Objections to

Environment Agency environmental permit application

EPR/BB3300XG/V007

(Horse Hill Developments Ltd at Horse Hill RH6 0RB)

by

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15 May 2021

Executive summary

The 1980s 2D seismic database used by the PEDL234 licence operator UKOG was adequate for mapping the simple hydrocarbon prospects of that era, which were then tested by vertical exploration wells, but is inadequate for drilling slant or horizontal wells away from the seismic control. No new seismic data have been obtained, either 2D or 3D. Problems arising from this inadequacy are illustrated by the history of UKOG (operator of PEDL234) drilling at Broadford Bridge.

The HHDL's interpretation of the Horse Hill geology has several severe internal contradictions, geologically unlikely geometry, and/or mapping errors:

- The location of the Collendean Farm-1 (CF-1) well used by HHDL is 90 m NW of its true position.
- The interpretation of a single fault with a sharp bend is geometrically unlikely.
- Misleading diagrams have been employed to try to show that the deviated Horse Hill-1 (HH-1) well has not been drilled in the vicinity of faults.

In contrast, my interpretation of the geology avoids these fundamental problems, and shows that:

- There are two separate *en echelon* faults, the Collendean Farm and the Horse Hill Faults, in the vicinity of HH-1 and CF-1.
- HH-1 has been drilled into the Horse Hill Fault damage zone, and probably intersects the fault itself. This accounts for the temporary high, but rapidly declining, Kimmeridge oil flow.

It is not clear whether HHDL revised its geology since 2016 in the light of my previous published critiques (a non-technical blog[1] and a technical analysis[2]); nevertheless the geological interpretation has been substantially modified in the last two years. So HHDL's understanding of the geology is neither stable nor well-founded. Some of the planning application diagrams imply the existence of two distinct faults, with CF-1 now on the correct (upthrown, southerly) side of the Collendean Farm Fault, but other submission documents stick to the erroneous interpretation of a single S-shaped fault. HHDL's own submissions are therefore inconsistent on this matter.

The 3D cartoon perspective views of actual and proposed drilling submitted by HHDL are inadequate for a proper scrutiny of the permit application. The application should have been supported by internally consistent structure contour maps of the several horizons which it is

[1] David Smythe 2017. *Horse play at Horse Hill*. Frackland blog posted 29 August 2017. http://www.davidsmythe.org/frackland/?m=201708
[2] http://www.davidsmythe.org/fracking/Smythe%20Horse%20Hill%20analysis%20v1.1.pdf

proposed to develop, together with illustrative properly-scaled cross-sections. But no such maps and cross-sections have been submitted.

The supposed target Kimmeridgian 'limestones' are in fact micrites, which are calcareous mudstone layers. HHDL purports to recognise six such layers, but the BGS recognises at most three micrites in the Weald Basin. One of HHDL's additional layers is merely an existing layer repeated by faulting, but mis-diagnosed by HHDL as a new layer. HHDL proposes only an acid wash (5% acetic acid) for the target micrites, but 15% hydrochloric acid is stored on site. It is not clear how HHDL will be able to stimulate flow within the Kimmeridge target shales and micrites without matrix acidisation or fracking. Its appeal to 'natural fracturing' of the micrites as a flow mechanism is based upon the results from drilling HH-1 into a fault zone, and therefore cannot be extrapolated more widely.

HHDL misleadingly cites historical earthquakes from outside the Weald Basin in support of its view that the Newdigate swarm of 2018-20 is not unusual. My analysis shows that earthquakes above local magnitude 2.0, had they occurred within the last few hundred years, would probably have been documented, but records of these do not exist; therefore the recent swarm is highly unusual. It started abruptly on 1 April 2018. There is no documentary evidence to prove that HHDL was not on site, noting annular wellhead pressures and bleeding off wellhead annuli, just before 1 April 2018. HHDL asserts without proof that these activities occurred a week later, and that there cannot therefore be a causal link between any wellhead pressure changes and the onset of seismicity. HHDL also supplies diagrams which misleadingly seek to minimise any link from faulting and well operations at Horse Hill to the Newdigate swarm. A plausible scenario is proposed in which heavy-duty earth movements within a few metres of the wellhead could have triggered the bleed-off of gas pressure built up over two years, and led to triggering of earthquakes a week later.

The applicant should be required to undertake a 3D seismic survey of the area of interest and submit these data, properly interpreted, before permission is granted for any further development.

Permission to re-inject fluids into the failed Portland Sandstone production well Horse Hill-2z should be refused outright, (a) because there are proven fault paths from the shallow injection zone up to the surface, and (b) because of the likelihood of inducing extra seismicity in what is now a seismically active zone.

Because of the severe internal errors and inconsistencies and unacceptably low standard of submission of the geology and proposed further development drilling, detailed herein, the current application should be **refused**.

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Professor Smythe: relevant details from CV

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.

My professional qualifications are: BSc Geology (Glasgow 1970), PhD Geophysics (Glasgow 1987); I was made a Chartered Geologist in 1991, but am no longer registered as such.

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. 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, 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 was closely involved with Nirex at this epoch. I planned 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 only just emerging as an essential tool of the oil exploration industry.

I have published around 70 technical and scientific papers and reports (44 papers in the peer-reviewed literature). Since my retirement from the university in 1998 I have carried out private research, acted as a consultant to the oil industry, and maintained a professional interest in the geological problems raised by nuclear waste disposal, unconventional hydrocarbon exploration and coal-bed methane exploration.

At the BGS I worked closely with the Department of Energy (DEn) and occasionally advised the Foreign and Commonwealth Office.

I worked part-time as a consultant to the oil industry 2001-2011, mapping conventional prospects in the south of England and abroad. This work frequently involved reprocessing existing 2D seismic data. I therefore have a profound understanding of the search for hydrocarbons, and possess the necessary industry-standard software tools for processing and interpreting data.

I am probably the only person ever to sit on both sides of the table at PEDL award interviews. I was once invited to join the panel at which the DEn (predecessor in hydrocarbon regulation to the DTI, DECC, BEIS and the OGA) interviewed BP for a licence west of the UK. I sat on the regulatory side. Some 25 years later, during the period when I worked as an oil industry consultant, I sat at the other side of the table, successfully representing an applicant for an onshore licence in the south of England.

Declaration of interest, independence and non-liability

I have no interests to declare. This report, which was requested by the Weald Action Group, has been prepared *pro bono* using my own resources, and is unfunded.

I am not connected to, nor am I a member of, any activist group, political party, or other organisation. I am solely responsible for the contents of this submission. It is supplied in good faith, but I can accept no liability resulting from any errors or omissions.

1 Introduction

Horse Hill Developments Ltd (HHDL; the operator of PEDL234 is UKOG, UK Oil & Gas PLC) has applied to the Environment Agency (EA) to vary its permits. My comments are relevant to the following aspects of the variations, as summarised by the EA:

- Construct up to 4 new boreholes in addition to the 2 boreholes already constructed.
- Use one of the 6 boreholes as a reinjection well to support production.
- Carry out well treatments such as an acid wash and solvent treatments.
- Run 90-day well tests for each of the 4 additional wells before they are either added as production wells at the site, or abandoned.
- Undertake an injectivity test within one of the wells (HH-2z) and any other wells as dictated by HHDL.

My comments are an update on, and development from, my objection[3] to the planning application by HHDL for hydrocarbon developments at Horse Hill submitted to Surrey County Council in 2019.

2 Inadequacy of the seismic database

HHDL is using a database of 2D seismic lines dating from the 1960s to the 1980s. Figure 1 illustrates the density of the lines (shown in brown) available over various oil and gas structures in the Weald Basin. These structures (red for gas, green for oil) are typically 2-6 km long, 1-3 km wide, and were tested by vertical or slightly deviated wells. The structures, being simple, could be fairly reliably mapped by interpolation between the control points of the seismic data.

But the new phase of exploration starting about a decade ago frequently involves highly deviated wells (up to 30-40° from the vertical), and now, in the case of Horse Hill-2z, horizontal. The problem is that the tracks of these new wells are often away from control by the seismic data. The licence operator is therefore drilling 'blind', leading to the problems such as occurred at Brockham (operator Angus Energy), at Broadford Bridge (operator UKOG), and now at Horse Hill.

Sometimes the seismic data have been reprocessed, and this can lead to slight improvements in quality. But there is no mechanism whereby a grid of 2D seismic lines can be made to fill in the

[3] Smythe, D.K. 2019. *Geological objections to Surrey County Council planning application no. 2018/0152 by UK Oil & Gas for hydrocarbon developments at Horse Hill* 21 June 2019, 19 pp. + 30 figs.

gaps between the lines. At Horse Hill the inadequacy of the existing seismic database is particularly apparent.

3 HHDL errors in well location

I refer to the supporting document[4] submitted by HHDL. Obviously the paramount requirement is for the locations of the wells and the seismic data to be accurate, say to within ±10 m or so. The seismic database is available for purchase from the UK Oil & Gas Library (UKOGL). Normally there is no problem in positioning these data if the primary survey reference frame, the OS National Grid, is retained. If, for some reason, the user wishes to use a geographic (latitude/longitude) coordinate system, then care is needed to ensure that the correct reference datum is used. This datum should be OSGB36 for the UKOGL seismic data, and not WGS84. A problem in accurately positioning the seismic data has arisen with the maps published by Hicks et al. (2019)[5] concerning the Newdigate earthquakes, discussed below. The UKOGL seismic database was mis-located by the seismologists on a Mercator projection map (which is typically that used by seismologists) by about 130 m NW of the correct position. The implications of that error will not be discussed further here, other than to note that the mapping work of this group of seismologists is sloppy in this respect.

The maps of UKOG/HHDL (and its predecessor/partner Magellan) did not suffer from the problem of misplaced seismic data; however there was a severe error[1] in the placement of the Collendean Farm-1 (CF-1) well, a vertical well drilled by Esso in 1964. In the current set of maps submitted by HHDL[2] the well has been repositioned, but it is still severely in error.

Figure 2A shows a detail of the Top Great Oolite depth structure map, submitted in application by HHDL in May 2019. The match of the digital seismic overlay (thin red lines) to the underlying colour image suggests an error of under 10 m in the registration of the image within the Kingdom v8.8 seismic interpretation package that I use for this study. However, the well locations are in error. CF-1 (yellow disc with red x) is about 130 m NW of its labelled correct location, which lies on the Collendean Farm Fault, in this interpretation.

HHDL has revised its geological interpretation since 2019. A detail of the Top Portland structure map is shown in Figure 2B. The scale and area of the two side-by-side maps in Figure 2 is identical. It can be seen that the location of CF-1 has been moved slightly SE (red x on yellow disc), and

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[4] Horse Hill Developments Ltd 2021. *Geological Reservoir Parameters*. Document Number: HHDL-EPR-HH-SWMP-014 Revision: 4 (28 January 2021.

[5] Hicks, S.P., Verdon, J., Baptie, B., Luckett, R., Mildon, Z.K., Gernon, T., 2019. A Shallow Earthquake Swarm Close to Hydrocarbon Activities: Discriminating between Natural and Induced Causes for the 2018–2019 Surrey, United Kingdom, Earthquake Sequence. *Seismological Research Letters* 90, 2095–2110. https://doi.org/10.1785/0220190125

now lies on the correct, southerly upthrown side of the Collendean Farm Fault. But it still lies about 90 m too far to the NW of the correct location.

The correct location, as given by Esso in its composite well log header, is also shown in Figure 3, labelled ‘CF-1 Esso BNG’ (BNG = British National Grid). It is situated in a large field, which I have personally viewed from the road to the east (inset photo). In contrast, all the 2019 UKOG/HHDL and earlier Magellan maps place the well in a stream in the vale (or dean, hence the name Collendean) to the NW. This is a highly unlikely location, given that the stream was there in the 1960s when the well was drilled (Figure 3 inset) and has, indeed, existed for least 100 years, as shown by archived OS maps. The current ‘HHDL 2021’ location now puts the well south of the stream, but beyond a hedge to the SE, and would therefore have been inaccessible by vehicles arriving from the road (unless a temporary gap had been made in the hedge).

The composite log header for the well gives a ground elevation of 263.6 ft (80.3 m). The Esso BNG location elevation is 81.2 m, from the DTM (OS 50 cm digital terrain model), whereas an 80.3 m elevation is to be found 15 m to the north. We do not know how the Esso elevation was derived. In the 1960s it could have been from interpolating contours on a 6” to the mile (1: 10,560 scale) OS map, or by surveying in from a benchmark on Collendean Lane. Matching the elevation, it can be concluded that the Esso location is accurate to 10 m or so.

However, the elevation of the current HHDL location is only 76.6 m, and that of the previous HHDL position in the stream is 74.6 m. So the current HHDL location is 4.8 m lower than Esso’s elevation, which is unlikely to be correct. The HHDL location is 95 m NW of the correct Esso location. Such an error can arise from a wrong datum being applied.

Figure 2A also shows that the 2019 surface location of HH-1 (southerly yellow disc marked with a red x) was mislocated by around 100 m, but this error has since been corrected.

It is not my job to correct such errors; however, the source of the error may be mis-application of interconversion of National Grid and geographic coordinates, with inappropriate datums being applied.

In conclusion, HHDL appears to be unable to position a crucial well correctly on the map, even after I pointed out the errors in 2019. This has implications for the resulting interpretations.

4 HHDL inconsistencies in fault interpretation

4.1 Interpretation errors continue

The errors in mapping of the Collendean - Horse Hill area go back to 2009. But after HH-1 was drilled in 2014, HHDL/UKOG merely made minor cosmetic alterations to the structure maps. The current interpretation, by HHDL, is shown by the red faults in Figure 4 at the Top Portland horizon.

HHDL has partially corrected the location of Collendean Farm-1, and now places it on the upthrown (south) side of the Collendean Farm Fault, but persists in its mapping of a single main fault, shown in red, running E-W through the centre of Figure 4. This single fault (on some HHDL maps labelled the Horse Hill Fault) corresponds approximately to my Collendean Farm Fault in the west, and to my *en echelon* Horse Hill Fault in the east (my black faults in Figure 4). Both these faults have a downthrow to the north.

My interpretation of the faults in the Brockham – Horse Hill – Newdigate area depicts a neat pattern of *en echelon* faults trending ENE-WSW. Outside of the Horse Hill – Collendean Farm locality it generally matches that of HHDL and earlier interpretations, including those of the oil companies which were active in the 1980s, as well as of the BGS. But HHDL's interpretation just north of Horse Hill shows two major faults abruptly swinging into an ESE trend, as highlighted by the ellipse in Figure 4.

