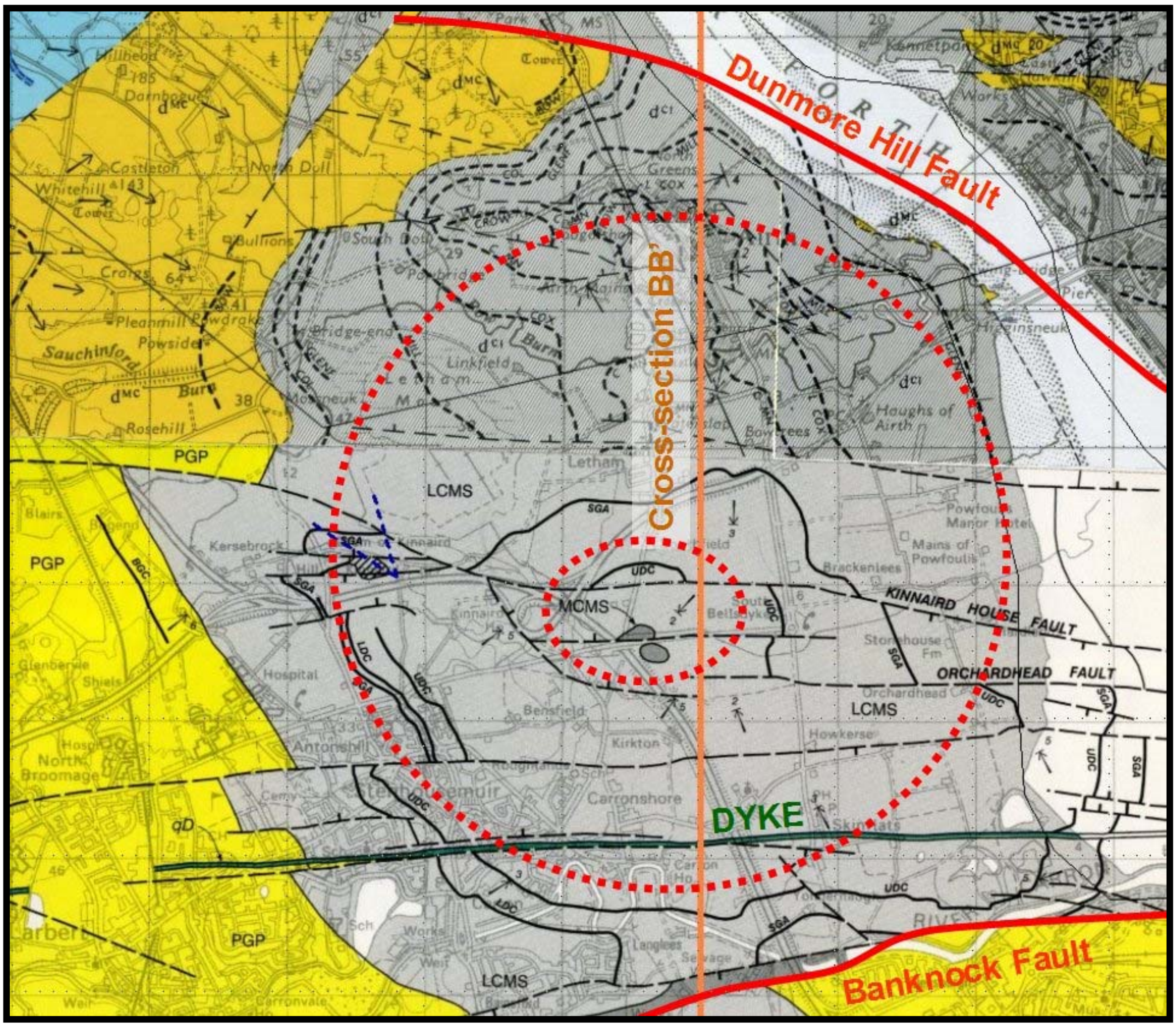

Fig. 5. The geological structure of the region around the PDA comprises a near-circular faulted basin, as illustrated by the larger dotted circle. The inner circle shows the centre of the basin where the youngest Coal Measures rocks are at outcrop. The Kinnaird House Fault runs west through the centre of the basin, where it is called the Carbrook Fault. A large quartz-dolerite dyke (green line) runs E-W through the southern part of the basin. Dart cross-section BB' is shown by the N-S brown line.

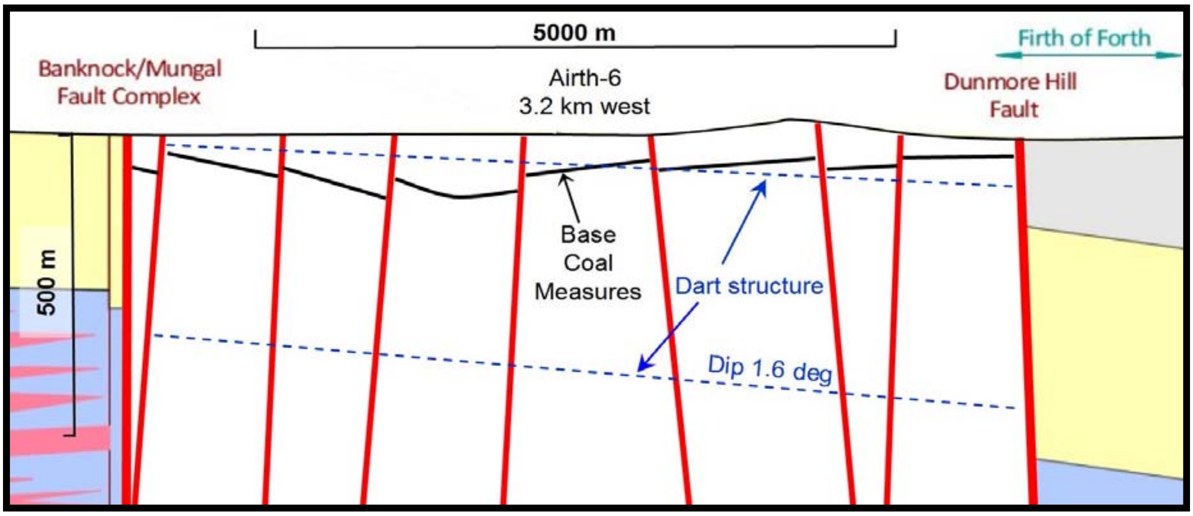

Fig. 6. Schematic re-interpretation of the central part of Dart cross-section BB'. The over-simplified Dart structure of a constant northward dip if about 1.6° has been replaced by a more accurate depiction of the structure of the base of the Coal Measures.

2.4.8 Dart's subsurface drilling plans depend heavily on its geological interpretation. Here I show that the latter is severely flawed. Figure 7 shows a detail of the geological structure map produced by Dart for the Lower Bannockburn Main Coal horizon, one of the target coals. Faults are shown cutting this layer as solid black lines; the same fault at the Earth's surface is shown by blue dashed lines. The two sets of lines are in general not at the same position because the fault surface is not vertical. For example, the surface position of the Carbrook Fault is about 500 m north of where it cuts the coal layer; this shows that the fault surface dips (slopes) to the south. The problem with Dart's interpretation is that it shows the Carbrook and the Kinnaird House Faults as separate structures, so that there is an unfaulted area of about 4 km^2 just west of Letham Moss, in the heart of the PDA.

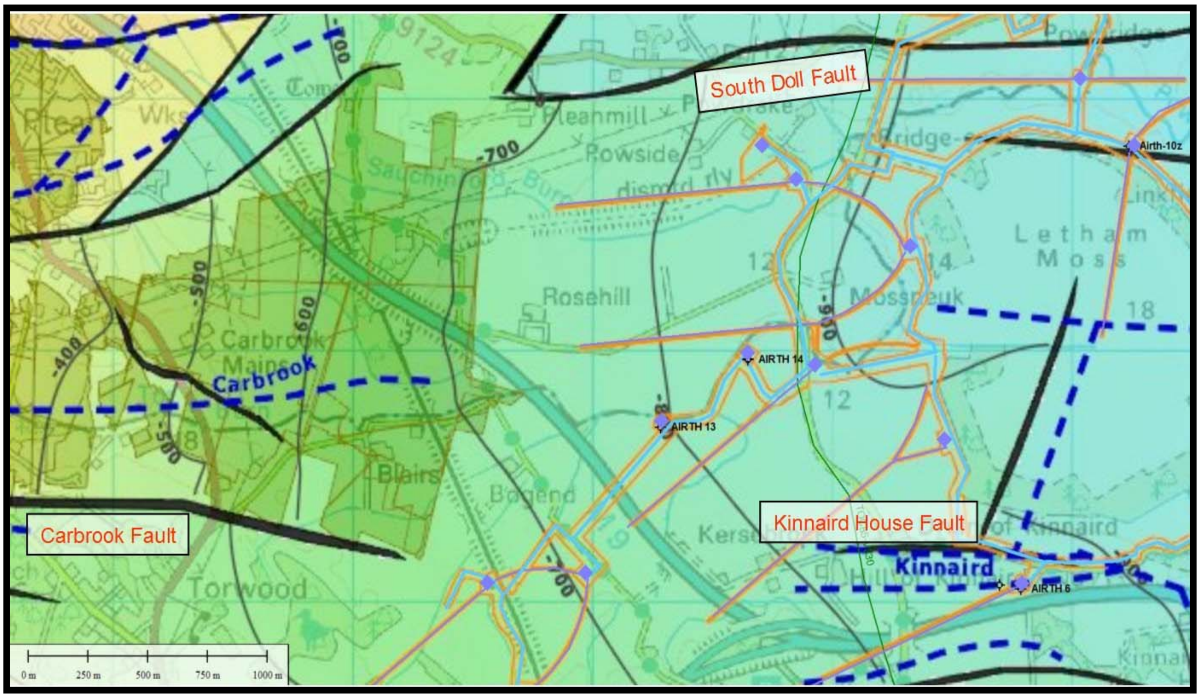

Fig. 7. Dart geological structure map of the Lower Bannockburn Main Coal horizon, showing the Carbrook and Kinnaird House Faults as two separate structures. Faults at the coal horizon are shown as solid black lines, and at the surface as dashed blue lines.

2.4.9 But Dart's interpretation is contradicted both by the BGS geological maps and by the available 2D seismic lines. Figure 8 shows the BGS-mapped faults in red. The Carbrook – Kinnaird House Fault is continuous as a single major structure across the area. The throw of the fault (vertical displacement) is marked in red, from which we can see that the expected throw in the vicinity of Airth-13 and Airth-14 is about 100 m. But Dart's map of the coal layer shown in Figure 7 has no (geological) faults at this locality.