It might be argued that the HHDL mapping is a viable alternative interpretation. However its interpretation is untenable, as is demonstrated in the more detailed map of Figure 5. In this map my versions of the faults are coloured from north to south in blue, salmon, red and lilac. Going in an easterly direction, HHDL has mistakenly correlated the Wolvers Fault to the Collendean Farm Fault, and the Collendean Farm Fault to the Horse Hill Fault (dashed green lines).

HHDL's error arose in part because it has not used the old Esso seismic line ESO-021(1), and relies only on the north-south lines C80-130 and BP-85-75. But the old Esso line confirms the local E-W trend of the Wolvers and Collendean Farm Faults, showing that there is no local ESE trend, as would be required if the green dashed line correlations were valid. In addition, ESO-021(1) proves the existence of the continuation of the Horse Hill Fault from east to west through HH-1.

In concluson, there remain major geological errors in HHDL's geological interpretation. These errors persist despite the company having had access to my critiques of its technical work going back to 2015, shortly after the drilling the HH-1. It also illustrates the inadequacy of the existing database of old 2D seismic lines in the current era of deviated and horizontal drilling.

4.2 *Inadequate detail provided by HHDL*

Detail in HHDL's proposals is woefully inadequate. Consider firstly an example 'well plat' from Pennsylvania (Figure 6). This is a detailed surveyor's plan for just one horizontal well, highlighted in yellow, and is a requirement before a drilling permit is issued. It shows the precision required before permission to drill is granted. Furthermore, this is in an area where the geology (the Marcellus Shale) is particularly simple. In contrast, Weald geology is heavily faulted and folded. Similar requirements for mapping prior to drilling exist in the other US states where unconventional drilling is taking place.

Instead of submitting the necessary detailed structural geology maps, HHDL in 2019 saw fit to supply merely a couple of cartoon perspective views of the geology and the proposed development drilling. These cartoons have not been modified or updated for the current application by HHDL. Figure 7 shows the first of these. It purports to be a perspective or isometric view of the geology, with the two existing wells shown in the N-S vertical faces, here labelled A and C, respectively. East-west face B shows no fault. Referring to Figure 8, this absence implies that there are two separate faults, conforming to my separate *en echelon* Collendean Farm and Horse Hill Faults, respectively. But if the HHDL interpretation of the Top Portland Sandstone structure shown in Figure 4 is correct, there should be a unique fault (red dashed line) which also has to cut face B.

The second cartoon submitted by HHDL shows the proposed developments, as of 2019 (Figure 9). Note that the vertical faces of the 3D perspective view are aligned E-W or N-S. So the wells depicted on these faces deviate in the same two directions. HH-2 and HH-2z, which have since been drilled, are labelled as the ‘HH-2 Portland Producer’. It is now desired to convert HH-2z into a water reinjector, to replace the proposed injection well shown in light blue in Figure 9. This well is discussed below.

4.3 *Structure along the proposed injection well*

It is surprising and unacceptable that the cartoon supplied by HHDL and shown in Figure 9 is the sole basis upon which the operator was granted planning permission by Surrey County Council in 2019, and has been able to start further drilling.

Horse Hill-2z was not drilled to the south, as implied by the cartoon shown in Figure 9, but instead followed an ESE direction along seismic line BP-85-74. HHDL now wishes to convert this failed production well into an injection well. Because of the change of use, the EA has commendably asked for more details. In response to this request, HHDL has provided an interpretation along the proposed injection well to confirm the:

“• *Location of identified faults in the reservoir with respect to the location of the re-injection well; and*

- *Lateral and vertical extent of these faults”*

The image (HHDL Figure 15) is reproduced herein as Figure 10 for comparison with my own interpretation.

Contrary to the table furnished by HHDL (p. 18) purportedly in answer to the question put by the EA (“*Confirm the key seismic lines which have been re-processed and when the data was re-processed to confirm the structural geological setting of the oilfield”)* this line, BP-85-74 has been reprocessed, and is the version displayed in Figure 10. But the version available to me is the original stack, labelled by the suffix ‘_OS’. However, the minor difference between the two versions is not fundamental to the present discussion. My version of BP-85-74 is shown in Figure 11. It has been overlain precisely on the HHDL image of Figure 10, so that toggling between the two images will show the similarities and differences.

The deviated well track coordinates for HH-1 are publicly available, but those for HH-2 and HH-2z are not. So I have constructed a simplified deviated well track for HH-2z from several images, for the purposes of comparison. The apparent difference between the location of the vertical legs of the two wells in Figures 10 and 11 is due to a difference in method of projection onto the vertical seismic display, but note that the toes of the wells in both versions match exactly. These are labelled at the top. I have applied a 20 ms shift downwards of my version to match the HHDL version; this shift is probably due to different static corrections having been applied in the two displays, and is not due to any significant difference in reflector processing.

The HHDL version shows just three interpreted faults. The most westerly fault, downthrowing to the east, corresponds in part to my Brittleware Farm Fault shown in light blue in Figure 11. The other main fault on the HHDL version (Figure 10) corresponds closely to the Horley Fault, shown in orange in Figure 11. The lilac fault that I have interpreted in Figure 11 is the Ferrier’s Forge Fault. The layer offsets corresponding to this fault are clearly visible in the HHDL version of Figure 10, but HHDL has omitted to interpret a fault there. Similarly, there are eight or so additional minor faults interpreted by myself (black lines in Figure 11) which HHDL has chosen not to recognise.

The Horley Fault has a throw of 30 ms (c. 40 m) at around 200 ms TWT, corresponding to the Ashdown Sands (which lie at only 228 m subsea depth at HH-1z). It is probable that this fault extends upwards to outcrop. It is curious that the crucial shallow data are missing from the reprocessed seismic line used by HHDL in Figure 10, leaving a V-shaped gap where the fault has been partially extrapolated upwards by HHDL.

The Brittleware Farm Fault has a vertical offset of up to 10 ms (about 12 m) at Ashdown Sands level. It is shown in more detail in Figure 12. This fault (light blue) merges downwards with an adjacent fault with an opposite sense of throw, so that the net displacement becomes zero downwards, below the Portland. However the reprocessed version used by HHDL shows this fault coninuing deeper. Figure 12 also shows the injection zone. At its eastern end it is cut by a fault with its vertical component having a displacement of a few metres.

Concerning the supposed unnamed fault splaying off in a westward direction from my Horse Hill Fault (labelled as 'HH splay' in Figure 4 above), HHDL comments:

> "*The structural map (Fig. 5) shows that the offset generated by the fault between HH-1 and HH-2z in the Portland Sandstone is very small, suggesting that fluid injection from HH-2z would allow to pressure support HH-1 via lateral migration*."

Insufficient detail has been provided by HHDL to justify the existence of this fault, although it may correspond locally to my Brittleware Farm Fault (Figures 11, 12). It cannot be mapped on the adjacent seismic lines, so there is no support for inferring that this fault is a splay fault off the Horse Hill Fault. To the east, on BP-85-75, the position of HHDL's splay fault corresponds to my Horse Hill fault (Figure 5). However, the statement demonstrates that HHDL believes that fluid injection into HH-2z can migrate *through* the fault towards HH-1. If this is the case (that the fault in question is transmissive to fluid flow), then it is equally plausible that the many shallow faults at Portland and higher levels up to outcrop (Figures 11, 12) will be equally susceptible to upward migration of injected fluids. HHDL cannot have it both ways.

In conclusion, and based on the very limited 2D seismic data available, the faulting in the area of the proposed shallow re-injection may permit upward migration and contamination of groundwater resources.

5 Kimmeridge Clay Formation

5.1 Micrites misleadingly labelled as limestones

The current application does not explicitly discuss the Kimmeridge Clay Formation (KCF), but only mentions it in passing:

> "*The Horse Hill discovery comprises several prospective intervals; however, only the Upper Portland Sandstone and the Kimmeridge Clay Formation are considered as possible resources at this time*."

and in the key to HHDL Figure 5:

> “*The HH-3 well is a potential infill well targeting the upper Portland Sandstone and the Kimmeridge Clay*.”

Therefore, despite the lack of detail provided, it is clear that HHDL is still considering exploiting the KCF, and, were the application to be approved, HHDL would be granted *carte blanche* to drill freely from the Horse Hill site and to stimulate wells. The following discussion is based upon my objection to the SCC planning application.

HHDL's production plans are targeting two so-called 'limestones' within the Kimmeridge Clay Formation, labelled KL #3 and KL #4, respectively (Figure 9). These layers are actually micrites, or calcareous mudstones. They are very far from being true limestones. Each of these is 30 m thick. Some of the wells appear be planned to traverse some of these micrites at very oblique angles. The only means of tracking the lithology that the bit is drilling through is by upward- and downward-pointing gamma ray sensors installed just behind the drill bit. These sensors are supposed to detect whether the bit is within a more calcareous layer (lower gamma readings) or within shale (high readings). The gradual approach of the bit to the roof or to the floor of a micrite layer being drilled horizontally is detected by a rise in gamma level. But if the bit passes through a small undetected fault and then proceeds through shale, there is no way of detecting whether the bit should be directed upwards or downwards to regain the micrite. The target layer is lost. The 30 m thickness of the two main micrites is at the limit of the vertical resolution of the 2D seismic method, even if there were seismic control at the location of the bit. Thus a fault with a 30 m (or greater) throw could displace the micrite completely away from the track of the horizontally-progressing drill bit.

There are no magic markers in the subsurface which tell the driller 'This is KL no. 3', for example. There are just several thin layers of shale which have a slightly greater proportion of calcium carbonate than normal shale. Therefore the risk of undertaking the proposed drilling is that the target layers may be missed, may disappear abruptly, and/or the wrong layer may be drilled. In consequence, the geology may then be re-interpreted wrongly. I have demonstrated this to be the case with UKOG's drilling fiasco at Broadford Bridge, discussed next.

5.2 UKOG at Broadford Bridge

In brief, UKOG firstly breached the conditions laid down in the permit issued by West Sussex County Council. The operator drilled, not to the explicitly defined permitted Triassic conventional target nearly vertically below the well pad, but at a shallow angle and at a very different azimuth to target the Kimmeridge micrites (Figure 13). It ran into borehole washout problems by foolishly trying to traverse the fault zone where the Purbeck Limestones are cut by the fault. It then drilled a sidetrack well BB-1z. My reconstruction of the geology in the two parallel wells (Figure 14) accurately fixes the tops and bottoms of the Kimmeridge Clay Formation. I have interpolated the expected depths of the four micritic layers by scaling the nearby Wineham-1 well log to fit, as a proxy. My explanation for the UKOG discovery of a supposedly new fifth and uppermost micrite is that the sidetrack well drilled micrite KL4 twice, once on either side of the fault. I have marked the fault as vertical, but applying a dip on it to the north or to the south makes no difference to the explanation.

In conclusion, the exploration of Broadford Bridge by UKOG was:

- Unpermitted,
- A technical fiasco, and
- Led to claims of a supposed new micrite layer.

Lastly, it should be noted that the BGS, in its Weald study of 65 wells, only recognises a maximum of three Kimmeridgian micrites in the Weald Basin; in UKOG/HHDL terminology these are numbers 3 and 4, with a locally recognised number 2. The three micrites depicted in the application documents by HHDL labelled KL#0, KL#1, and KL#5 (Figure 9) have never been documented by any non-UKOG/HHDL earth scientists. It is apparent that HHDL's understanding of the geology is simply inadequate.

The methods proposed by UKOG, HHDL and other operators in the Weald to exploit the unconventional resource of the Kimmeridge Clay Formation have been progressively watered down over a decade, presumably in an attempt to deflect criticism of the public over its justifiable fear of fracking. Part of this softening up process has been to avoid the use of the word 'shale', and, instead, to misleadingly call the micrites 'limestones', when they are no such thing. They are merely thin (<30 m) layers of calcareous mudstone or marl.

5.3 Correlation from exposed rock to the Weald

I have carried out my own correlation of the Kimmeridge Clay Formation from the exposures in cliffs in Dorset into the Weald. This exercise had already been carried out two decades ago as part of an academic study, but was somewhat flawed in that the fence diagram (a well-to-well log correlation, with no interpolative seismic control) proceeded northwards over the Purbeck-Wight Fault zone. The stratigraphy there was explained by a severe thinning of the formations over a supposed palaeo-high in Dorset. My revised interpretation comes to the same conclusions as this earlier study about the detailed link from Dorset to the Weald, but is more robust in that my correlation ties each well to the next *via* seismic data. Furthermore, my fence diagram starts from the Dorset coast, heading eastwards across Bournemouth Bay and the Isle of Wight, and only finally heading north-eastwards into the Weald using mainland wells east of the Isle of Wight. This path from the cliffs of Dorset to the Weald avoids the problematic Purbeck-Isle of Wight Fault Zone.

This study confirms that the exposures of the lower main micrite (KL#2 in HHDL parlance) as seen at Horse Hill are the identical rocks as seen in the cliffs (Figure 15). The cliffs show calcarous mudstones, as photographed and labelled by Dr Ian West of Southampton University. The thin white shelves are sandstones, not limestones. Therefore by no stretch of the imagination can this 30 m thick cliff section be termed a 'limestone' as UKOG, HHDL (and other Weald licensees) call it.

6 Exploitation of the Kimmeridge Clay Formation

6.1 Stimulation of the tight formation

The methods proposed to exploit the Kimmeridge Clay Formation (KCF) have evolved over the last decade. Cuadrilla's planning application for Balcombe in 2010 mentioned the possibility of fracking the target micrite. Explicit references to the Bakken shale play of North Dakota have been made by several operators, including HHDL, as an analogue to the Weald micrites. The Bakken is a thin limestone layer embedded in shale. Its geomechanical properties make it amenable to fracking. The wells are drilled horizontally along the limestone, which is then fracked so that oil in the shales above and below can be extracted.

Cuadrilla later denied in May 2013 that it would employ any kind of fracking, even the relatively safe vertical stage-by stage stimulation, in that round of exploration. UKOG, at its Broadford Bridge site, asserted that not only would fracking never be employed, but even matrix acidisation, which was attempted at Broadford Bridge apparently without consent, would no longer be employed[6]. It now stated that 5% acetic acid would be employed (an acid wash), for a couple of hours only, over the perforated zone.

The difference between an acid wash and matrix acidisation is shown in the graph of Figure 16. An acid wash, generally of 7% strength hydrochloric acid, is applied at around the formation pressure (green line). Matrix acidisation, which is properly regarded by the states of California and Florida as a kind of fracking, is applied at fluid injection pressures up to the fracture strength of the rock (red line). For reference, the acid strengths of various fluids on the pH scale are shown in Figure 17. The scale is logarithmic, so that acetic acid (e.g. lemon juice) with a pH of around 2.3,

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6 Drill or Drop. *New questions as oil company rules out acid injection in Weald wells*. 21 March 2019. https://drillordrop.com/2019/03/21/new-questions-as-oil-company-rules-out-acid-injection-in-weald-wells is around 1000 times weaker than 15% hydrochloric acid commonly used by the industry for a wellbore wash (pH -0.7).

If HHDL does indeed restrict itself to acetic acid, that is well and good; but we know that 15% hydrochloric acid is on site, and that the regulation of such activity is effectively uncontrolled, because it relies on self-reporting.

The differences between the methodologies of hydraulic fracturing (however defined) and bulk acidisation of carbonate-rich rocks are, in a sense, irrelevant, because the common purpose of such unconventional treatments of the bulk rock is to permanently increase the permeability. The legal flaws in current UK legislation, and proposals to clarify and simplify the law, are discussed in a recent paper[7] of which I am a co-author.

6.2 Drilling into the fault damage zone – HH-3

I first pointed out in August 2017 that HHDL had probably drilled into the damage zone of the Horse Hill Fault. I have since refined this interpretation with the aid of:

- Correction to the location of the 1962-vintage seismic line ESO-021(1), and
- Plotting the tops of the deviated HH-1, previously assumed to be vertical.

Although it is very poor quality, the seismic line above is crucial because it is the nearest existing line to HH-1. Interpretation of this line (Figure 18) suggests that the Horse Hill fault extends westwards through the track of HH-1. CF-1, shown as a vertical dashed green line, is projected from about 300 m to the west. The vertical offsets depicted in Figure 18 across the fault vary from zero at the Portland to 15-20 ms TWT at the Corallian.

A contour map of the Horse Hill Fault is shown in Figure 19. The fault may splay into two or more parts as it dies out westwards.

An isometric cartoon of the intersection of HH-1 with the Horse Hill Fault is shown in Figure 20. The damage zone cartoon is from Johri et al.[8] The wellbore, superimposed upon the cartoon, started vertically about 200 m south of the fault, then deviated northwards so that it was 130 m further north of the surface location at Kimmeridgian micrite level, at 770 m depth subsea. Here it will have penetrated the damage zone extending for about 50 m on either side of the fault surface. This inference accounts successfully for the temporary high flow rates encountered within the

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[7] Zalucka, A., Goodenough, A., Smythe, D., 2021. Acid stimulation: Fracking by stealth continues despite the moratorium in England. *Energy Policy* 153, 112244.

[8] Johri, M., Zoback, M.D. and Hennings, P. 2014. A scaling law to characterize fault-damage zones at reservoir depths. *AAPG Bulletin*, v. 98, no. 10 (October 2014), pp. 2057–2079.

Kimmeridgian (the infamous 'Gatwick Gusher'). This inference is supported by the rapid decline of the flow rate up to 2019 (as I predicted in 2017), shown in the inset figure. Such a decline is to be expected from drilling into a fault zone.

Proposed well Horse Hill-3, with a trajectory between north and NE in azimuth (Figure 19, inset) is likely to penetrate the fault zone in a similar manner to HH-1. HHDL portrays an interpretation of seismic line BP-85-75, with the track of proposed well HH-3 projected from between 800 and 1000 m from the west. Once again, this line has been reprocessed and migrated, even though HHDL wrongly states in its table (page 18) that it has not. Regardless of the interpretation of this line, it is an inadequate basis on which to plan such a deviated well.

7 Possible link between Horse Hill and the Newdigate earthquake swarm

7.1 Introduction

UKOG has submitted to SCC a document entitled '*Why Earth Tremors in Surrey Should Not be Blamed on Oil Exploration*'[9]. It is an attack on the hypothesis devised by a group of earth scientists at Edinburgh University[10]. This group, led by Professor Stuart Haszeldine, proposes a link between Horse Hill-1 well activities and the triggering of earthquakes. I shall leave Professor Haszeldine and the University of Edinburgh (to which UKOG has also had the temerity to complain directly) to rebut the main accusations; however, some allegations made by UKOG fall within my domains of expertise in structural geology, applied seismology, and seismic interpretation, so I shall discuss them here.

7.2 Historical seismicity

The UKOG submission deals with historical seismicity in the Weald. It quotes the Edinburgh report[9] as follows:

> *"Prior to 2018, there are no shallow earthquake clusters on record for the Weald since records began in 1969. It is reasonable to conclude that the 2018 Newdigate cluster sets a precedent for the Weald."*

then responds, concerning the Edinburgh report:

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[9] UKOG 2019. *Why Earth Tremors in Surrey Should Not be Blamed on Oil Exploration*. Document submitted by HHDL to SCC, May 2019, 10 pp.
https://planning.surreycc.gov.uk/planappdisp.aspx?AppNo=SCC+Ref+2018%2f0152

[10] Cavanagh, A., Gilfillan, S. and Haszeldine, S. 2019. *Further Potential for Earthquakes from Oil Exploration in the Weald*. Note for the All Party Parliamentary Group on the impact of shale gas. 2 April 2019.

"*This statement is both inaccurate and misleading. Firstly, although a relatively quiet seismic area, the Weald of SE England has recorded significant numbers of earthquakes in recent times, most notably in Chichester and Folkestone*."

But this UKOG retort is itself "*inaccurate and misleading*". Let us confine ourselves to the Weald, firstly defining the limits of the Weald Basin as a geological feature.

The Weald, topographically, is the region lying between the chalk escarpments of the North and South Downs. The Weald Basin, as a geological feature, is somewhat broader than that. It is illustrated by the regional seismic profile depicted by Pullan and Butler (2018)[11], reproduced here as Figure 21. Its southern limit can be defined by the Portsdown High in the south. Here the Triassic and Mesozoic sedimentary infill is about 1500 m thick. On the north side the basin edge corresponds to a line running E-W about 10 km north of the crest of the North Downs, where the Upper Cretaceous oversteps the Jurassic to the north.

Using this definition we now search the BGS catalogue for all earthquakes since 1700. The search limits were set at 50.8° to 51.3° N, -1.0° to +1.0° E. This rectangle is shown in Figure 22, on which the earthquakes resulting from the search (up to 21 April 2021) are plotted.

The Chichester earthquake swarm of 1833-34 and the 1864 Lewes event are outside the Weald Basin. Furthermore, one of the Chichester events and the Lewes event have a (probably very approximate) depth of 4 km assigned to them. This is more than double the depth of the sedimentary infill at their respective epicentres, and shows that the events probably occurred within the basement.

The 1985 Fleet (Surrey) earthquake is similarly outwith the Weald Basin, and at 4.4 km depth is once again twice as deep as the sedimentary basin in that locality. The 2016 Maidstone earthquake, magnitude 1.6, occurred at a depth of 3.5 km, so is equally outwith the Weald Basin, and also too deep.

So we are left with the three Billingshurst earthquakes of 2005, the 1996 East Grinstead earthquake (magnitude 1.4, depth 5.1 km) and the 2018 Scaynes Hill event (magnitude 1.6, depth a nominal 1 km) as lying geologically within the Weald Basin.

The Three Billingshurst events are plotted on a regional seismic cross-section shown in Figure 23 (the same seismic line used as the basis for the geological cross-section of Figure 21). The Billingshurst events lie within about 1 km from the section; the Newdigate events have been projected 16-20 km westwards along strike, and are shown by a generalised box, with depths

[11] Pullen, C.P. and Butler, M. 2018. Paleozoic gas potential in the Weald Basin of southern England. From: Monaghan, A. A., Underhill, J. R., Hewett, A. J. & Marshall, J. E. A. (eds) Paleozoic Plays of NW Europe. Geological Society, London, Special Publications, 471, https://doi.org/10.1144/SP471.1

varying from 1.5 to 3.0 km (Hicks et al. 2019[12]; note that an earlier report by Dr Hicks quoted the most accurately located events as being at only 800-1000 m depth; the reason for the subsequent depth adjustment is not clear). The depths to the hypocentres of the three Billingshurst earthquakes have not been very accurately determined, but they appear to lie within the Variscan basement. They may be due to movement on the Variscan thrust complex, one such example of which is interpreted at the bottom centre of the section. So their mechanism will be different from that determined for the Newdigate events, which are clearly within the mid to lower Mesozoic basin infill.

That leaves just two relevant historical earthquakes, the East Grinstead and the Scaynes Hill events, which have hypocentres within the Weald Basin sedimentary fill.

7.3 Completeness of the earthquake catalogue

UKOG claims that the BGS catalogue is incomplete; that is, many historical events may be missing. The BGS states[13] that:

> "*After 1970: Instrumental monitoring of British earthquakes started about 1970, and after this date all events recorded by the BGS within the limits of the catalogue area and greater than magnitude 3.0 ML are included. Also included are some smaller earthquakes that were felt, chiefly those for which one or more isoseismals can be drawn. The catalogue is probably complete above 3.5 ML for 1970-1980 and above 3.0 ML thereafter (the BGS database is complete above 2.5 ML for 1981 onwards). Completion date is 31 December 1993.*" [red highlighting added]

The BGS website states "*All earthquakes of magnitude 2.5 and above have been captured since 1979.*"

So the record is not as incomplete as UKOG implies. The BGS detection capability map reproduced by UKOG refers only to instrumental recordings. But the recent macroseismic historical record, not discussed by UKOG, tells a different story. The 27 Feb 2019 M_L=3.1, depth=2.4 km Newdigate earthquake was felt out to about 15 km away. This range is plotted in Figure 24 (blue circle). The 19 Feb 2019, M_L=2.0, depth=2.4 km event was felt to about 8 km distance from the epicentre. This range is plotted as a red circle. So in the Weald, which has been

[12] Hicks, S.P., Verdon, J., Baptie, B., Luckett, R., Mildon, Z.K., Gernon, T., 2019. A Shallow Earthquake Swarm Close to Hydrocarbon Activities: Discriminating between Natural and Induced Causes for the 2018–2019 Surrey, United Kingdom, Earthquake Sequence. *Seismological Research Letters* 90, 2095–2110. https://doi.org/10.1785/0220190125
[13] Musson, R.W. 1994. *A catalogue of British earthquakes*. BGS Technical report WL/94/04.

densely peopled by a literate population for several centuries, it is likely that most earthquakes of around $M_L \geq 2.0$ would have been documented and thence compiled into the BGS catalogue[12]. The absence of any such records strongly suggests that no such seismicity occurred.

In conclusion, the Newdigate swarm is exceptional, in that it has appeared within a sedimentary basin which has probably not experienced such a swarm for hundreds of years. It started abruptly on 1 April 2018, and has continued sporadically ever since. The last recorded earthquake was on 16 December 2020. All except one lie within 4.5 km horizontal distance from the Horse Hill site. The statement quoted in section 7.2 above by Cavanagh et al. is therefore not only valid, but is rather conservative.

7.4 Possible permeable fluid pressure link from Horse Hill to Newdigate

UKOG has presented an interpreted seismic line[9] (its figure C) purporting to show one of the strongest earthquakes (2019 February 27, M_L=3.2, depth 2.1 km) located on the Newdigate Fault. The two-way time (TWT) is about 1.0 s, corresponding to the depth of the Great Oolite. But the UKOG map disingenuously shifts the epicentre about 1 km to the west, to place it on line TWLD-90-15. This is demonstrated in the map of Figure 25. Assuming that Hicks's depth and general correlation with the Newdigate Fault is correct, a more accurate portrayal of the possible link between this (and, by implication, other) events and Horse Hill is shown in the seismic section of Figure 25. This is a composite of two lines, shown in blue on the map.

The upper Kimmeridgian micrite is mapped by the lilac horizon; the Corallian is shown in blue, and the Portland in orange. The earthquake has been projected along the strike of the Newdigate Fault, which dies out eastwards. On line TWLD-90-21 the fault displaces the Great Oolite and the Corallian, but in dying out upwards it does not cut the Kimmeridgian micrite. I disagree with the Hicks et al. geological mapping here, in not extending the fault further to the ENE as they do.

The interpreted cross-section of Figure 25 shows that there is a plausible physical link of just 2000 m between the Horse Hill Fault (which intersects Horse Hill-1) and the Newdigate Fault. Pressure changes at the well, caused, for example by releasing shut-in pressure build-up, could pass down the Horse Hill Fault and/or its damage zone, and thence along permeable horizons such as the Great Oolite (not mapped by myself) at ~1 s TWT, to reach the earthquake zone.

7.5 Activities at the Horse Hill site before the start of the seismicity

Questions remain unanswered about the incomplete disclosure of wellhead activities at Horse Hill-1. For example, rigless well testing operations were notified to the HSE on 9 March 2018, and were claimed to have been carried out on 5-6 April. But the HSE has no weekly record of any such activity between March 2016, when the well was suspended, and the week ending 19 August. Therefore we only have the word of HHDL that pressure testing was actually carried out in the first week of April, and not the week before.

The OGA summary of the Newdigate seismicity workshop[14] held on 3 October 2018 concluded:

> "*There is no annular pressure evidence of impaired wellbore integrity in the Horse Hill 1 well because of the seismic events, nor evidence of migration of gas outside the wellbore between different zones. The strata are normally pressured and at formation pressures all gas is solution gas and there is no free gas*.", but added a footnote stating:

> "*Some questions were not answered during the event about activity at the Horse Hill site, and that information has since been made available: prior to the recent commencement of the Horse Hill 1 testing in 2018, there had been no sub-surface work at the Horse Hill site since 18 March 2016. Surface activity included the excavation of a nearby new cellar starting on 21 March 2018 using a JCB for a future well and the site was visited by tankers to remove rainwater collected above the impermeable layer*."

The workshop considered the criteria, a set of yes/no questions, framed by Davis and Frohlich[15], and updated by Frohlich et al.[16] in 2016, for judging whether nearby well activity might have triggered the Newdigate swarm. So although Horse Hill fulfilled the spatial correlation distance of less than 5 km from the tremors, Brockham, at 7 km distance, did not.