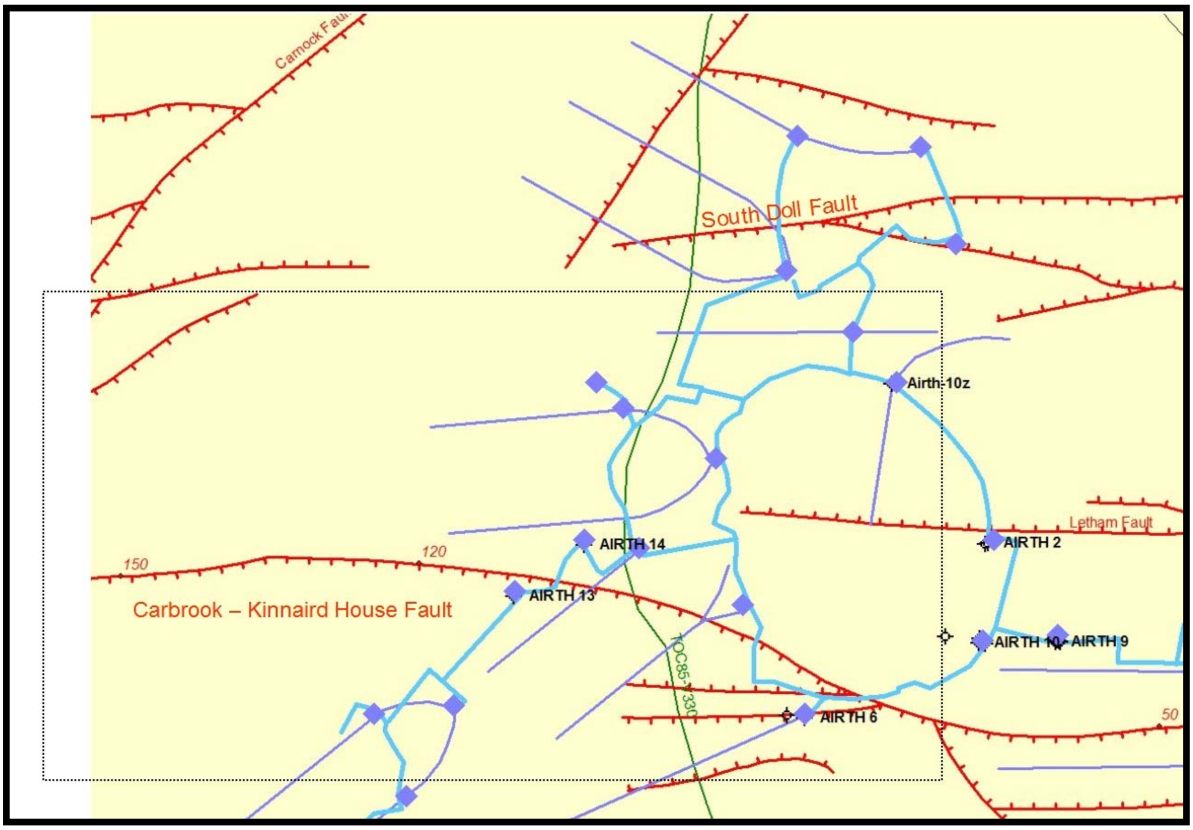

Fig. 8. BGS surface-mapped faults (red) in relation to the subsurface PDA (shades of blue). The Carbrook – Kinnaird House Fault is continuous as a single major structure across the area. The throw of the fault (vertical displacement) is marked in red. The location of seismic line TOC85-V330 is shown by the green line. The area of Figure 7 is shown by the dotted rectangle. The seismic data are shown in Figure 9.

2.4.10 To resolve the source of this inconsistency I have examined several of the seismic lines that traverse the PDA. These were used in Dart's interpretation. Two seismic lines have now been supplied by Dart for the Inquiry (but not, as pointed out in 2.1.4 above in support of the planning application). One of these is the N-S line shown in Figure 9; the other, an E-W line, TOC85-V328, is not shown here. The lines are presented with two-way time as the vertical scale, with interpretation superimposed upon the seismic data. The two lines have also been converted to depth and presented as line drawings. There is an accompanying shot-point location map of these two lines and also a map of the entire seismic dataset used by Dart.

2.4.11 Seismic line TOC85-V330 (shown by the green line in Figure 8) crosses the area from south to north. This line is crucial to the geological interpretation. Such data are available for free inspection and image download at the UK Onshore Geophysical Library (UKOGL):(http://maps.lynxinfo.co.uk/ukogl_new/). I am relying on these UKOGL downloadable images, rather than the digital SEGY data, which have to be purchased. The seismic data for part of this line are shown Figure 9.

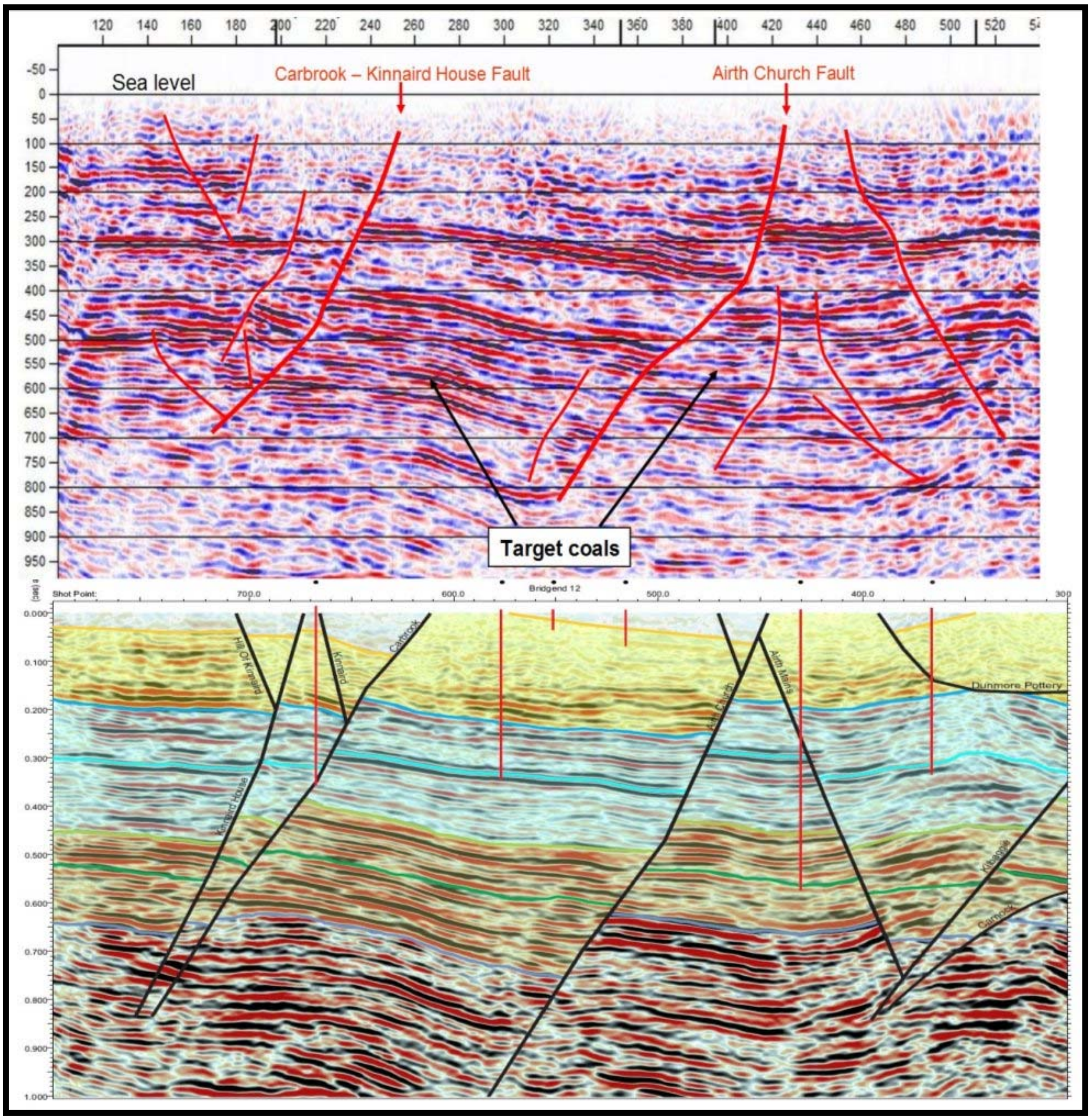

Fig. 9. Detail of two versions of seismic line TOC85-V330, crossing the PDA from south to north, both at the same horizontal and vertical scales. The upper panel shows the raw migrated data with fault interpretation in red added by me. The lower panel shows Dart's reprocessed migrated data with its interpretation of faults (black) and geology (colour). Wells and boreholes are shown as vertical red lines.

2.4.12 Figure 9 shows two versions of seismic line TOC85-V330, crossing the PDA from south to north, both at the same horizontal and vertical scales. The upper panel shows the raw migrated data over the PDA, to which I have added an interpretation of faults, as shown in red. The surface locations of the Carbrook – Kinnaird House Fault, and another E-W fault which Dart calls the Airth Church Fault, are shown above the section, marked by red arrows. These clearly correlate with the major faults seen on the seismic data.

2.4.13 The upper panel fault interpretation was drawn up before I had access to Dart's own interpretation, which is shown at the same horizontal and vertical scales in the lower panel of Figure 9. Dart's seismic image is based on data which has been reprocessed, relative to the UKOGL data (Fig. 9, upper panel). This does not necessarily imply that it is of better quality. However, there is evidently substantial agreement between the two versions, although there are minor differences in the shape and curvature of the faults. My guesstimate (without access to well logs and detailed interpretation software for the purpose) of where the coal horizons would plot on the seismic data (Fig. 9, upper panel) is only in error by around 50 milliseconds (ms). The coal horizons are indicated by the green line on Dart's interpretation.

2.4.14 The vertical scale of the seismic data is measured in milliseconds of reflection time, not in metres. To convert this to depth we would need some sort of velocity or sonic log data, but these do not seem to be available. No sonic log was run for Airth-6 (Dart G20 revised submission, Appendix 3). We have no details of how Dart has converted the vertical scale of the seismic data from time to depth.

2.4.15 The problems with Dart's interpretation start when we go west from line TOC85-V330 discussed above. Relevant data are shown on the map of Figure 10. The map shows that there is a N-S seismic line 200-500 m west of line TOC85-V330, which must belong to a speculative survey, as it has not been released by DECC even though it was obtained in 1982. I therefore do not have access to it. However, as its termination is 700 m south of the surface position of the Carbrook – Kinnaird House Fault, it is unlikely that it can contribute much to the problem in hand; this is because the starting and ending kilometre or more of seismic lines have reduced quality data compared to the middle sections.

2.4.16 On the right-hand side of Figure 10 the Carbrook – Kinnaird House Fault cuts the coal horizons on line TOC85-V330 where the puce dashed line has been interpreted by Dart. According to Dart this Kinnaird Fault dies out 400 m to the WSW, where the number 0 marks the throw (displacement) of the fault (0 m at its tip; throws elsewhere are indicated from the BGS mapping in red or the Dart interpretation in puce).