The lack of timely disclosure at the workshop, revealed by the second OGA paragraph quoted above, misled participants into believing that Horse Hill could be ruled out because there was no surface activity there; they instead concentrated on the Brockham site. Had they known about the activity at Horse Hill in the week preceding the onset of seismicity it is likely that the focus of discussion would have been there and not at Brockham.

HHDL vehemently denies that any wellhead bleed-off (whenever it was carried out, before August 2018) could have had any effect in the deep subsurface, because three retrievable bridge plugs had been set, one above the Portland. But that explanation presumes that the upper plug had remained tight for two years, <u>and</u> that the pressure bleed-off that HHDL admitted was necessary was only due to shallow biogenic gas build-up. But this discussion concerns only Annulus A, between the 8-1/2" production tubing and the 2-7/8" kill string (refer to the HHDL schematic lower

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[14] Oil and Gas Authority 2018. *OGA Newdigate Seismicity Workshop – 3 October 2018*. 6 pp.

[15] Davis, S.D., Frohlich, C., 1993. Did (Or Will) Fluid Injection Cause Earthquakes? - Criteria for a Rational Assessment. *Seismological Research Letters* 64, 207–224. https://doi.org/10.1785/gssrl.64.3-4.207

[16] Frohlich, C., DeShon, H., Stump, B., Hayward, C., Hornbach, M., Walter, J.I., 2016. A Historical Review of Induced Earthquakes in Texas. *Seismological Research Letters* 87, 1022–1038. https://doi.org/10.1785/0220160016

abandonment/Portland suspension diagram[17]). No mention is made of Annulus B (9-5/8” to 8-1/2”). In Annulus B prevention of pressure build-up depends upon sound cementing between the 9-5/8” tubing and rock all the way below 1787’ (545 m) MD.

HH-1 was deviated from the vertical, building from below about Portland, and reaching inclinatons of >40° between 930 m and 1400 m MD, approximately between the upper Mid Kimmeridgian micrite and the Corallian. Problems can arise in the cementing of the casing, because the casing is excentric in the inclined wellbore. The annulus, in this case between the 9-3/8” and the wellbore, does not get fully cleaned of mud, so that the cement pumped in makes an incomplete barrier[18]. Recall the severe problems due to slant drilling and washout encountered by the same operator at Broadford Bridge (section 5.2 above).

Surface works comprising excavation of a new cellar for HH-2 were started on 21 March 2018 and completed a day or so later (Figure 26). The external dimensions of the cellar, which is cylindical, are about 2.75 m in diameter and 2 m deep. It was dug by a mechanical digger. Its centre is 6 m north of the existing HH-1 cellar. Caterpillar-tracked JCB excavators of the types seen at Horse Hill during the period in question (see Figure 26) weigh between 5 and 8 tonnes.

Figure 27 shows a true-scale cross-section through the two Horse Hill cellars as of late March 2018. Taking a simplified picture of static elastic stress, we note that the (approximate) 6 t (tonnes) mass of the digger is a significant fraction of the vertical stress component of around 30 t/m^2 at the 14 m depth of the shoe of the 20” surface casing. In addition, about 20 t of clay was removed to create the cellar. Weald Clay has a low modulus of rigidity, implying that stress differentials lead to large strains. A more accurate dynamic picture of the digger moving and shifting material, is of course much more complex. But from these ballpark figures we can see that shear strains at the cementing of the HH-1 wellbore 10” surface casing, even if only a fraction of a millimeter of displacement, caused by the digger movements, would be sufficient to release the build-up of gas over the previous two years.

So this possible scenario is as follows:

- Suspension of HH-1, March 2016, with bridge plugs to prevent connection from any overpressured zones to Annulus A.
- Slight overpressure remains in the Kimmeridgian and deeper section, and builds up over two years of well suspension.

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[17] Horse Hill Developments Ltd 2018. *Horse Hill-l Rig-less Intervention and Well Testing Programme HHDL*. HHDL-HHI-RIWTP-RO, Rev 0 February 2018.
[18] Dusseault M. B. et al. 2014. *Towards a road map for mitigating the rates and occurrences of long-term wellbore leakage.* Report, Department of Earth and Environmental Sciences, University of Waterloo, 22 May 2014, 75 pp.

- Cement bonds between rock and 9-5/8” casing, and between rock and 13-3/8” casing fail gradually, starting immediately in the inclined wellbore zone.
- Disturbance of the uppermost 14 m of HH-1 by the excavation works damages the bonding of the 20” tubing sufficiently to release pressured gas in Annulus B.
- Diffusion of the resulting pressure drop reaches the Newdigate Fault a week later.

In conclusion, firstly, UKOG's attempts to dissociate its activity from a possible temporal and causal link to the earthquake swarm are erroneous and disingenuous. The conclusion reached by the OGA workshop, expressed by the OGA as follows:

> “*The workshop participants concluded that, based on the evidence presented, there was no causal link between the seismic events and oil and gas activity although one participant was less certain …*”

should be given little weight because of the omission of significant relevant facts by UKOG.

In general, I support the Edinburgh group's hypothesis that there may be a link between the drilling activities at Horse Hill and the Newdigate earthquake swarm, and that it deserves serious consideration. The jury is still out.

Secondly, even if the start of Newdigate earthquake activity had no causal connection to drilling at Horse Hill, and the temporal correlation is purely by chance, it is a fact that Horse Hill is now situated in a seismogenic zone, and it is incumbent upon the EA to take this into account, particularly on the question of re-injection.

8 Conclusions

The evidence analysed above shows that UKOG has a dismal record of technical competence, both at Broadford Bridge and now at Horse Hill. The luck, or misfortune, that HH-1 was drilled into a fault zone, resulting in temporary high oil flow from the Kimmeridgian, has been used by UKOG to propose over-ambitious but badly documented proposals to drill a series of production wells, plus one water injection well, at the Horse Hill site.

I have documented that some of HHDL/UKOG's geological mapping is nothing less than incompetent. It should not be permitted to form the foundation of such an application.

The geology, and in particular the faulting, is evidently more complex than can be resolved adequately using the existing database. However, it can be concluded that there are many shallow faults, such as are seen along the line of the proposed injection well HH-2z, which could permit the upward migration of wastewater into aquifers.

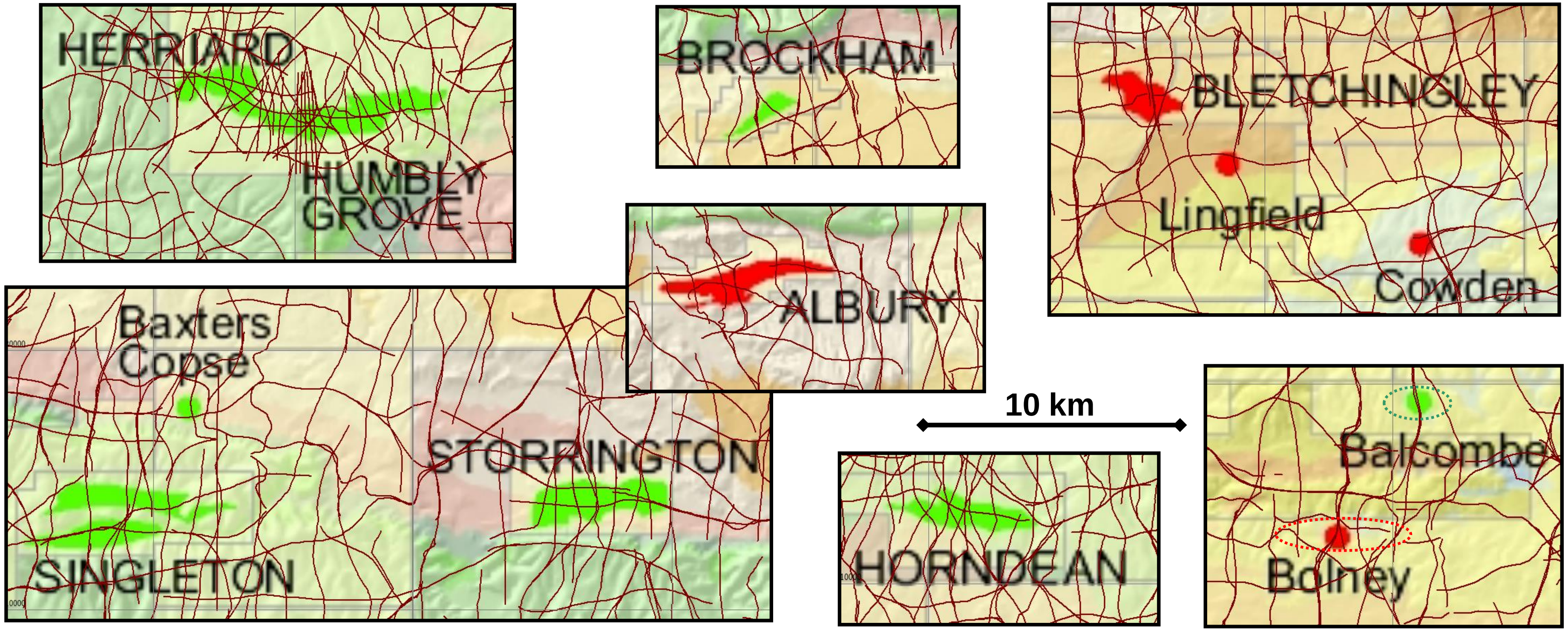
Given that there is the possibility of well activity at Horse Hill acting as a trigger for earthquakes (which have already caused expensive property damage), and given that new seismic (and perhaps ancillary geophysical) data need to be obtained, I recommend that:

- The current application be refused.
- The Applicant be required to acquire, process and interpret a new 3D seismic survey of at least 30 sq km in area, before submitting a revised application.

The survey should encompass the specified extraction area, and be extended somewhat to the SW to include the zone of seismicity at Newdigate. The cost of such a survey is of the same order as that of drilling one well. The time taken to commission such a survey, have it processed and interpreted, then prepare a new application, of the order of one to two years, will also act as a *de facto* moratorium on Horse Hill activities. Then we shall be able to see whether the seismicity dies out during that period.

Given that Horse Hill is now situated from just 1 km to 5 km NE of a seismically active zone, it would be irresponsible for the EA to permit any re-injection into HH-2z, or, for that matter into any other well in the locality, given the accepted fact that re-injection is known worldwide to be a trigger of induced seismicity.

Weald oil and gas fields



The conventional structures (green/red) are typically 2-6 km long and 1-3 km wide. They are defined by 2D seismic lines at 1-3 km spacing.
They were then drilled with vertical or deviated wells by the majors.

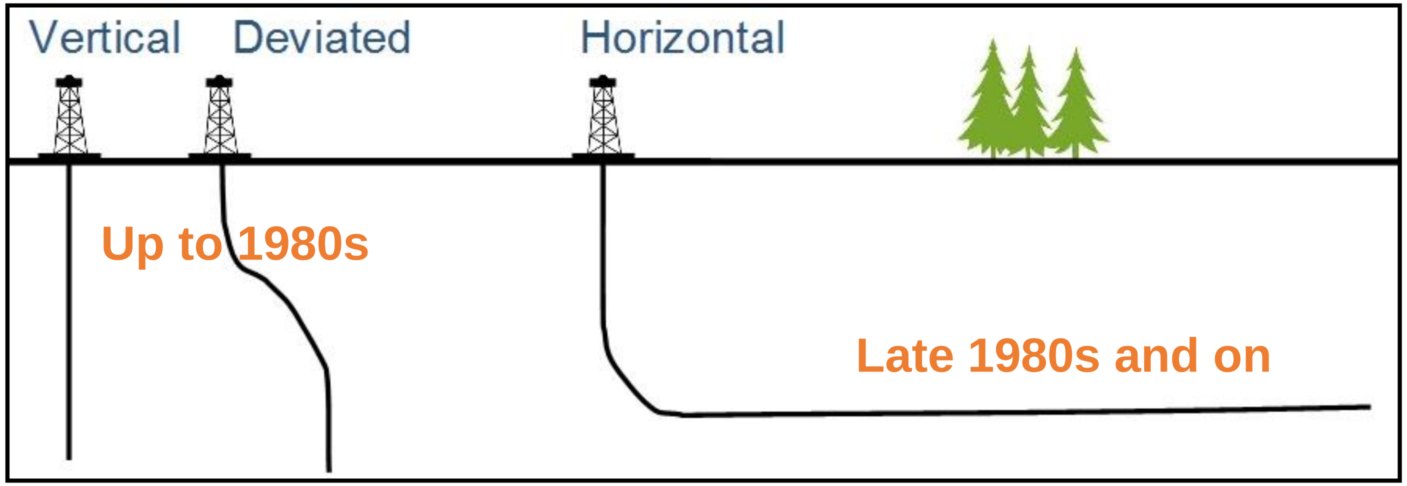
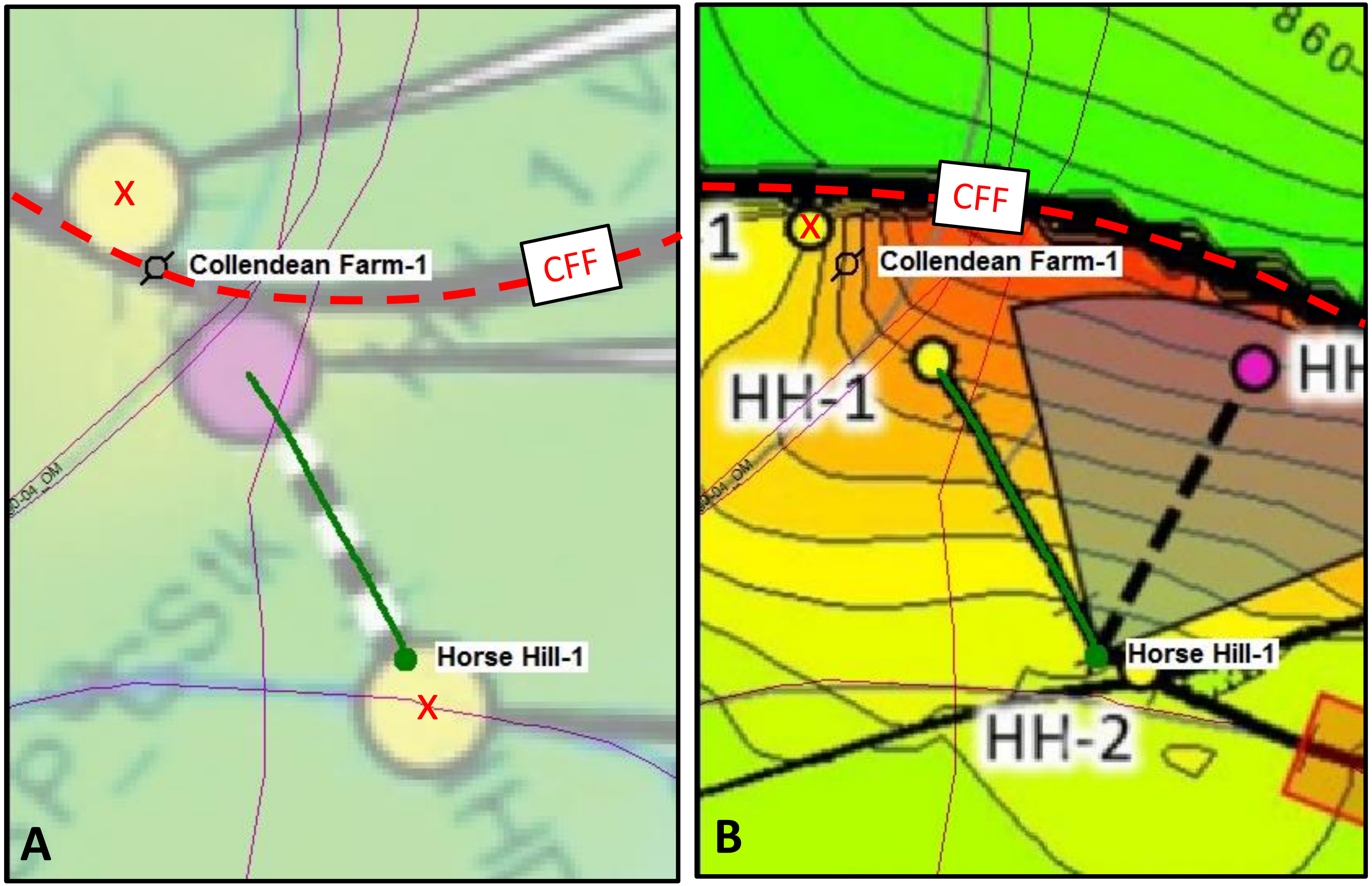


Fig. 1

Fig. 2

Continuing error in location of Collendean Farm-1

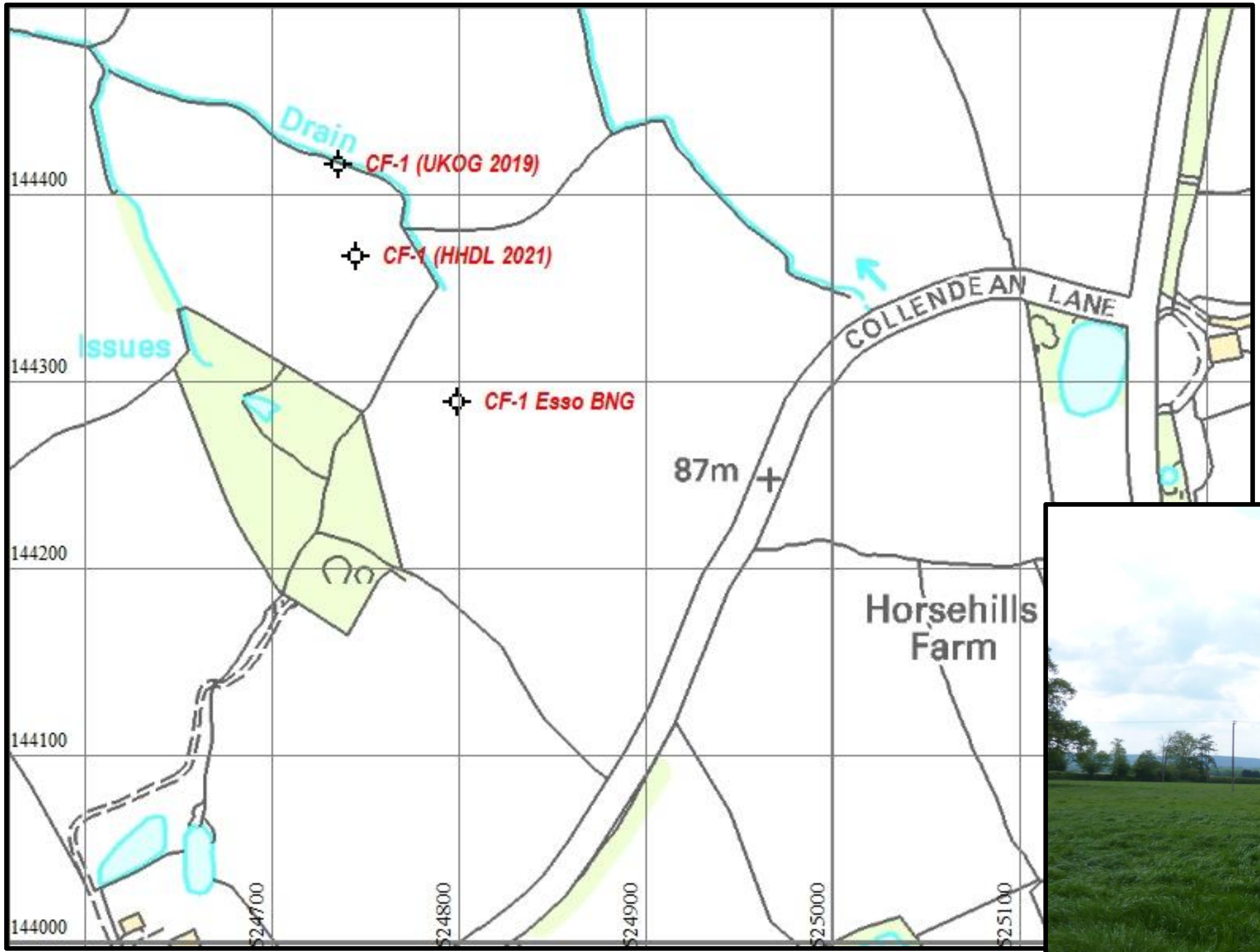
Erroneous positions are marked by an x. The Collendean Farm Fault is highlighted by a red dashed line (CFF)

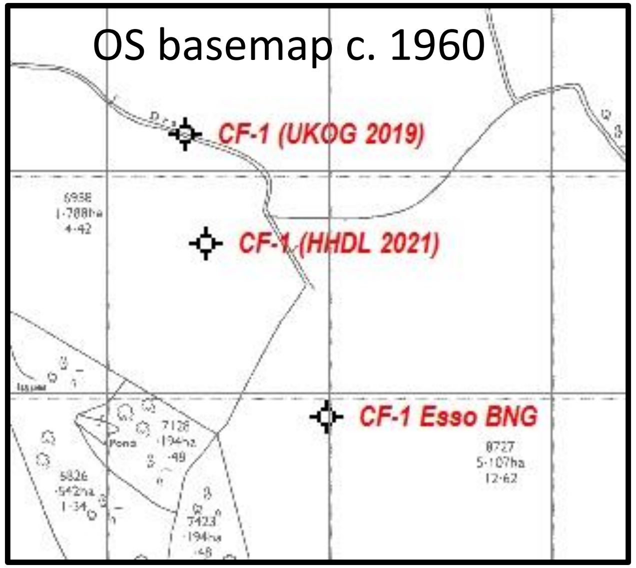


A. Collendean Farm-1 (yellow disc) is shown by UKOG (Top Great Oolite map, 2019) about 130 m NW of its correct location as shown by the 'plugged and abandoned' well symbol. The well is positioned on the downthrown side of the Collendean Farm Fault (CFF). The surface location of Horse Hill-1 (yellow disc) is too far SE by about 100 m.

B. The well location error has been reduced to about 90 m (Top Portland map, HHDL 2021, red x on yellow disc). The well now lies on the correct (southern, upthrown) side of the fault. The Horse Hill-1 surface and bottom hole locations are now correct (my green line).

Fig. 3





Erroneous location of CF-1 by UKOG (2019) in a stream, and HHDL's revised location in 2021. The upper right inset shows the OS map from the 1960s, demonstrating that the stream existed then. Both the incorrect locations are beyond a hedgerow, so access would have been difficult. The correct location, as defined by the operator Esso in 1964, is shown, specified in British National Grid (BNG) coordinates. It lies in the large field (photo), viewed looking west from Collendean Lane.

Comparison of HHDL mapping of faults at Top Portland level (red) with mine (black).
The contentious area of interpretation, where HHDL shows faults trending WNW-ESE, is highlighted by the dotted ellipse.

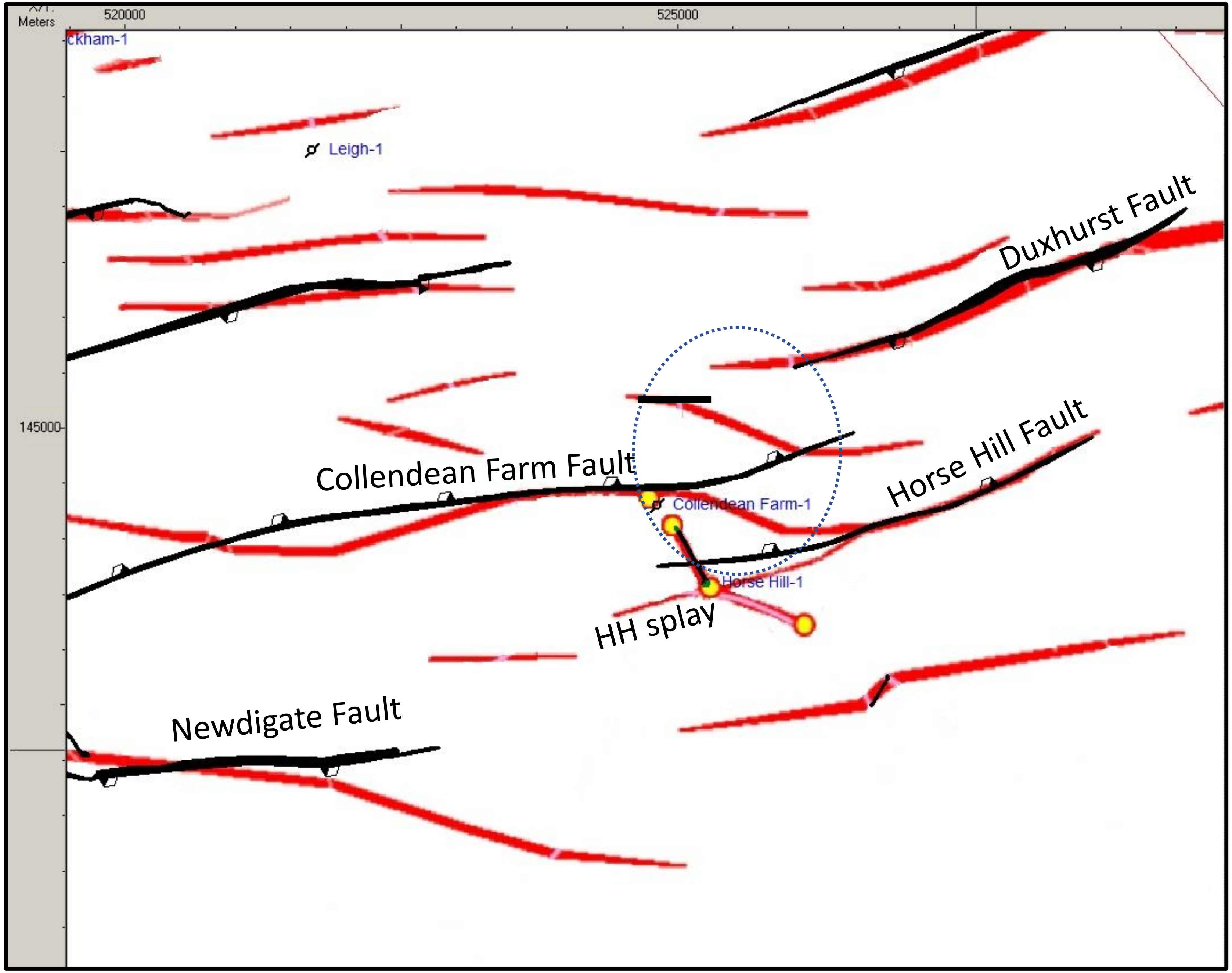


Fig. 4

Mis-correlation of faults by HHDL

Map of Top Portland Sandstone showing faults only. Picked seismic lines are coloured purple, unpicked lines are shown by thin red lines.

Going in an easterly direction, HHDL has correlated the Wolvers Fault to the Collendean Farm Fault, and the Collendean Farm Fault to the Horse Hill Fault (dashed green lines).

HHDL did not use the old seismic line ESO-021(1). This line confirms the E-W trend of the Wolvers and Collendeam Farm Faults, and also proves the existence of the continuation of the Horse Hill Fault from east to west through HH-1.