2.4.17 Moving eastwards from the western edge of Figure 10 we see that Dart has mapped a separate 'Carbrook' Fault dying out just at the intersection at depth with seismic line TOC85-V212. So according to Dart there is a zone about 1.5 km wide where the Carbrook – Kinnaird House Fault does not exist. But this interpretation conflicts with the BGS map of the major fault, which shows a throw of 120 m at the surface in the upper-central portion of Figure 10.

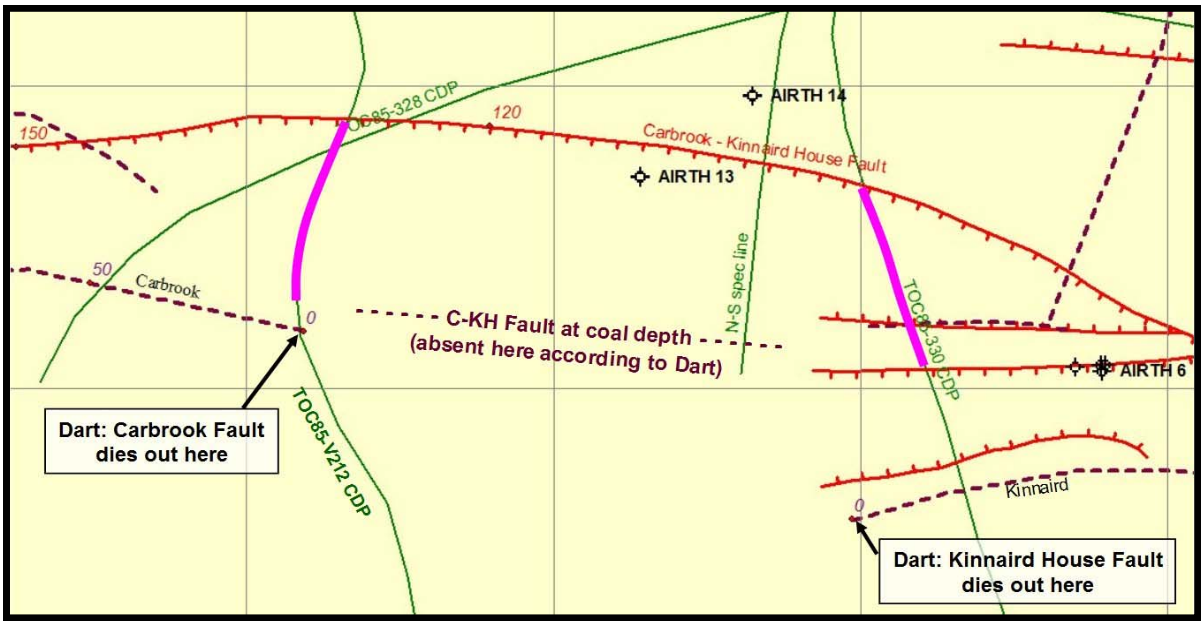

Fig. 10. Seismic lines (green) west of Airth-6. Surface-mapped faults shown in red with tick marks on downthrown side. Puce dashed lines mark location of the faults intersecting the coal horizons at depth, according to Dart. Note the gap in the Carbrook – Kinnaird House Fault in the centre of the area. Lilac colouring on two seismic lines indicates my trace of this fault from the surface down to the coals. National grid squares are 1 km interval.

2.4.18 North-south seismic line TOC85-V212 (located in Figure 10) is shown in Figure 11. The image is taken from the UKOGL database. As with the upper part of Figure 9, I have added an interpretation of the faults, shown as red lines. The Carbrook – Kinnaird House Fault is present as an important fault, along with several others. But according to Dart it should not exist on this image because the fault has died out going eastwards. Therefore if Dart is correct the layers shown in this image should run continuously across the right-hand side of this image without displacement. This is clearly erroneous.

2.4.19 I conclude that Dart's interpretation of the geology in this part of the PDA is seriously in error. The error occurs in the middle of the PDA, where there is a 1.5 km data gap with no seismic lines, nor drill holes. The simpler interpretation, which is consistent both with the BGS surface fault mapping and with the seismic data, is that there is a single major fault, the Carbrook – Kinnaird House Fault, running right through the area. Dart's error has probably arisen from allowing an automated gridding and contouring computer program to construct the depth map for the Lower Bannerman Main Coal (Figure 7 above). A better method would have been to have used hand contouring by an experienced geologist, who could have taken into account both the serious data gap and the prior knowledge of the BGS surface geology maps.

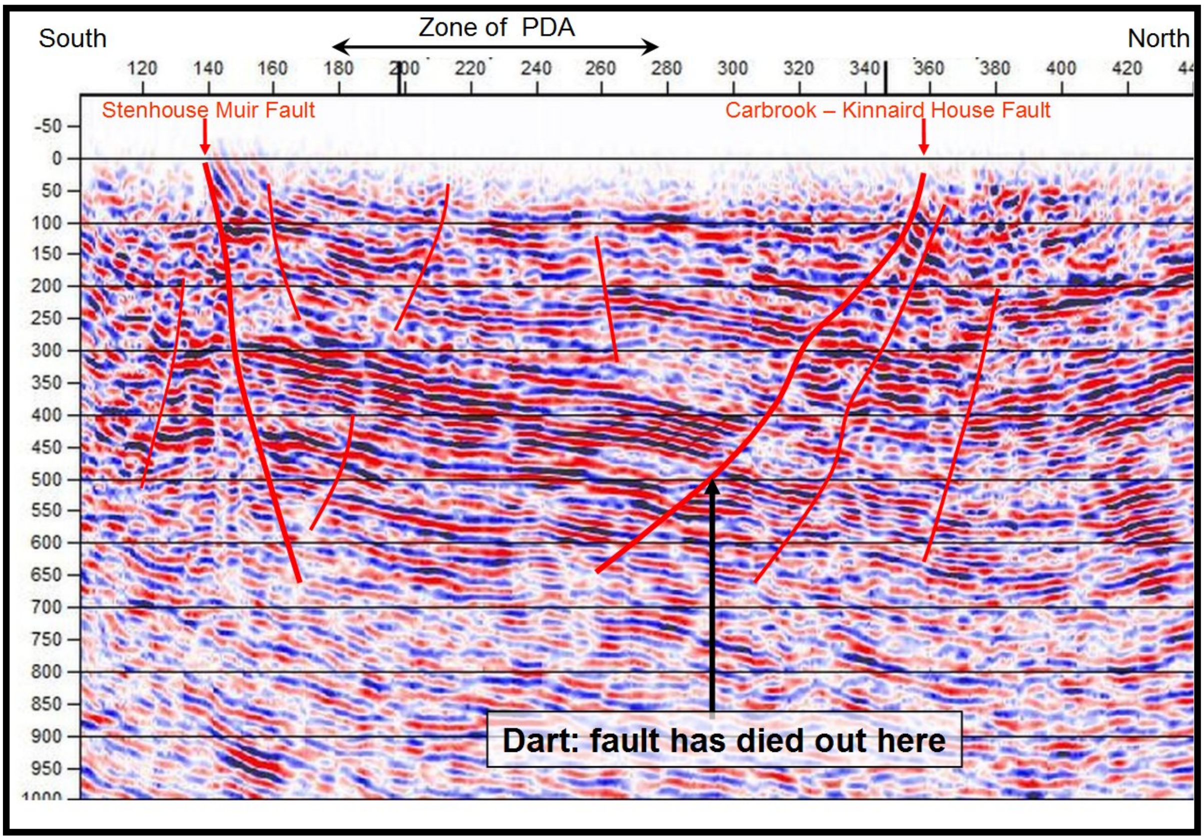

Fig. 11. N-S seismic lineTOC85-V212, with my fault interpretation shown as red lines. The Carbrook – Kinnaird House Fault is clear at depth, dipping to the south from its mapped surface location. The footwall of the fault (below it, on the north side) is disturbed by other faults.

2.4.20 There is an additional anomaly in the area of the Carbrook – Kinnaird House Fault, revealed by the existing sidetracked wells. Details are shown in Figure 12. Planning application documents show that the sidetracked wells were intended to be drilled in a NNW and NW directions from Airth-6 and Airth-8, respectively. The planned tracks are shown as dark blue dashed lines in Figure 10. But the Airth-6z horizontal was drilled with a dogleg. We need to understand why. The actual trajectory of Airth-8y is more curious; this is the solid dark blue track shown in Figure 12. Why did it diverge, increasing into a more westerly azimuth, away from the vertical hole? According to the current Dart interpretation this Airth-8y horizontal should be in the footwall of the Carbrook – Kinnaird House Fault. If it was in fact in the hanging wall of the fault, the drill bit, guided by gamma-ray logging, may have been repeatedly grazing it on its right-hand (north) side, and was therefore steered in a progressively more westerly direction as drilling proceeded. On the other hand, if the sidetrack was deviated into the hanging wall, why was the drill bit steered in a direction locally parallel to the Fault just below it? Whatever the correct explanation, we need to know why the sidetracked well took this path.

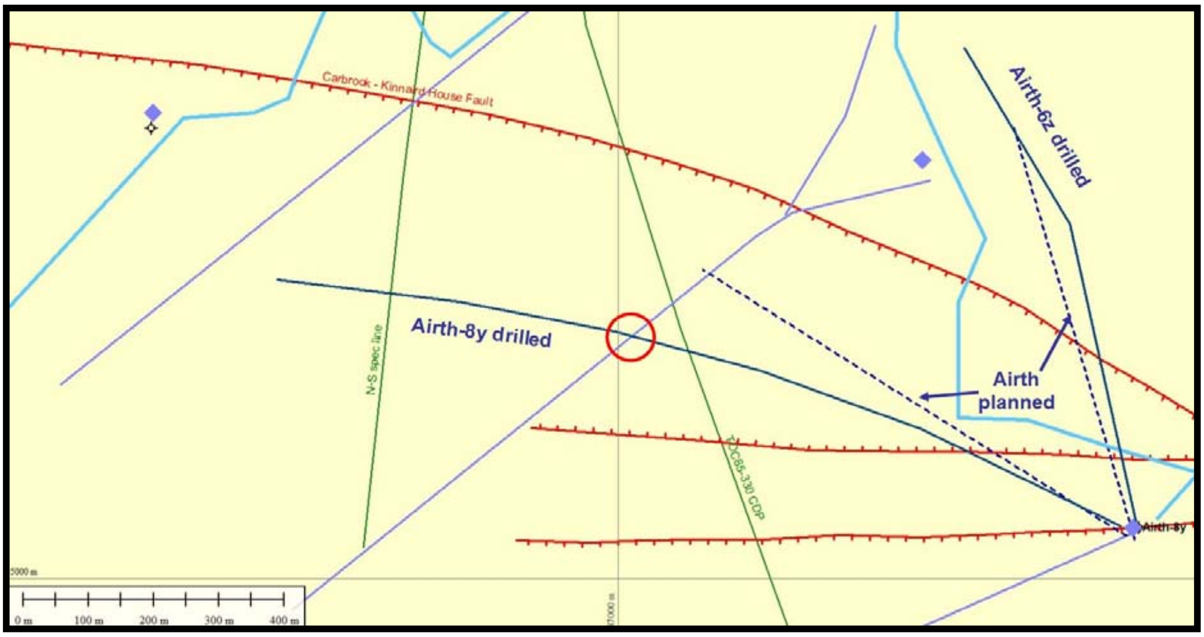

Fig. 12. Horizontal wells Airth-8y and Airth-6z drilled by Composite Energy. Dashed dark blue lines show the planned trajectories; solid dark blue lines are the actual trajectories. Mid-blue lines are proposed Dart horizontals. The circle highlights where horizontals will cross one another.