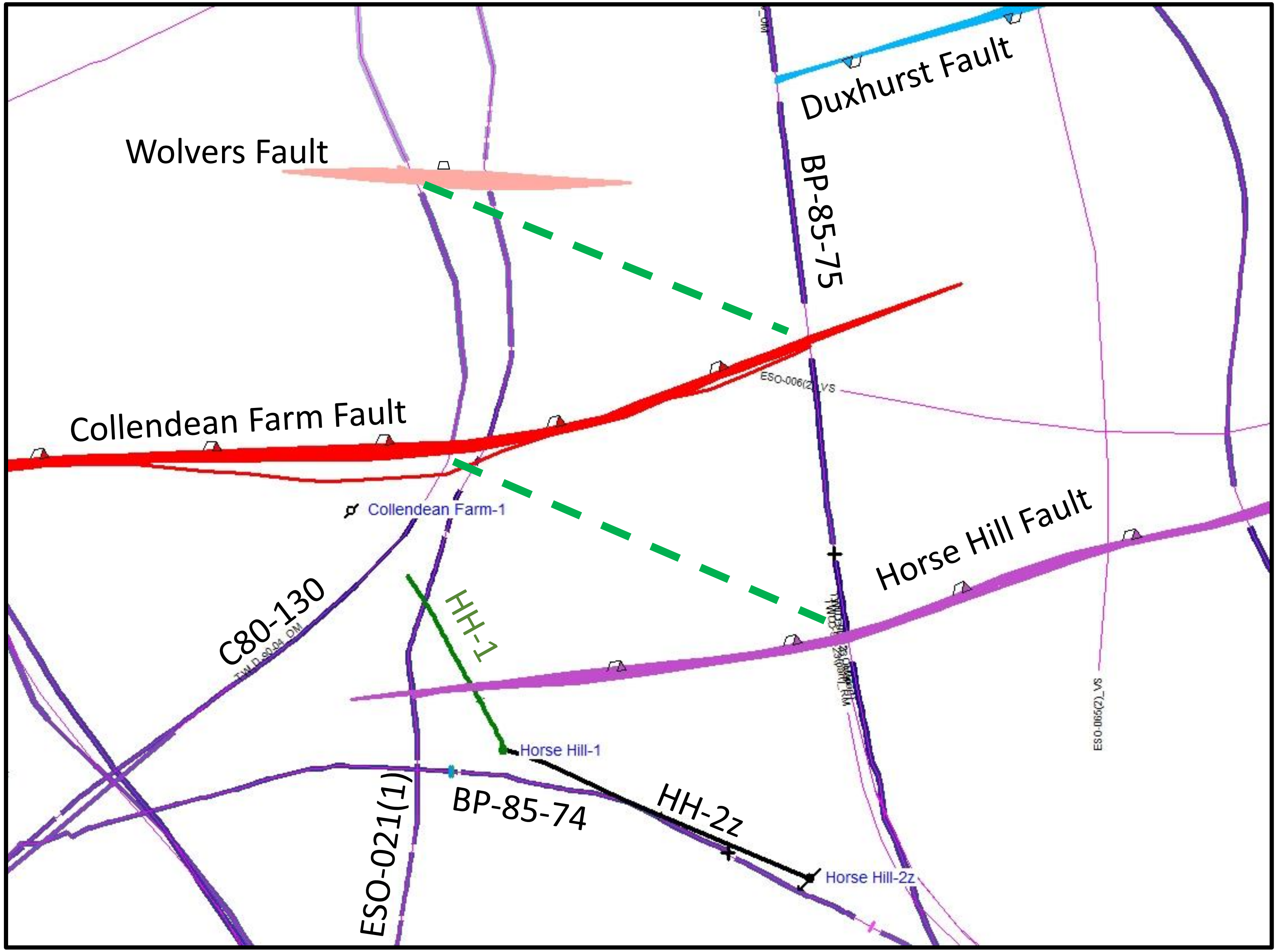


Figure 5.

Horse Hill development plans

Compare HHDL's planning application cartoons (Figures 7-9 below) with this typical US 'well plat'.

This is a surveyor's plan showing the exact trajectory, land ownership, etc. of the proposed horizontal well, highlighted in yellow

Such well plats are mandatory in Pennsylvania, Texas, Colorado, North Dakota, and no doubt other states as well.

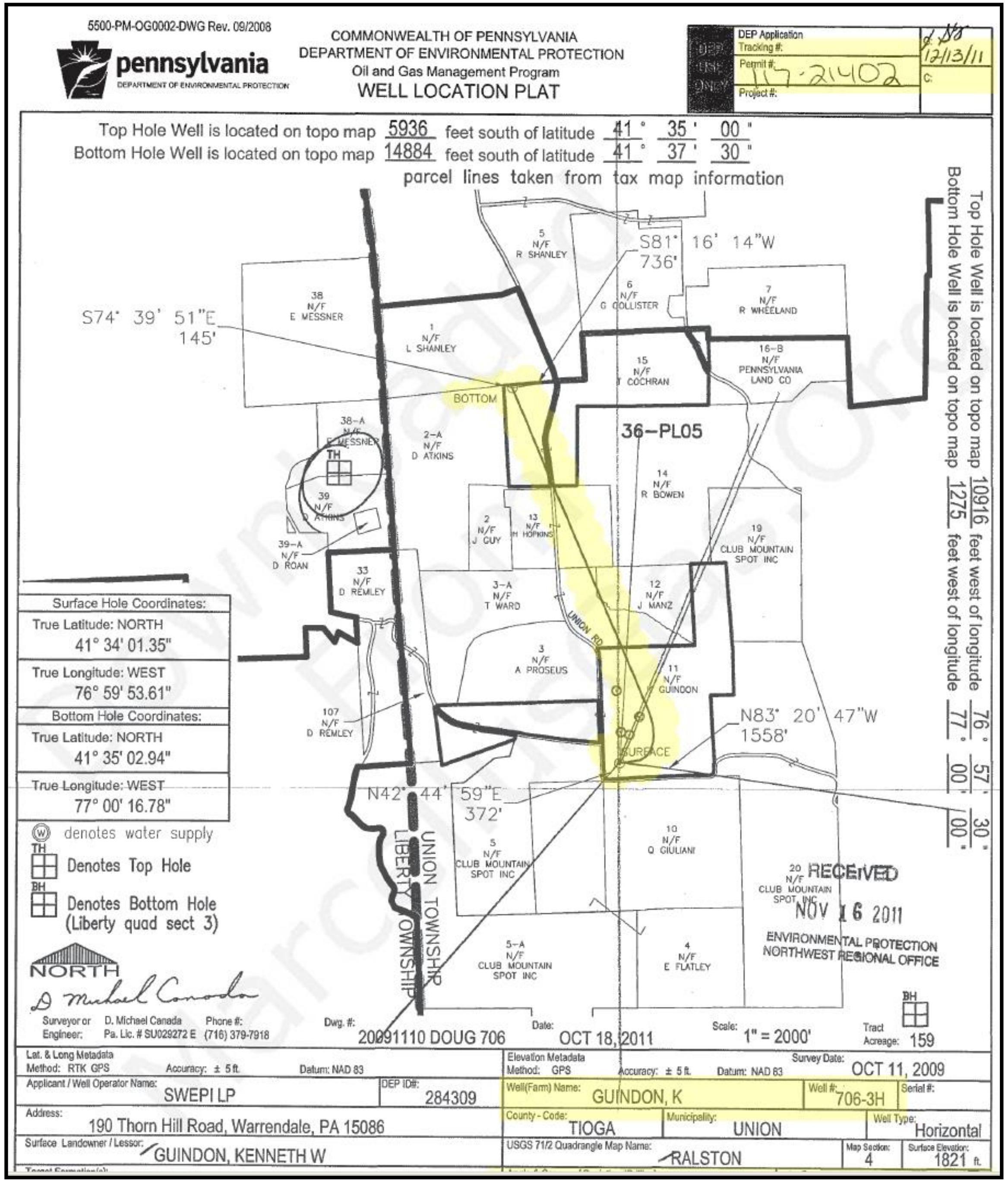
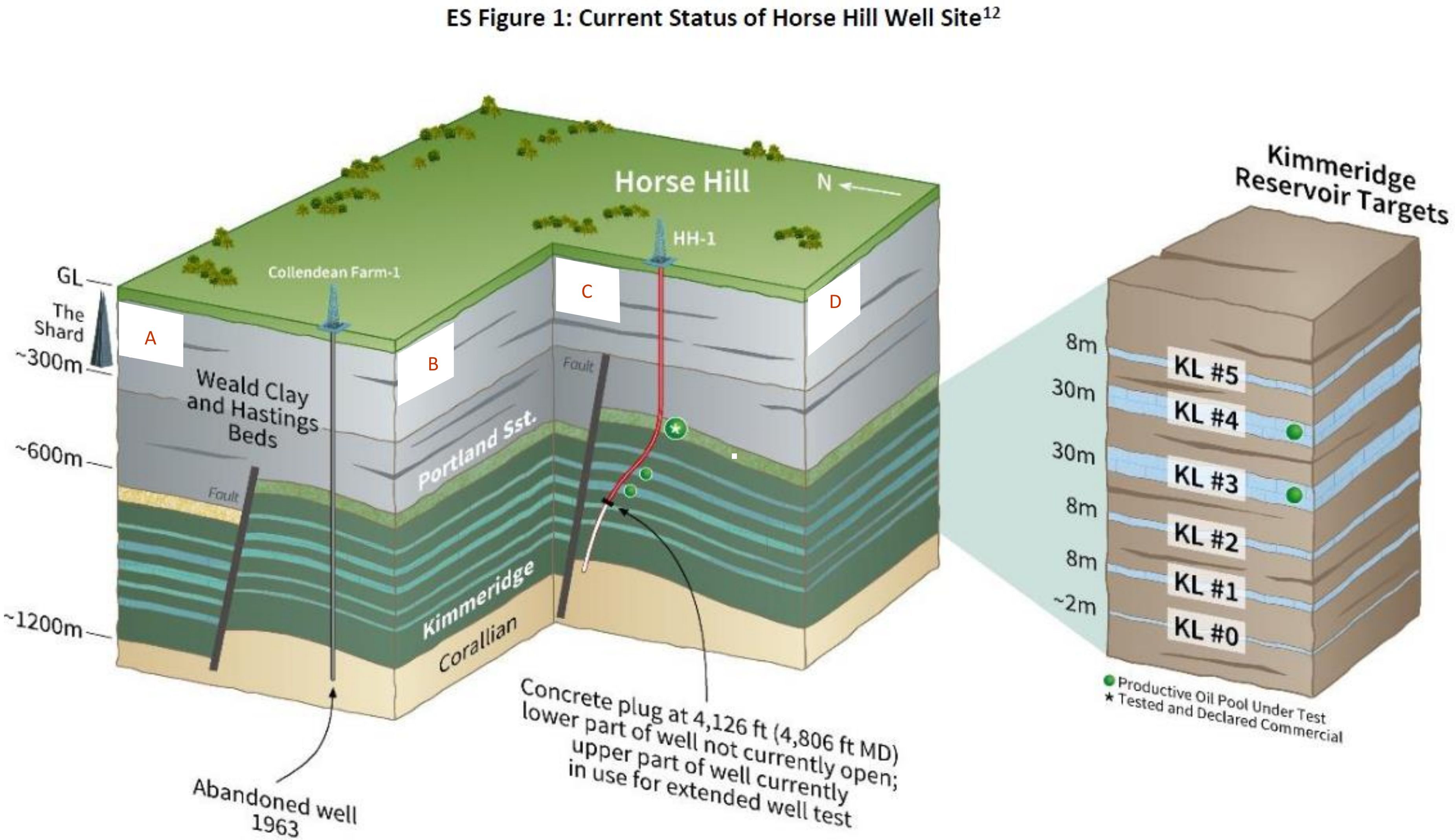


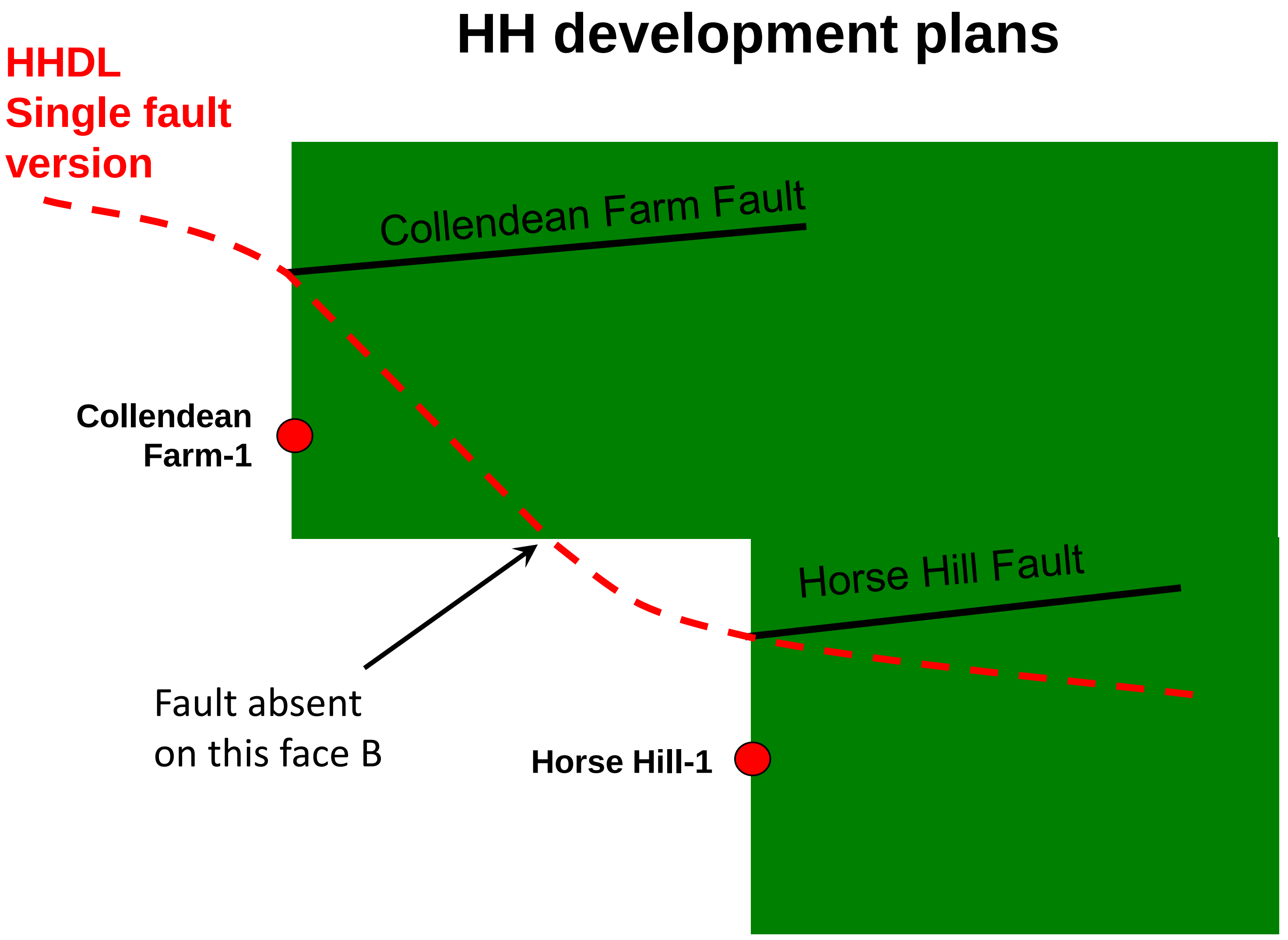
Fig. 6

HH development plans



This cartoon implies two separate faults, because if there were only one fault it should intersect the south-facing vertical section B.