2.4.21 If and when Dart drill horizontally to the SW (mid-blue lines shown in Figure 12), the proposed well track at each coal horizon will cross the old Composite Energy sidetrack of Airth-8y. This intersection is highlighted by the red circle in Figure 12. How will Dart deal with this intersection? It would appear to provide scope for uncontrolled leaks of drilling or dewatering fluid and methane.

2.4.22 I have concluded above that Dart's structural interpretation is untenable, since it disagrees both with the BGS mapping and with the seismic data. In addition, Dart's own maps, as presented to this appeal, are internally inconsistent. Dart's 'Draft Monitoring Plan on Solid Geology Map' (drawing no. PEDL133-FDP-0037) shows precisely the same set of faults as mapped by the BGS and shown in Figure 8 above. These faults conflict with Dart's subsurface and surface fault interpretation analysed above.

2.4.23 In view of the serious data gaps and resulting faulty geological interpretations of the PDA, it is my view that a high-resolution 3D seismic survey is required over the PDA to clarify the faults before any more drilling is carried out. In parallel with this survey, velocity logging of several of the existing vertical wells should be undertaken (if this has not already been done) to enable an accurate time-to-depth conversion of the 3D seismic volume obtained from the 3D survey.

2.5 Faults as potential conduits or barriers

2.5.1 The extensive faulting in the PDA is crucial, because the whole question of vertical hydraulic conductivity depends on how the faults behave. We are concerned here, not with drawdown from the principal aquifer to the target coal beds, as illustrated in Dart's G20 submission, figure 4.1, but in the potential for *upward* pathways of fluids, particularly fugitive methane.

2.5.2 Dart contends that the faults can affect fluid flow, but conclude that because the fault throws are only of the order of 30-40 m, they do not juxtapose higher- and lower-permeability strata. Were this to be true, the scale of the alternations in layering has to be greater than 30-40 m. But the scale of alternations in lithology, as shown by the Airth-6 log (G20, Appendix 3), is as follows (scale is true vertical depth below mean sea level):

- Lower Coal Measures (-19.6 to 68.8 m) - 5 to 30 m,
- Passage Formation (68.8 to 284.0 m) - 4 to 40 m, the sandstones being the thick units,
- Upper Limestone Formation (284 to 696.7 m) - 5 to 30 m, sandstones being the thick units,
- Limestone Coal Formation (696.7 to top target coal) - 1 to 15 m, sandstones being the thick units.

2.5.3 In the analysis above the periodicity of units in the Passage Formation is irrelevant, because it is of high permeability (a Secondary A aquifer). Similarly, in the Upper Limestone and Limestone Coal Formations, the thicker sandstone units are irrelevant. In conclusion, any faults with a throw of more than 5 or 10 m will juxtapose layers of differing permeability.

2.5.4 Just as in domestic plumbing, where a water leak comes from the weakest point in the system, and the integrity of the rest of the pipework is irrelevant, fugitive methane and other fluids will find the weakest path upwards. Even the lowest permeability rocks in the succession - mudstones and siltstones - are moderately permeable. This is discussed below. The hydraulic conductivity properties of faults zones are also discussed below.

2.6 Permeability, hydraulic conductivity and vertical flow

2.6.1 The BGS, in an aquifer productivity study (CCoF 65: MacDonald *et al.* 2004, table 1) has classified the Passage Formation sandstone as having high productivity (defined as 10-20 l/s), the flow mechanism being *"dominantly intergranular".* All other Carboniferous rocks, except mudstones, are classified as moderately productive (1-10 l/s), and Carboniferous mudstones have low productivity (0.1-1 l/s). Note that these productivity ratings are applicable to a borehole, so the figures are only a rough order-of-magnitude guide to relative permeabilities at depth.

2.6.2 Dart cites a laboratory measurement of permeability in the Limestone Coal Formation, observed on a 10 m long core from the Inch of Ferryton-1 well.

2.6.3 Tellam and Lloyd (1981; CCoF 82) studied the hydraulic conductivity of British mudrocks. The laboratory measurements gave values 2 to 3 orders of magnitude lower than the *in situ* values. So the Inch of Ferryton-1 results should be scaled accordingly. Furthermore, we are interested in the maximum conductivity. In short, the relevant hydraulic conductivity from this core is 10^{-5} to 10^{-6} m/s. This range is somewhat higher than the Mercia Mudstone Group (MMG), and two to four orders of magnitude higher than true clays such as the London Clay, Oxford Clay, Gault Clay and Lias Clay.

2.6.4 In the East Irish Sea Basin it is reported that at least 600 m of MMG is required for it to be an effective hydrocarbon seal there, due to the inversion uplift (CCoF 79: Duncan *et al.* 1998). However, the MMG is an effective seal in the Wessex Basin, where 300 m of MMG caps the oil of the Wytch Farm field, together with another 200 m of Liassic mudstone above. The difference in the latter case is that the Tertiary uplift has never taken the MMG into the brittle tensional strength regime, which is the reason for the higher hydraulic conductivity in the Irish Sea region. The Carboniferous mudstones of the PEDL133 area have also undergone uplift, since they are now at shallow depth or at outcrop.

2.6.5 In conclusion, by comparison with the MMG, the mudstones of the Limestone Coal Formation above the target coals are unlikely to provide much of a seal to prevent fugitive methane and other fluids escaping upwards. This conclusion does not even take into account the presence of the faults. I would expect a similar result for the overlying Upper Limestone Formation, although there appear to be no data on hydraulic conductivities of that formation.

2.7 Hydraulic conductivity of faults

2.7.1 The literature on the fluid sealing or conducting properties of faults in sediments is large and confusing. Research is driven by the need to understand sealing of hydrocarbon reservoirs at depths of 2-3 km on the one hand, and engineering properties of faults in the near-surface (down to a few hundred metres), especially in unconsolidated sediments. In addition, the subset of research into the effects of faulting in pelitic rocks (e.g. mudstones) is very limited.

2.7.2 The paper cited by Dart on clay smearing (CCoF 81: Manzocchi *et al*. 2002) is just one within a large field of active research. Dart states in support of its case that faults are not significant conduits:

> *"clay-rich material becomes incorporated into the fault zone during the movement of*

the fault, by abrasion of clay rich zones against clay poor zones as the hanging wall moves past the footwall, by smearing, and the production of shale gouge. Depending on the clay content, this can act as an effective seal to groundwater and other fluid movements."

2.7.3 There are dozens of academic research groups and oil-industry service companies working on the problem of whether faults act as conduits or barriers to fluid flow. The default position in the industry is the conservative one, that <u>faults do not act as seals</u>. In oil or gas exploration, if a fault is wrongly judged to be a seal when in fact it is permeable, no damage is done, other than to the bank balances and share prices of companies and individuals. However, in the case of CBM exploitation, the consequences of over-optimistically assuming that faults act as seals may be extremely damaging to the environment.

2.7.4 My brief and necessarily incomplete review of this large field of research and development leads me to the following impressions and tentative conclusions:

1. There are field measurements of faults at outcrop and at shallow depth; it is realised that small-scale structures associated with faults dominate the bulk hydrogeological properties. <u>These are characteristically fractures sub-parallel to the master fault plane, which are collectively termed the 'damage zone'. Such zones can be several metres to tens of metres in horizontal width, and are often the locus of fluid flow up or downwards, rather than across the master fault plane.</u>

2. In an unconsolidated mixed sand/clay stratigraphy, the conductivity in the damage zone can be enhanced by several orders of magnitude, but clay smearing along the core fault plane reduces the bulk conductivity.

3. Iron oxide re-precipitation in the core fault, due to the enhanced flow in the damage zone, is another mechanism which can reduce the core conductivity.

4. The relative hydraulic conductivity of a fault cutting indurated low-conductivity clays is neutral; i.e. the conductivity of the fault zone remains within the same order of magnitude as the unfaulted clay. An example is the set of measurements across the Down Ampney fault, made by the BGS, in which Oxford Clay is juxtaposed against Oxford Clay or Forest Marble Clay.

5. However, the same dataset shows that the conductivity of the fault zone as a whole is enhanced by one or two orders of magnitude, because the succession includes limestones and sandstones as well as the aforementioned clays. This will be the case with the successions present within PEDL133.

6. Smectite in shear zones can be dehydrated to anhydrous illite minerals as a shear fabric develops; this in turn can account for overpressure build-up. This mechanism

accounts for high hydraulic conductivity observed in accretionary wedges, but contradicts laboratory experimental studies suggesting that sheared clays in fault zones represent aquitards.

2.7.5 Lunn *et al.* (2008: CCoF 80) have modelled the fluid flow pathways across models derived from detailed outcrop observations. Starting with their summary that:

> "*Faults can be barriers to flow, conduits, or combinations of the two, and their hydraulic properties vary considerably over both space and time*".

they conclude from their study that the *micro* properties as opposed to the *average* hydraulic properties in a fault zone are crucial, but that these properties are *unmeasurable at depth*. A multi-variate stochastic approach is the only way forward, they say, which:

> "*implies that a <u>very large</u> database of fault architecture is needed to accurately characterize fault permeability distributions. This can only be achieved by pooling a large number of field datasets. This would require an international consensus on the recording of the gross parameters (e.g., lithology, offset, stress history) and the architectural detail at each site*." [NB authors' emphasis on *very large*].

2.7.6 From Lunn *et al.*'s observation (which was already widely known across the hydrocarbon exploration industry) that "*faults can be barriers to flow, conduits, or combinations of the two*", one can construct a cartoon of how normal faults cutting sediments will affect flow direction (Figure 13). I have indicated in this cartoon the general flow parallel to sedimentary bedding, in this case moving down-dip from right to left. But when the flow encounters a fault zone it will be redirected upwards; this is irrespective of whether the fault is acting as a barrier or as a conduit to fluid flow.

2.7.7 Dart acknowledges the concern raised by AMEC regarding faulting and old mine workings. The G20 document states:

> *"the geology of the area, including past mining activities has the potential to be a route for methane migration. However, were methane likely to migrate through faults in the overlying rock -to an area of lower pressure -there is no reason why it would not do so in the absence of Dart's activities -albeit only from the coal directly around the fault, due to hydrostatic pressure binding the gas within the coal matrix."* [para. 4.10]

2.7.8 Dart here appears to be admitting that faults are indeed potential pathways for methane migration. But since the virgin coal (i.e. undewatered or otherwise exploited) has been around for a long time, as have the faults, any localised migration such as described above would have long ago ceased. But when release of methane is started by dewatering, a new phase of methane escape could begin, but this time it will be orders of magnitude greater in volume.

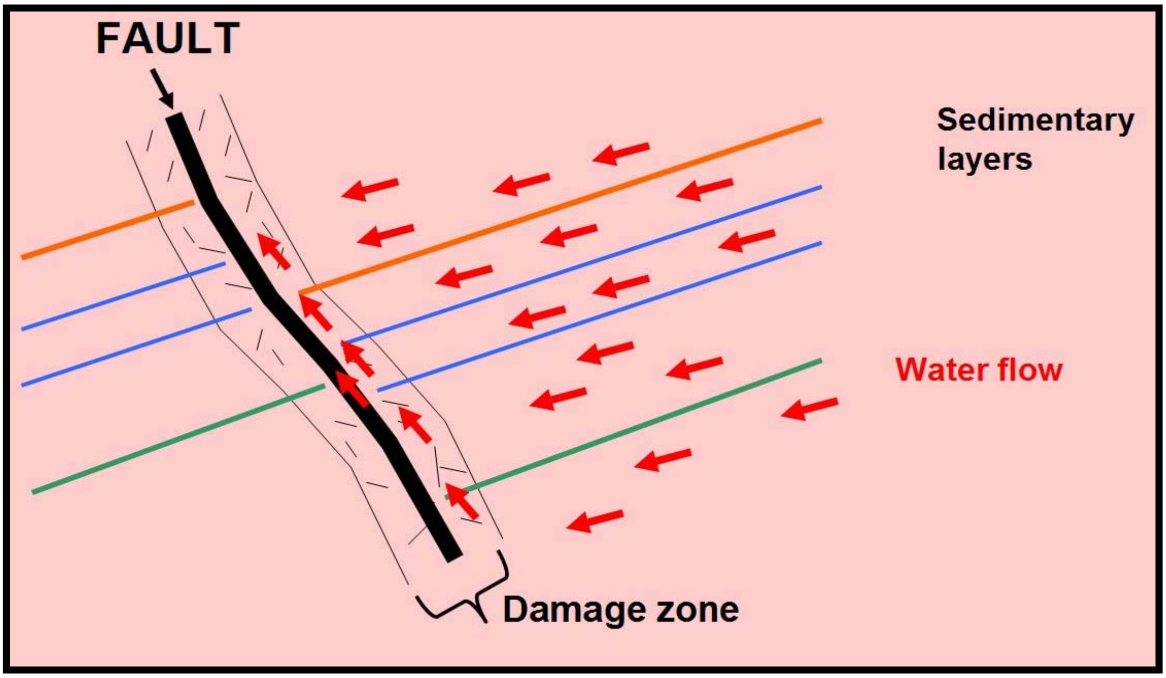

Fig. 13. Cartoon of a fault zone and resulting fluid flow. The core zone (black) could be a barrier, or it could be a conduit. The damage zone on either side is always a conduit because it is fractured.

2.8 Compartmentalisation by faults

2.8.1 Dart discusses presumed compartmentalisation of the groundwater flow system by certain faults. The G20 document states:

> *"3.24 There is a potential horizontal and sub horizontal component to groundwater flow also, since the deep Lower Coal Measures strata may be recharged from the strata at outcrop around Bannockburn. However significant vertical displacement of the target coal bed units by the Carnock and Dunmore Farm Faults in the west and Kilbagie Fault in the east means that the target coals are likely to lie within a hydrogeologically isolated fault block."*

and

> *"4.16 Within the Limestone Coal Formation, relevant workings would be to the west, around Bannockburn, which could be affected by workings from sites H (paired with G and I) or M. However, the target coal beds in the gas field and the corresponding beds at outcrop are hydrogeologically isolated from one another by fault displacement, in particular by vertical displacement at the intervening Carnock and Dunmore Farm Faults. The faults in these clay rich strata are unlikely to act as a significant hydrogeological pathway to permit significant groundwater flow across the faults."*

2.8.2 Dart quotes a BGS report (CCoF 47: British Geological Survey 2011), closely quoting text from the latter. On hydrogeology, the BGS states:

> *"The hydrogeology of the Carboniferous sedimentary aquifers in the Midland Valley is complex. The cyclical sedimentary sequences of alternating fine- and coarse-grained rocks form multi-layered aquifers in which sandstone units effectively act as separate aquifers, interspersed with lower-permeability siltstones and mudstones. Some of these aquifers are effectively confined by overlying low permeability rocks. The hydrogeological complexity is increased by the predominance of fracture flow, and by the compartmentalising of groundwater flow within fault-bounded blocks."* [my underlining].

2.8.3 This is the only mention of compartmentalisation in the entire BGS report. The underlined phrase above refers to a scale of compartmentalisation which is evidently much larger than any area as small as the PDA, or even PEDL133, since the report concerns the whole of the Midland Valley.

2.8.4 No evidence is presented to support the concept of compartmentalisation at the local scale of the proposal. The named faults referred to by Dart on the quoted extracts above are shown in Figure 14. The three named faults are all north of the PDA, and are large, but not exceptional in importance. The supposed compartmentalisation seems to depend on the assumption that the faults in these *"clay rich strata"* will act as barriers due to clay smear along the fault plane. This assumption has been discussed and refuted in section 2.7 above.

2.8.5 Furthermore, if the Dart geological structure map of the Lower Bannockburn Main Coal horizon (see Figure 7 above) is to be believed, the whole PDA comprises just two compartments; (1) the northern area north of the Aith Church Fault and east of the Dunmore Farm Fault (see Figure 14 for the latter), and (2) the rest of the PDA. However, I accept neither the evidence for fault sealing and compartmentalisation in the PDA zone, nor the details of Dart's mapping of the faults.

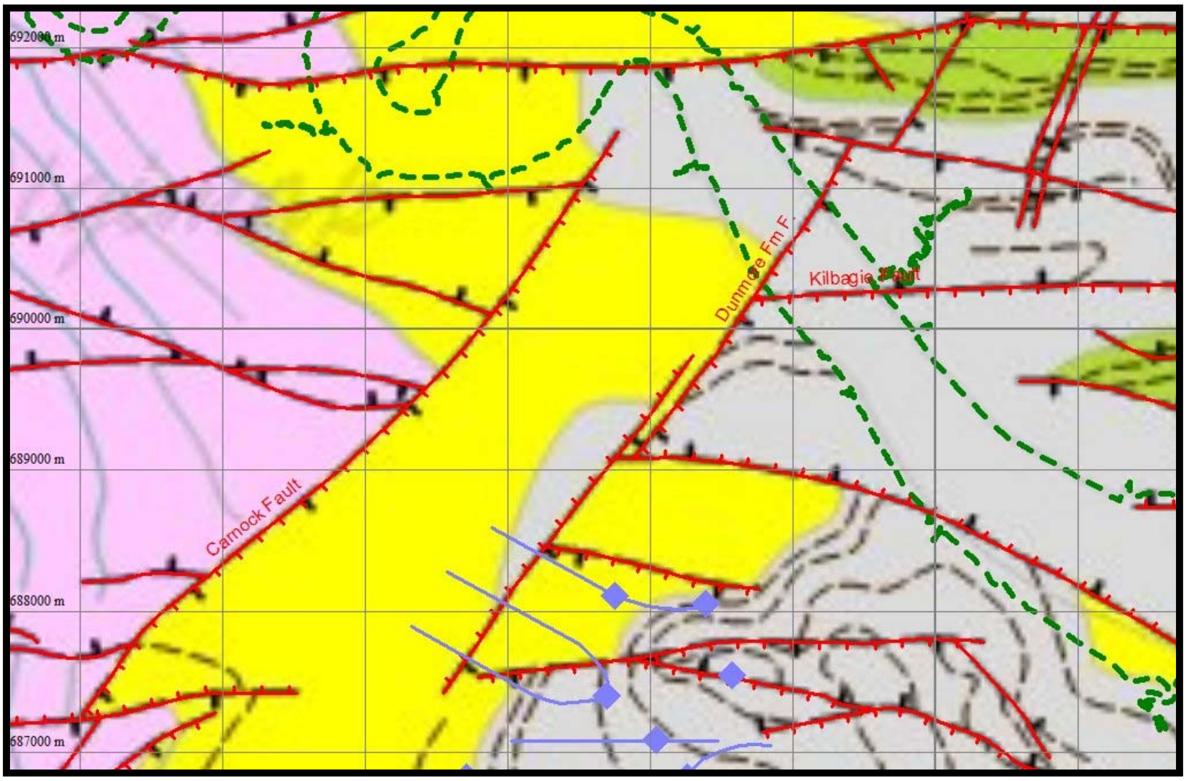

Fig. 14. The Carnock, Dunmore Farm and Kilbagie Faults, to the north of the PDA. The solid geology comprises, from younger to older, Lower Coal Measures (grey), Passage Formation (yellow) and Upper Limestone Formation (pink). The shores of the Forth are indicated by the dashed green lines.

2.9 Hydrocarbon seepages

2.9.1 Two American oil industry professional societies, the American Association of Petroleum Geologists and the Society of Exploration Geophysicists, have recently published a memoir on hydrocarbon seepage (CCoF 109: Aminzadeh, F. *et al.* 2013). Such seepages have been known since antiquity, and now provide an indication of an active petroleum production and migration system for the oil explorer. But their relevance here is that successful imaging of such underground chimneys, where upward migration of fluid is localised, or of more diffused gas clouds above a hydrocarbon accumulation, can provide an indication of whether or not particular faults are acting as seals, and/or whether the overburden itself is acting as an efficient seal. CCoF 109 reproduces 8 selected pages from the book, to illustrate the modern methods of directly or indirectly imaging the seepages. Three-dimensional seismic reflection data are invariably required as a basis for the imaging.

2.9.2 Selley (1992) has compiled an exhaustive list of natural hydrocarbon seepages known in the UK. Two of these occur in East Lothian. The source of the oil seepage is in both cases the Oil Shale Formation, a sequence of Lower Carboniferous rocks of which the top is about

300 m below the target coals of the PDA. The seepage at St Catherine's Well (NT273684) is *via* a fault; the Straiton oil-saturated sandstones (NT273667) occur on the crest of an anticline (an upfold in the rock layers). Both these instances illustrate the potential for upward migration within Scottish Carboniferous strata, whether the strata are faulted or folded (the first and second example, respectively).

2.10 Volcanism-induced pathways

2.10.1 The Midland Valley, including the PDA, is underlain by a vast system of sills and dykes of late Carboniferous age. Both comprise what were molten basalt-like rock at the time of intrusion. The dykes are vertical walls of dolerite (a coarse-grained basalt), running generally E-W. One of these is shown in Figure 5 above. The still-molten dykes acted as feeders for the sills, which are near-horizontal intrusions formed by the molten rock forcing its way between layers of sediment. The contemporary land or seabed surface would have been just a few hundred metres above the intrusion level.