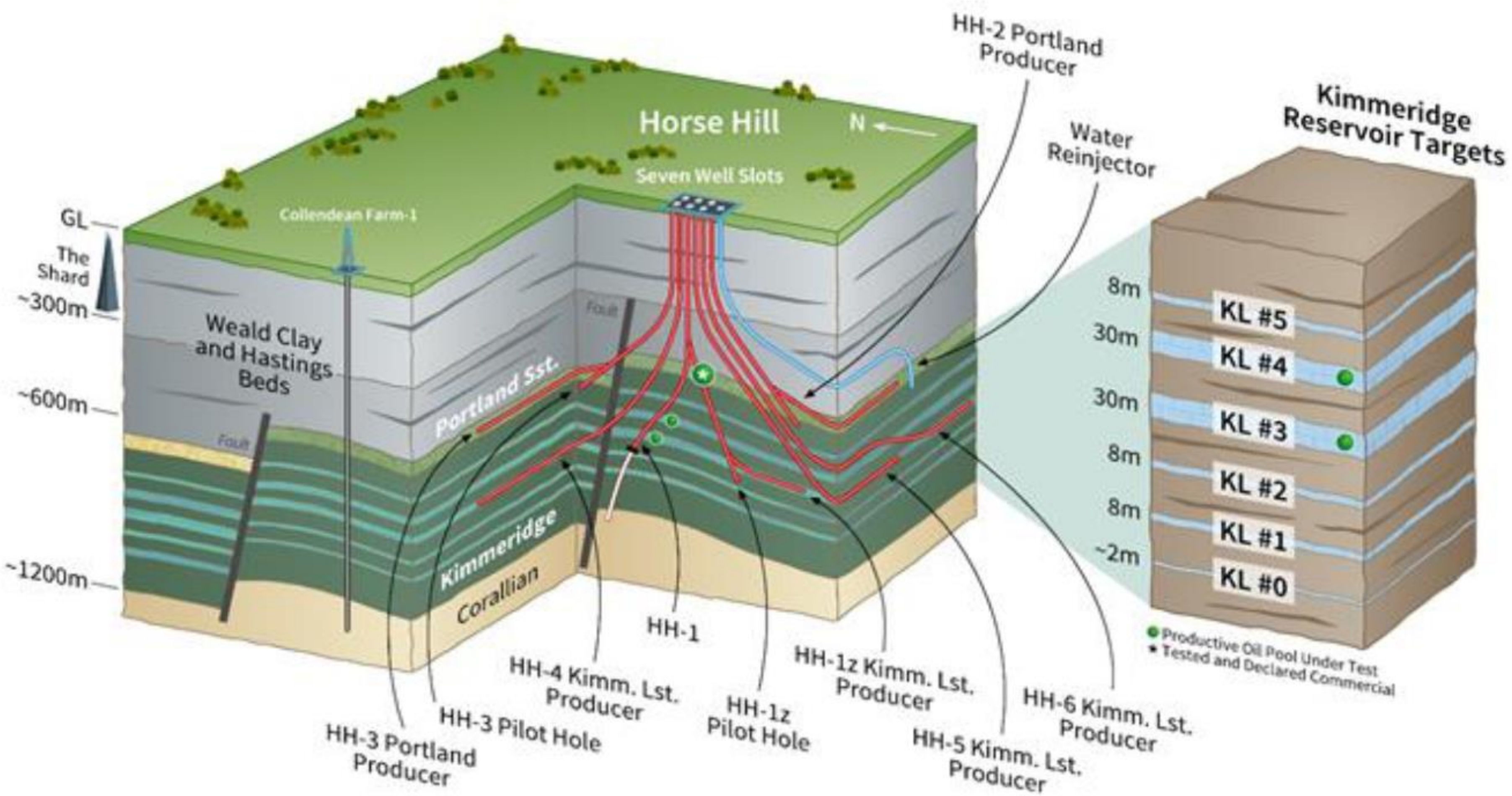
Fig. 7



Plan view of Figure 7, demonstrating that the HHDL single fault version (red dashed line) is internally inconsistent, even though CF-1 is now correctly positioned on the south side of the Collendean Farm Fault.

Fig. 8

HH development plans, late 2018



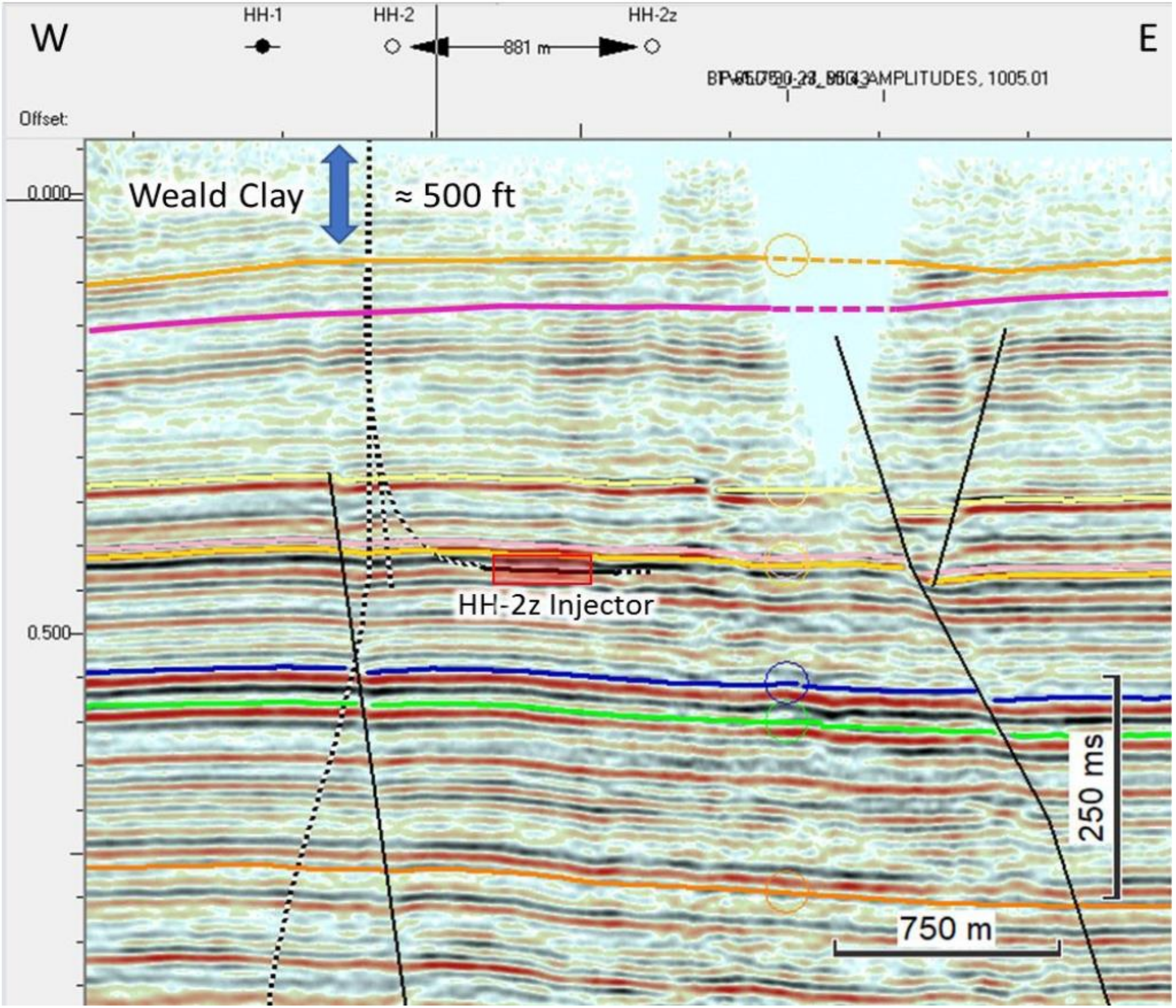
ES Figure 5: Proposed Development at Horse Hill Well Site[12]

Fig. 9

This cartoon grossly is insufficient in detail for a serious production planning application.
But the required detail has not been submitted.

HHDL interpretation along HH-2z

Wells (dashed black/white lines) are projected onto the reprocessed version of seismic line BP-85-74.
The injection zone of HH-2z is shown by the orange box within the Portland Sandstone.
Three faults (black) are interpreted by HHDL.



Toggle between this image and the next image to compare interpretations

Figure 10

Seismic line BP-85-74_OS, as mapped and interpreted by myself. The coloured faults are:
Brittleware Farm – light blue
Ferrier's Forge – lilac
Horley – orange
Other faults are depicted in black.

The projected tracks of HH-1 and HH-2z are shown by green/white dashed lines. The proposed injection zone is shown by the red rectangle

Toggle between this image and the previous image to compare interpretations

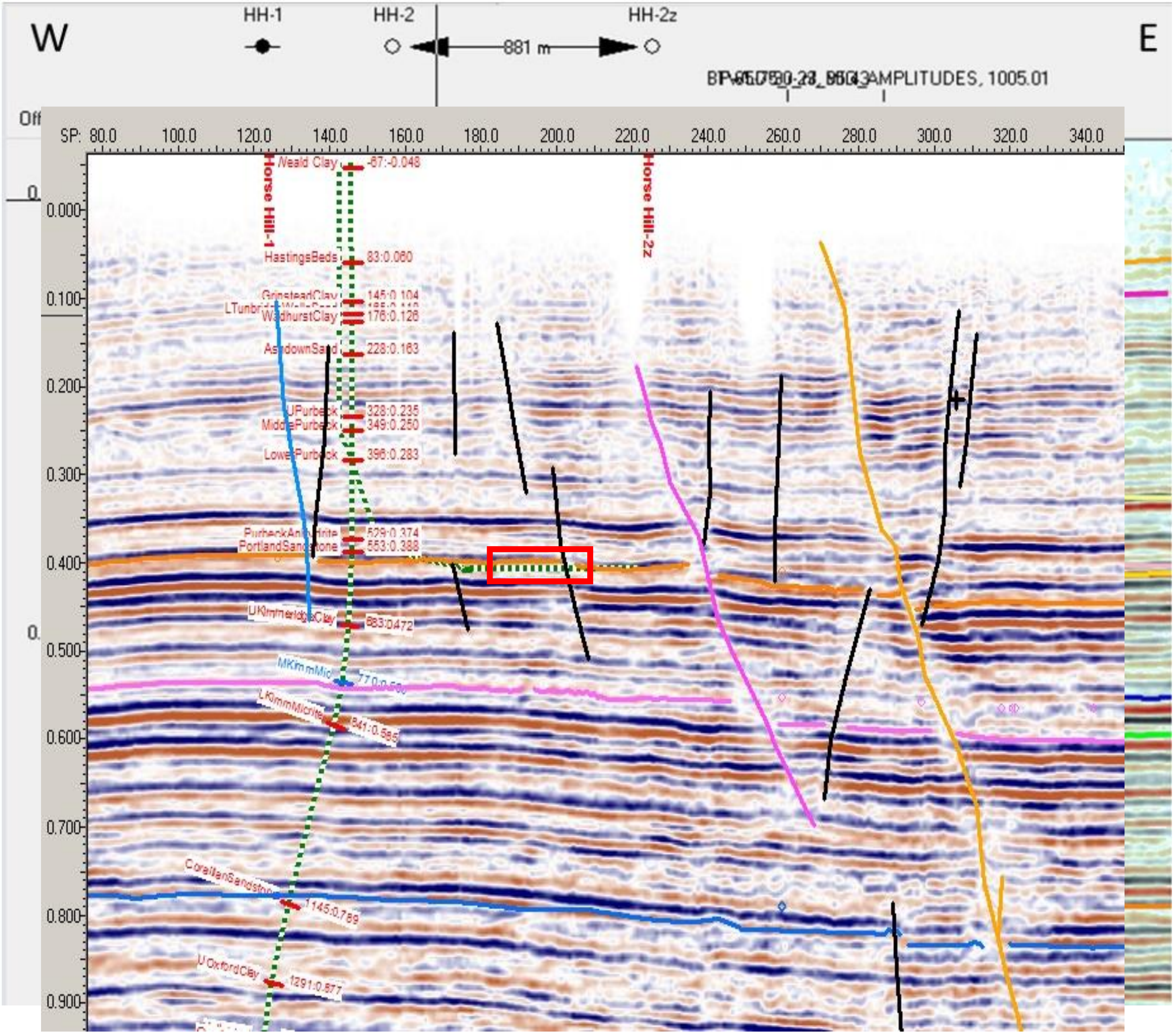


Figure 11

Detail of BP-85-74 showing proposed injection zone

The Brittleware Farm Fault is shown in light blue. It may correspond locally to the splay fault interpreted by HHDL (Figure 4 above).