2.10.2 Bell and Butcher (CCoF 263) have demonstrated the 3D structure of a buried sill complex in the Faroe-Shetland Basin. By interpreting modern 3D seismic data they show that the feather-edges of sills (i.e. where the intrusion has petered out) often turn upwards, and are the source of seismic chimney structures which progressed upwards to feed vents on the contemporary sea floor. In other words, the intruding sill edges were locally creating hydrothermally-driven fluid escape features. This is shown in Figure 15.

2.10.3 The same mechanism could equally well apply to the Midland Valley Carboniferous sill complex. Once created, such a hydrothermal chimney would be an easy escape pathway for any subsequent upward-migrating fluids. Any such vents in the PDA would today be cut by the contemporary ground surface, and would cross the target coal horizons. No such structures have yet been identified in the Midland Valley, but that is because the onshore area does not have the wealth of detailed imaging inherent in 3D surveys. A high-resolution 3D survey of the PDA would go some way towards mitigating the risk of drilling through such potential leakage features.

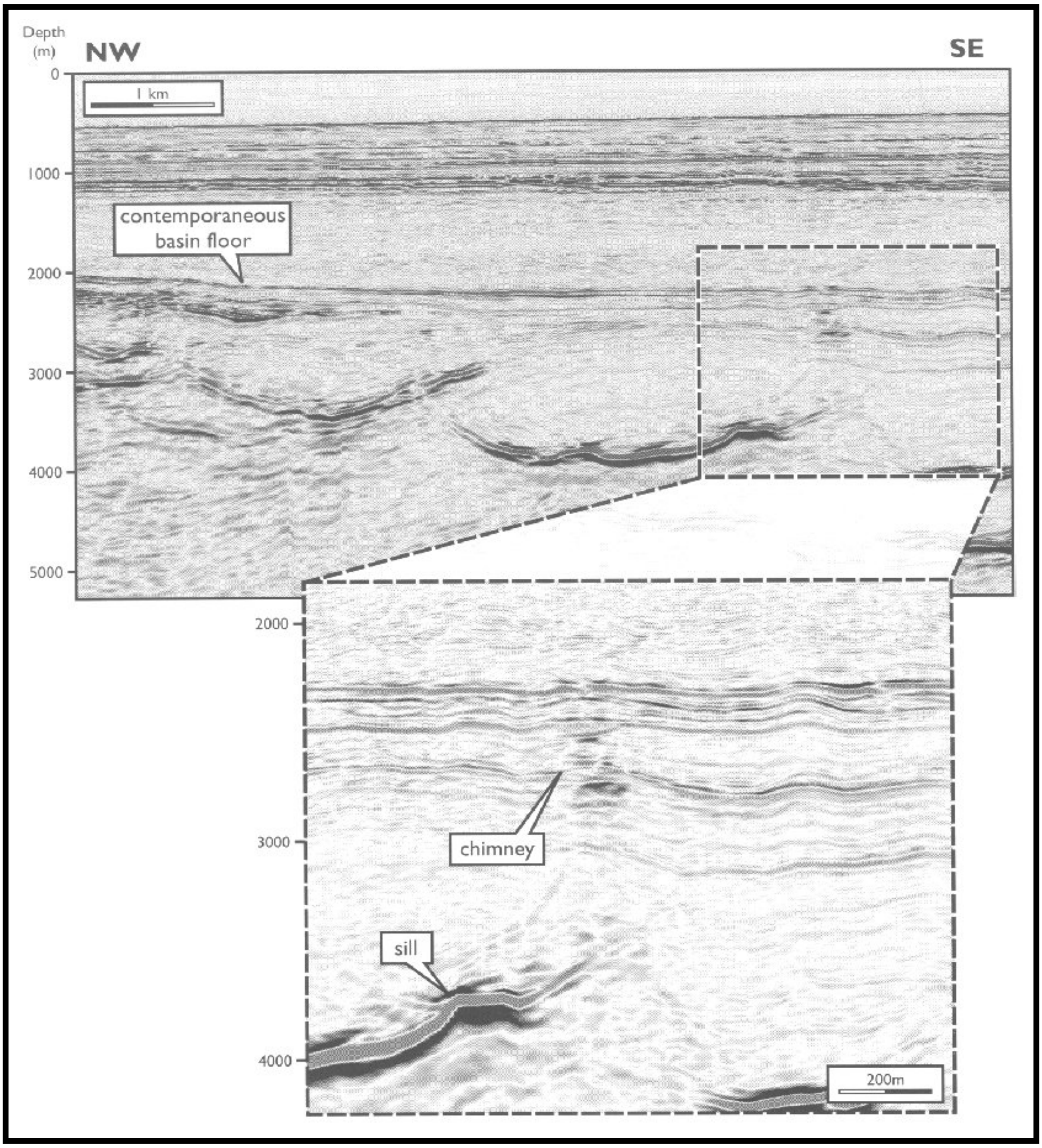

Fig. 15. Sills and associated 'seismic chimneys', interpreted as fluid escape and sediment remobilization phenomena, possibly resulting in small vent-like accumulations of sedimentary breccia on the basin floor (text and figure from CcoF 263: Bell and Butcher 2002).

3 IMPLICATIONS FOR POTENTIAL RECEPTORS

3.1 Migration up faults

3.1.1 Figure 16 shows the proposed horizontal wells, together with the existing Composite Energy wells on the OS 1:50K basemap. The underground corridors have been omitted as they are unlikely to be a source of upward fluid migration. The surface locations of the faults are shown in red.

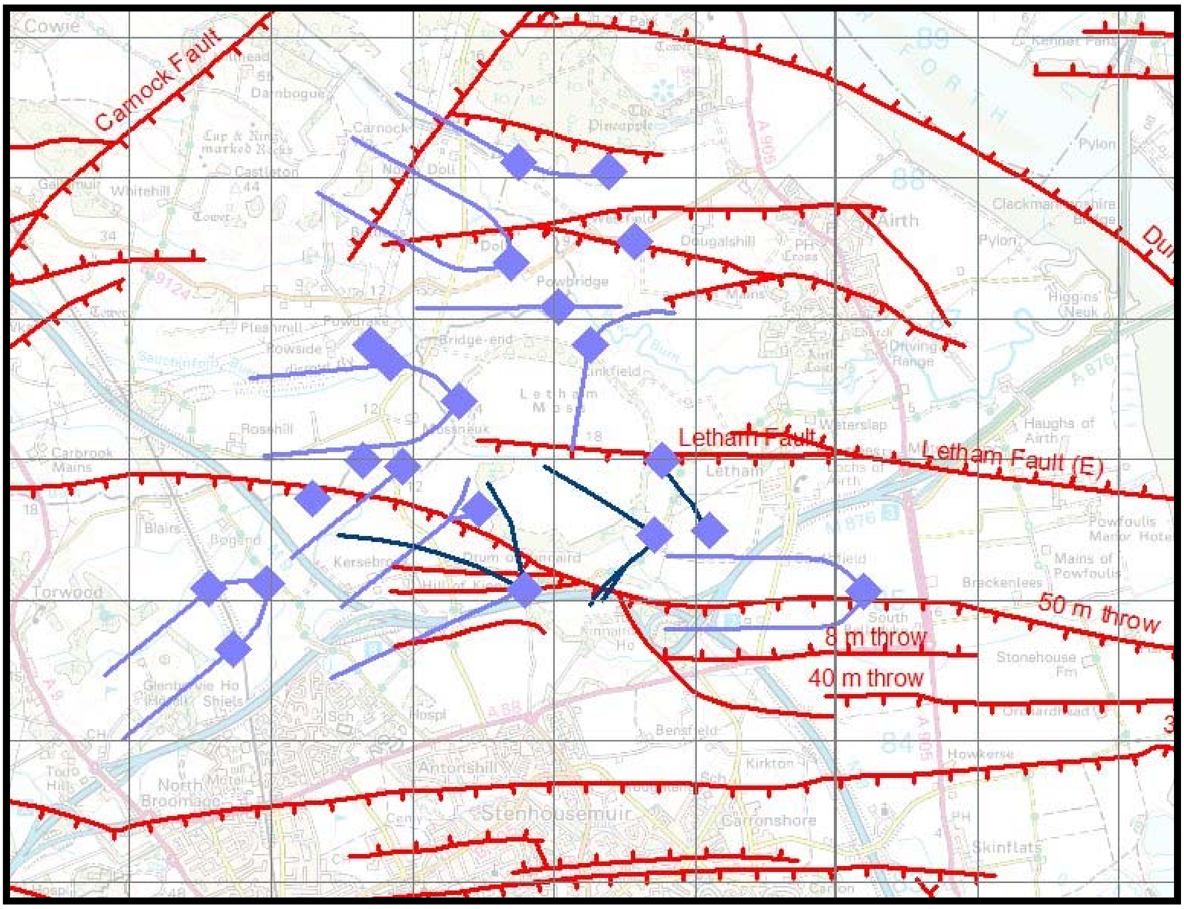

Fig. 16. The PDA in relation to faulting (red lines) and the OS map.

3.1.2 Several of the proposed horizontal wells cut the faults. Allowance must be made for the slight difference in the underground location of the faults, since they are likely to have a hade (a dip, or slope, usually on the downthrown side; see for example the faults shown in the seismic sections in Figures 9 and 11 above); however, the location of the faults at 800 m or so below the ground surface will probably lie between 100 m and 250 m of the surface location, on the downthrown side.

3.1.3 Other smaller faults which remain unmapped may also exist, sufficient to create a permeable flow surface between the target coals and the Passage Formation. Unfortunately the existing 2D seismic lines do not have the resolution to permit faults with a throw of less than 30 m or so to be reliably identified.

3.1.4 I conclude that the numerous normal faults in the PDA are more likely to act as conduits for fluid flow and fugitive methane than to be barriers to flow. Furthermore, the conduit only has to extend in a vertical sense for 500 m to connect the target coals to the Secondary A aquifer of the Passage Formation. Within the latter further upward migration will be probable, and once any such fluids reach the Lower Coal Measures there is an additional easy route for upward migrating fluids provided by the old mine shafts (Fig. 2 above).

3.2 High risk development zones and groundwater vulnerability

3.2.1 The Coal Authority has mapped zones of high risk. This is shown by cross-hatching in Figure 17 below. It is defined as follows:

> *"The Development High Risk Area is the part of the coal mining reporting area which contains one or more recorded coal mining related features which have the potential for instability or a degree of risk to the surface from the legacy of coal mining operations. The combination of features includes mine entries; shallow coal workings (recorded and probable); recorded coal mining related hazards; recorded mine gas sites; fissures and breaklines and previous surface mining sites. New development in this defined area needs to demonstrate that the development will be safe and stable taking full account of former coal mining activities."*

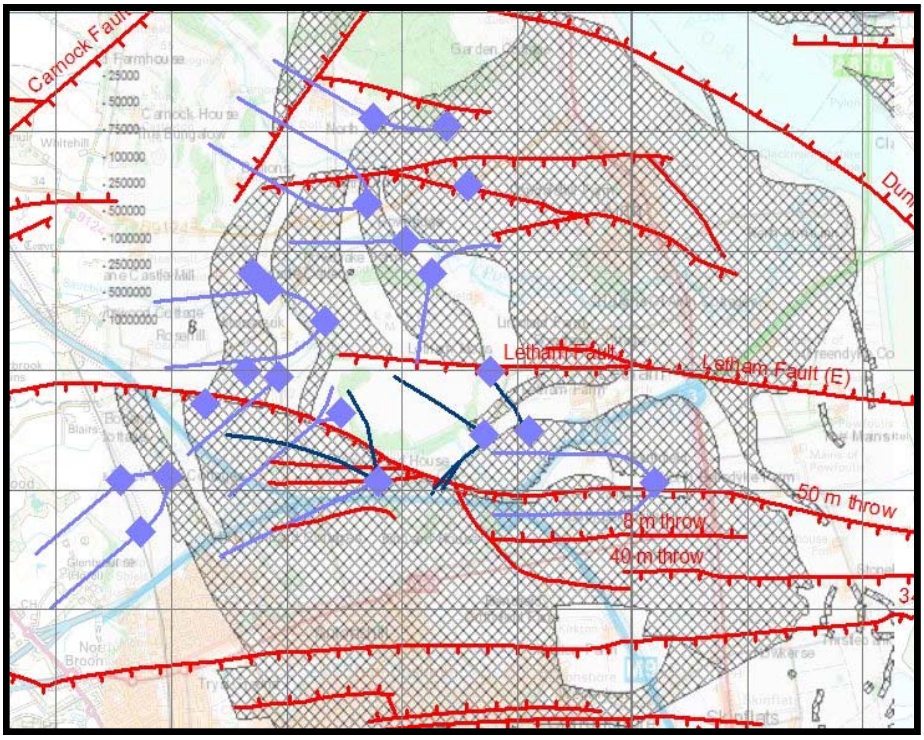

Fig. 17. Horizontal wells of the PDA and existing horizontal wells, in relation to faults (red) and the Coal Authority development high risk area (black cross-hatching).

3.2.2 The map of Figure 17 gives an indication of where surface development may be at high risk, and is therefore an indirect measure of legacy coal-mining operations. It is relevant to the subsurface elements of the PDA inasmuch as it is a proxy map for risk of fluid migration at shallow levels, mostly within the Lower Coal Measures. It can be regarded as complementary to the map of old mine shafts (Fig. 2 above), but is probably based on more complete information.

3.2.3 The BGS (CCoF 66: Dochartaigh *et al.* 2005) has assessed the vulnerability of groundwater to risk. The published sample area happens to include PEDL 133. Figure 18 shows this map in relation to the PDA and the faulting. Much of the groundwater in the area is in Class 1 ("*Only vulnerable to conservative contaminants in the long-term when continuously and widely introduced*".), but small patches in black belong to the highest class, 5 ("*Vulnerable to most water contaminants with rapid impact in many cases*").

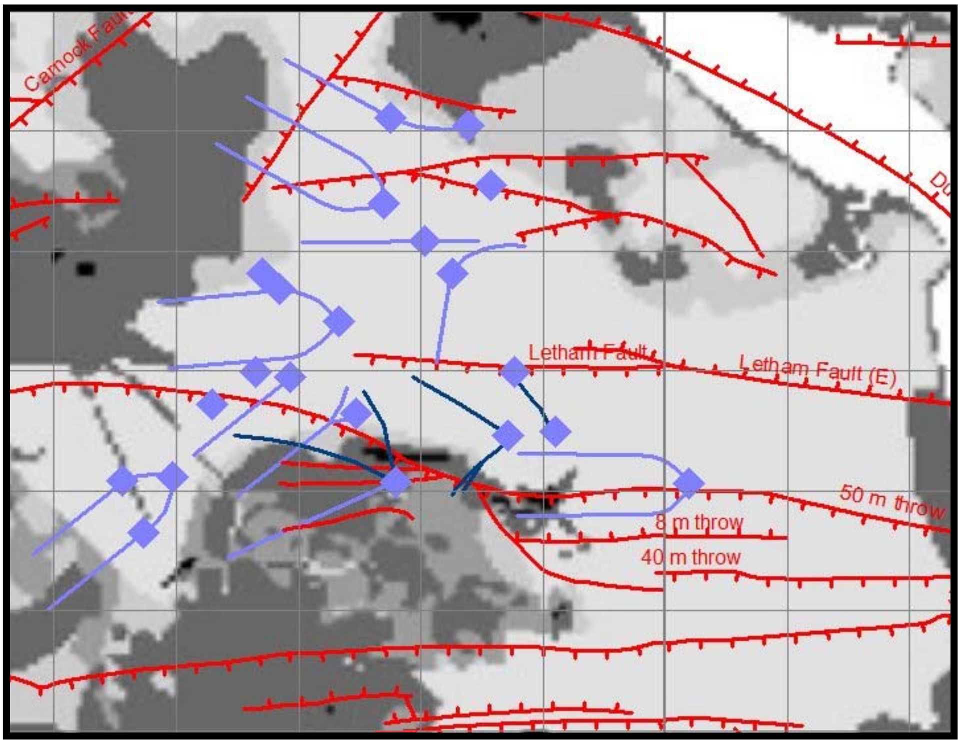

Fig. 18. Groundwater vulnerability map of the PDA. There are 5 classes, from 1 (light grey) to 5 (black).

3.2.4 Note that even Class 1 vulnerability means that fugitive methane migration is a problem. It could be *widely introduced* over the PDA, it could be a *long-term* problem (for at least the 30 year life of the installation), and it is a *conservative contaminant* (i.e. it does not die off). The italics here refer back to the definition of Class 1.

3.2.5 The issue of individual private water wells remains to be considered. They were mentioned in Dart's original planning application Environmental Statement at para. 8.24.

3.3 Relevance of US evidence on fugitive methane emissions

3.3.1 The SEPA regulatory guidance on coal bed methane and shale gas (CCoF 60) refers to the US experience of fracking (to which I shall return below). Paragraph 30 states that SEPA controls impacts on the water environment using CAR (Controlled Activity Regulations, 2011), and cites five heads which it regulates. None of these concern the nature of the geology to be drilled and exploited.

3.3.2 The initial exploration licence (PEDL133 in this instance) was granted by DECC; likewise, the details of the geology are not examined during the licence examination. I know from the experience of having sat on both sides of the table at DECC licence interviews (as a BGS expert for the then Department of Energy in one instance, and as a consultant for an applicant in the second instance) that DECC is concerned primarily with how much 'work' will be carried out during the tenure of the licence. This means essentially how much money the applicant is prepared to commit. The details of its geological prognoses are of little import. Some background financial checks are also run to ensure that the applicant has the experience and funding commensurate with the licence commitment.

3.3.3 In my view the Scottish (and UK) hydrocarbon exploratory regulation regime is therefore weak, inasmuch as there is no adequate control or wider oversight over how a licensee will drill and exploit the subsurface resources. By and large the system works well for conventional oil and gas exploration, but unconventional resource exploitation is a different and untested field in the UK.

3.3.4 Returning to the relevant CAR activities regulated by SEPA (omitting fluid injection and fracking operations which are not part of Dart's present proposals), the geological or engineering aspect of SEPA's regulation is limited to well construction, to ensure that the well does not contaminate groundwater (I exclude abstraction and treatment of flow-back water from this discussion, since that is essentially a hydrological and not a hydrogeological issue).

3.3.5 In the relatively new area of unconventional hydrocarbon exploitation (under which coal bed methane falls) there is thus no wider regulatory oversight of the potential environmental risks of drilling and stimulating vertical and/or horizontal boreholes. My concern is that there may exist various classes of geological pathways, as described in section 2 above, which may lead to environmental contamination.

3.3.6 SEPA's guidance quotes a widely cited US oil industry paper, as follows:

"Figure 2 illustrates the maximum fracture length compared to typical aquifer thickness of the Woodford shales in the United States of America. This shows that the created hydraulic fractures remain within the planned range, even in the presence of faults.", but the relevant figure below the text comprises a near-empty box including the statement *"copyright SPE"*.

SPE is the Society of Petroleum Engineers. Below the empty box there is another diagram, presumably also referring to the Woodford Shale. It is surprising that SEPA's guidance should depend on quoting, without adequate explanation, and without even an adequate citation, a copyrighted US oil industry paper.

3.3.7 The paper in question is Fisher, K. and Warpinski, N. 2012. Hydraulic-fracture-height growth: real data. Society of Petroleum Engineers Annual Conference Paper SPE 145949, Denver 2011. *SPE Production & Operations*, February 2012, pp 8-19. This paper has to be purchased, and I am unable to supply a copy for the inquiry because it is in copyright. It is also unlikely that many UK research institutions will subscribe to this journal. However, a conference presentation coming to similar preliminary conclusions can be found online, and that is the origin of the SEPA diagram of the Woodford Shale added below the empty box.

3.3.8 The paper referred to above was written by employees of a subsidiary company of Halliburton, a major hydrocarbon service company. The Royal Society report (CCoF 134) into shale gas development accepted this paper uncritically, as did a DECC report (CcoF 265: Green *et al.* 2012). This uncritical attitude towards an industry publication is surprising, given that:

- Halliburton has not published its database, which remains confidential.
- The paper appears in a Society of Petroleum Engineers journal; as with conference abstracts, it is 'grey' literature, having been given only low-level peer review.
- Wells are only located by county, and individual wells cannot be identified.
- We do not know whether inconvenient results have been omitted.
- We do not know how complete is the database.
- There are no wells in areas where pre-existing faults break the surface.

3.3.9 Even if we accept Halliburton's main thesis at face value – that creation of new fractures by fracking has a natural upward limit above the horizontal wellbore of around 500 m, perhaps 1000 m at the most – the story is erroneous at several places, which I will not discuss here.

3.3.10 The main points to learn from this seemingly irrelevant diversion into shale fracking are as follows:

- Artificially created fractures are regarded as potential pathways for contaminating fluids and fugitive methane.
- In the PDA natural fractures (i.e. faults) must therefore be considered as pathways for contamination.

- Of the half a million fracked horizontal well in the USA, less than a score occur in the vicinity of a geological fault which links the stimulated rock layer to the surface.

- The claim by the US hydrocarbon industry that fugitive methane does not occur by passage up faults or artificially created fractures is thus largely irrelevant to the UK, as a glance at the faulting shown in the various figures above will confirm.

3.3.11 The US oil industry advises that faults, sometimes present at the fracking level, are to be avoided if possible, because they reduce the effectiveness of the fracking treatment. But the problem of environmental contamination by fugitive methane and/or fracking fluids reaching the surface rarely arises in the USA, because there are <u>essentially no faults</u> which extend from the fracking level up to the surface.

3.3.12 Controversy over contamination in the USA due to fracking operations has therefore concentrated on the problem of faulty well construction, which can lead to fugitive methane emissions. In the scientific literature there are industry-sponsored papers purporting to show that methane emissions are 'natural' (pre-dating the advent of drilling, and/or negligible). One example of this is a recent paper (CCoF 267 : Allen *et al.* 2013) purporting to show low methane emissions – but the sites were pre-selected by the industry and remain confidential. This paper was immediately criticised on the ground that other independent studies report methane emissions ten to twenty times higher (CCoF 268: Howarth 2013).

3.3.13 An equally recent (non-industry-funded) study of drinking water wells in Pennsylvania (CCoF 269: Jackson *et al.* 2013) shows that elevated (including up to dangerous) methane levels correlate with nearness to well sites, at a probability level of well under 1% (i.e. the chances of this correlation being by random chance), *and* that the characteristic signature of the methane and higher hydrocarbons shows that it originates in the fracked Marcellus Shale, and is not a shallow biogenic product. In the Pennsylvania study area there are no geological faults breaking the surface.

3.3.14 Even if the source of the methane leak is due to faulty well design and/or construction techniques (CCoF 270: Ingraffea 2013), the interesting fact remains that fugitive methane is not found just at some wellbores, but also up to several kilometres away. This suggests that the cover rocks above the Marcellus Shale, which here is at depths of 1500 to 2100 m, do not make a perfect seal.

3.3.15 Comparing the drilling of the Marcellus Shale in Pennsylvania with the PDA, we see that the depth to the coal horizons to be stimulated to release methane is about half of that in Pennsylvania. The permeability of the PDA cover rocks is too high to be considered a seal (section 2.5 above). Unlike Pennsylvania, the PDA is also criss-crossed by faults.

4 CONCLUSIONS

4.1 Despite the fact more than a dozen vertical wells, and several sidetracked holes (horizontal wells) have been drilled in or near the PDA over the last decade or more, the geology of the PDA seems to be remarkably poorly understood by Dart.

4.2 There is no 3D seismic reflection survey over the PDA. Such a survey should have been commissioned to image the faults down to a resolution of a few metres, and would have gone some way to mitigating the incomplete and conflicting knowledge of faulting in this area. Such a survey would also provide a basis for modern interpretation and imaging techniques to reveal the existence of hydrocarbon chimneys, gas clouds, or volcanic chimneys. These are all indicators of a naturally 'leaky' subsurface. The PDA, excluding the outfall tunnels, covers about 15 km^2. In order to image this subsurface area a surface survey covering about 35 km^2 would be required, as the source vehicles (vibrators) would need to cover an area with a fringe of at least a kilometre outside the subsurface area to be imaged. As the target is shallow compared to orthodox oil industry targets, a high-resolution survey would be required, with receiver lines at a 25 m spacing. Such a survey is perfectly feasible; it would cost several million pounds and would take around eighteen months to two years to plan, acquire and interpret. Sonic logs and velocity surveys should be run in several existing vertical boreholes (if they do not exist already) for calibration of the 3D seismic dataset.

4.3 There is no reliable and continuous caprock or barrier layer over the PDA. The entire edifice of confidence that fugitive emissions are very unlikely to occur is constructed on a single measurement of hydraulic conductivity from an old oil industry well some 5 km NE of the PDA centroid, combined with the highly optimistic assumption, based on a single research paper citation, that the faults will act as seals due to clay smear. Dart's assertions about local compartmentalisation of blocks of hydrogeology by sealing faults is also unfounded.

4.4 Many more measurements of hydraulic conductivity, both *in situ* and in the laboratory, need to be made. In addition to the *in situ* measurements downhole, cross-hole fluid flow testing should be carried out between pairs of existing boreholes to characterise the behaviour of the faults. This should be followed up by three-dimensional computer modelling of the fluid flow under various coal dewatering and methane extraction scenarios. These measurements and modelling would require a further year or two of work after the finalisation of the 3D seismic volume image discussed above.

4.5 There are several places where horizontal wells will penetrate through a fault. Due to the use of slimhole drilling technology, there is no way to cement up the fault zone, even if such a zone could be recognised. Faults not infrequently go unrecognised even in fully logged and cored vertical boreholes and wells. These facts need to be taken into account in the design of the development.

4.6 Dart has not explained how it will be able to confine each horizontal well to its respective coal seam. The gamma ray method of 'measuring while drilling' is a relatively crude tool, and normally requires the prior existence of a guiding image, that is, a 3D seismic survey. Furthermore, no thought has been given as to what will happen if and when the borehole penetrates through a fault and the coal layer on the far side is 'missing', because it has been displaced vertically upwards or downwards.

4.7 No consideration appears to have been given to what may happen if new horizontal wells are drilled across the paths of previous laterals drilled by Composite Energy. Even if the new horizontal well in each seam avoids actually intersecting an existing hole, it will pass by within the order of a meter or so of the old hole. Once the dewatering process begins there will be a short-circuit set up between each such intersecting or near-crossing pair of boreholes, with resulting loss of control of pressure and fluid flow.

4.8 There are various natural channels through the Earth, in addition to the possibility of faulty well construction, for contamination of groundwater resources and even of the atmosphere, as a result of the dewatering and methane extraction process. These include faults, gas and volcanic 'chimneys', and permeable cover rocks above the coal horizons. Oil industry experience shows that the Earth rarely forms a perfect seal, particularly for fugitive methane. The images shown in the extracts from Aminzadeh *et al.* (2013: CCoF 109) vividly illustrate this. The old coal mine workings all over the PDA only serve to exacerbate this natural leakage pathway problem.

4.9 Following Australian experience of fugitive methane and other volatile hydrocarbon emissions from coal bed methane fields, a long-term baseline study of the current methane and CO_2 atmospheric concentrations over and around the PDA should be carried out before any development is permitted; these observations could perhaps use measurements of radon as a proxy for methane production at depth (CCoF 76: Tait *et al.* 2013).

4.10 The current regulatory regime of DECC and SEPA is ill-prepared to cope with unconventional oil and gas development, because DECC is only interested in maximising the UK's oil and gas resources, whereas SEPA appears only to have (limited) powers to intervene *after* a potential or actual pollution event is reported. SEPA has neither the remit nor the resources to scrutinise adequately such novel (to the UK) large-scale industrial techniques. Therefore there is no regulatory mechanism in place to scrutinise development proposals such as the Appellant's, which, as I have demonstrated, has serious geological and hydrogeological design flaws. The currently proposed development poses a threat to groundwater resources over the entire area of the PDA, and there is the additional risk that fugitive methane may even reach the surface. Therefore, in my view, the development should be refused.

REFERENCES (in CCoF document number order)

CCoF 47: British Geological Survey 2011. *Baseline Scotland: groundwater chemistry of the Carboniferous sedimentary aquifers of the Midland Valley*. British Geological Survey Open Report OR/111021.

CCoF 60 [also FoES 18]. *SEPA Regulatory Guidance: Coal Bed Methane and Shale Gas*, November 2012.

CCoF 65: MacDonald, A.M., Ball, D.F and Dochartaigh, B.E.O. 2004. *A GIS of aquifer productivity in Scotland: explanatory notes*. Commissioned Report CR/04/047N.

CCoF 66: Dochartaigh, B.E.O, Ball, D.E., MacDonald, A.M., Lilly, A., Fitzsimons, V., Del Rio, M. and Auton, C.A. 2005. Mapping groundwater vulnerability in Scotland: a new approach for the Water Framework Directive. *Scottish Journal of Geology* **41**, 21-30.

CCoF 76: Tait, D.R. *et al. 2013.* Enrichment of radon and carbon dioxide in the open atmosphere of an Australian coal seam gas field. *Environ. Sci Tech.* ***47**, 3099-3104.*

CCoF 79: Duncan, W.I., Green, P.F and Duddy, I.R. 1998. Source rock burial history and seal effectiveness: key facets to understanding hydrocarbon exploration potential in the East and Central Irish Sea Basins. *Am. Ass. Petrol. Geologists Bull*. **82**, 1401-1415.

CCoF 80: Lunn, R.J., Shipton, Z. K. and Bright A. M. 2008. How can we improve estimates of bulk fault zone hydraulic properties? *Geological Society, London, Spec. Publ.* **299**; 231-237.

CCoF 81: Manzocchi, T., Heath, A.E. ,Walsh, J.J., Childs, C. 2002. The representation of two phase fault-rock properties in flow simulation models. *Petroleum Geoscience,* **8**, 119-132.

CCoF 82: Tellam, J.H. and Lloyd, J.W. 1981. A review of the hydrogeology of British onshore non-carbonate mudrocks. *Quarterly Journal of Engineering Geology and Hydrogeology*, **14**, 347-355.

CCoF 109: Aminzadeh, F. *et al.* (eds.) 2013. *Hydrocarbon Seepage: From Source to Surface*, Society of Exploration Geophysicists and American Association of Petroleum Geologists, 244 pp. ISBN 978-1-560-80-310-2. [selected pages reproduced].

CCoF 134: Royal Society (2012) Shale Gas Extraction: a review of hydraulic fracturing. June 2012. Royal Society and Royal Academy of Engineering, London.

CCoF 263: Bell, B. and Butcher, H. On the emplacement of sill complexes: evidence from the Faroe-Shetland Basin. In Jolley, D. W. & Bell, B. R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes.* Geological Society, London, Special Publications, **197**, 307-329. http://sp.lyellcollection.org/content/197/1

CCoF 264: Selley, R.C. (1992). Petroleum seepages and impregnations in Great Britain. *Mar. Petrol. Geol.* **9**, 226-244. http://www.sciencedirect.com/science/journal/02648172/9/3

CCoF 265: Green, C.A. *et al*. 2012. *Preese hall shale gas fracturing review & recommendations for induced seismic mitigation*. Report to DECC.

CCoF 266: Baker Hughes 2013. *Fault Seal Analysis: Improve reservoir understanding with fault seal analysis.* Web page available at: http://www.bakerhughes.com/products-and-services/reservoir-development-services/consulting-services/geomechanics/fault-seal-analysis

CCoF 267: Allen, D. et al. 2013. Measurements of methane emissions at natural gas production sites in the United States. *Proceedings of the National Academy of Sciences.* Available at www.pnas.org/cgi/doi/10.1073/pnas.1304880110.

CCoF 268: Howarth, R. 2013. *Cornell University press release September 11 2013 re Allen et al. paper in the Proceedings of the National Academy of Sciences.*

CCoF 269: Jackson, R.B. *et al.* 2013. Increased stray gas abundance in a subset of drinking water wells near Marcellus shale gas extraction. *Proceedings of the National Academy of Sciences Early Edition*, available at: www.pnas.org/cgi/doi/10.1073/pnas.1221635110.

CCoF 270: Ingraffea, A. 2013. *Fluid migration mechanisms due to faulty well design and/or construction: an overview and recent experiences in the Pennsylvania Marcellus play.* Physicians, Scientists and Engineers for Healthy Energy website: http://www.psehealthyenergy.org/site/view/1057