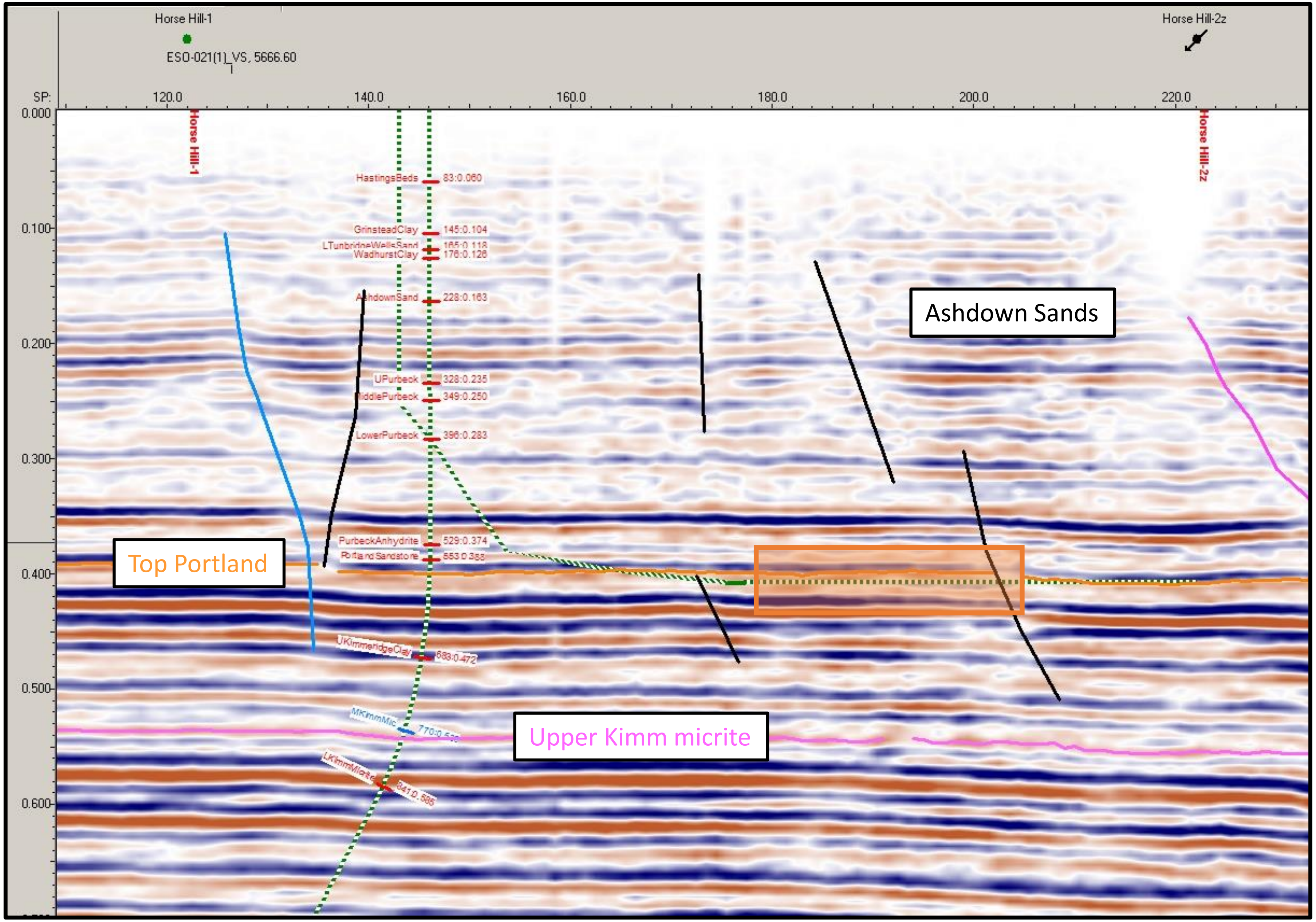


Figure 12

Broadford Bridge

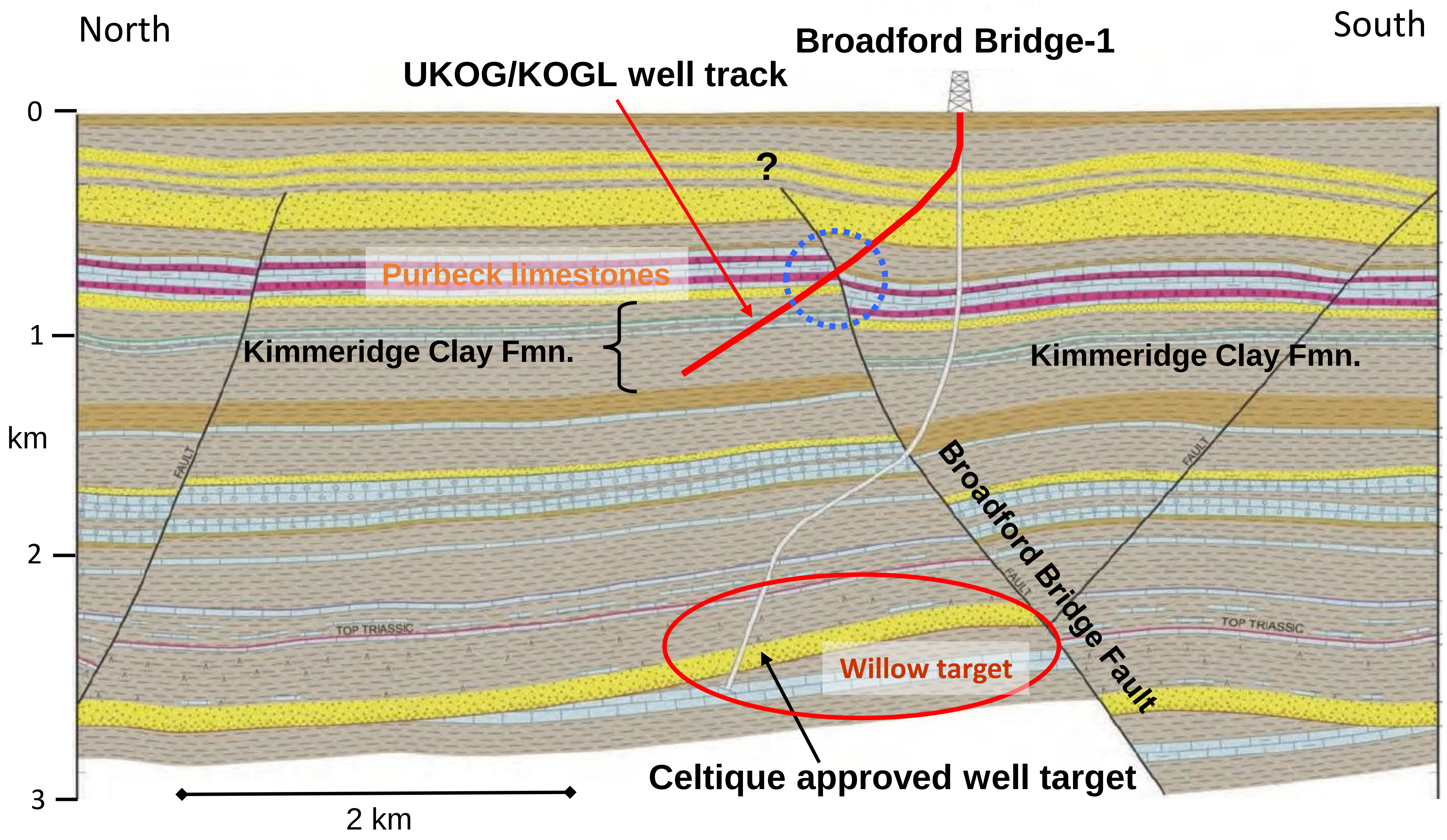


Figure 13

UKOG subsidiary KOGL illegally flouted the permit conditions, drilling a very steeply inclined well at a different azimuth to test the Kimmeridge Clay Formation and not the permitted 'Willow' conventional target. In doing so it encountered borehole washout problems because they were crossing the Purbeck Limestones at a fault zone. KOGL then had to sidetrack. The next diagram (Fig. 4.2) shows a reconstruction of the main well and the sidetrack.

Broadford Bridge

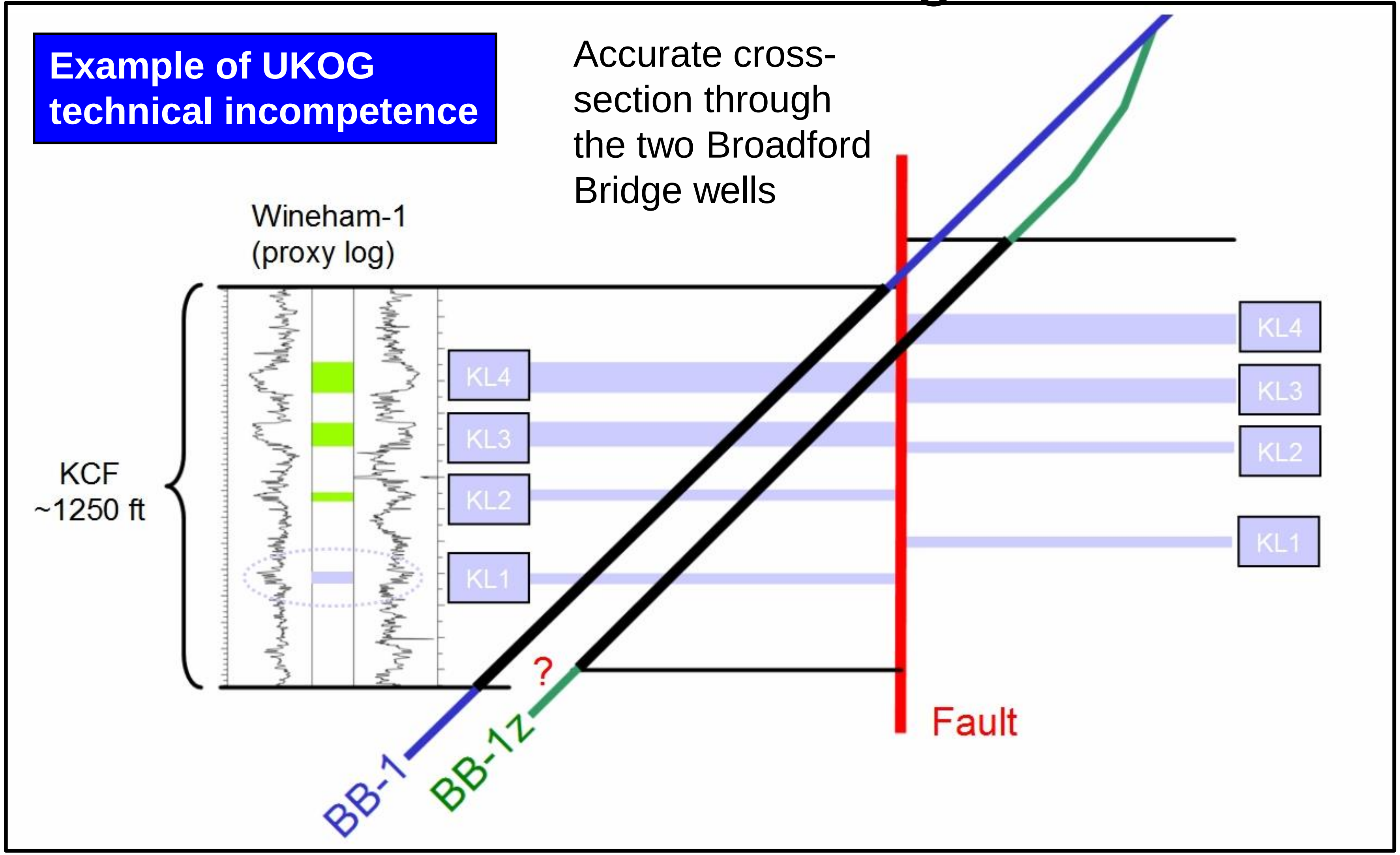


Figure 14

UKOG / KOGL Broadford Bridge drilling fiasco
I have interpolated the tops for the micrites by using nearby Wineham-1 as a proxy, scaled to the Kimmeridge Clay Formation thickness here. The light green micrites are as recognised by the BGS. KL1 is dubious; My explanation of the fifth 'limestone' seen by KOGL is that KL4 has been penetrated twice by going through a fault, so that UKOG's KL5 = KL4.

Cliffs at Kimmeridge Bay, Dorset

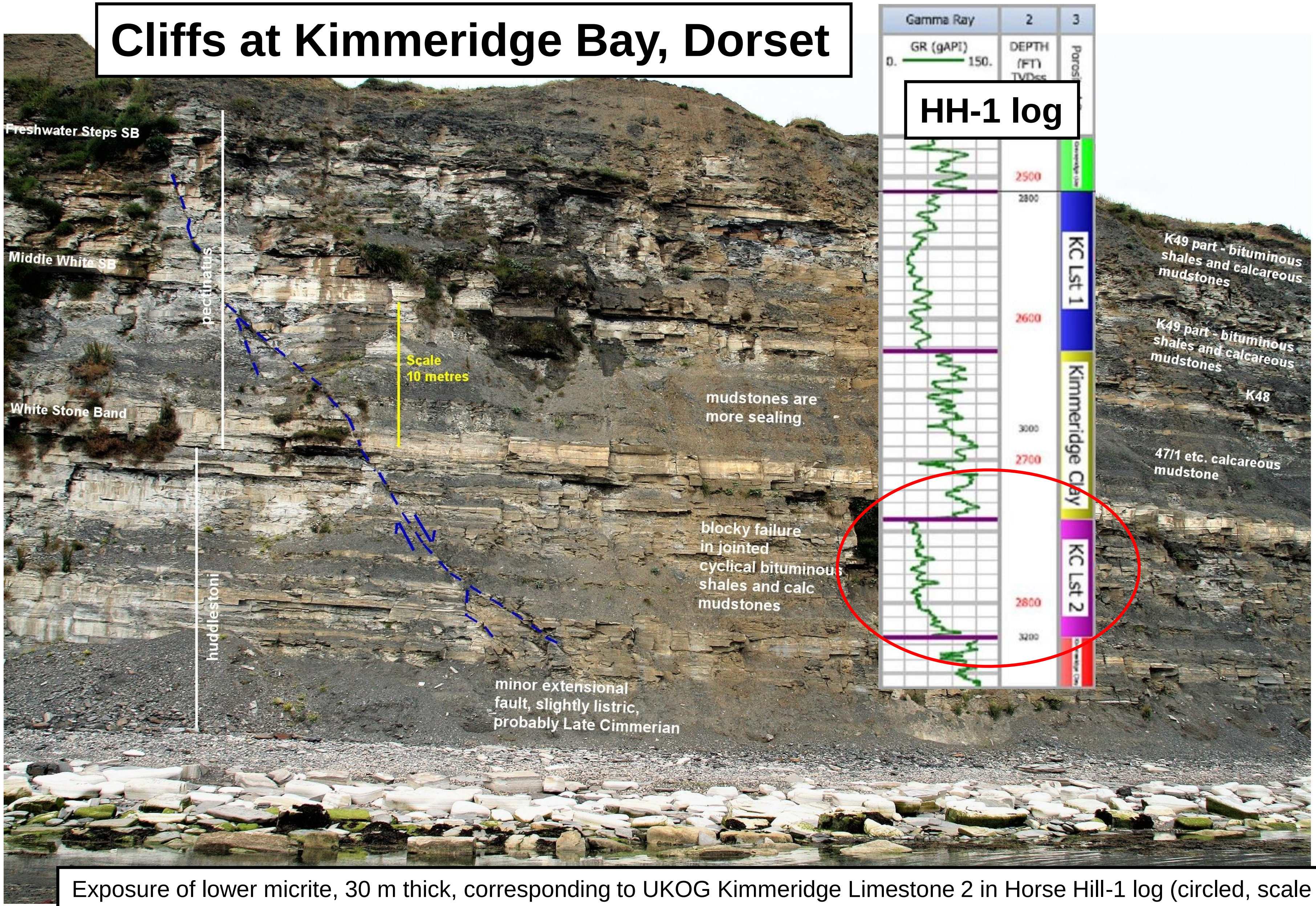


Fig. 15

Exposure of lower micrite, 30 m thick, corresponding to UKOG Kimmeridge Limestone 2 in Horse Hill-1 log (circled, scale in feet). In detail, the exposure comprises calcareous mudstones with thin sandstone bands. My log correlation from the borehole at Southard Quarry, just inland from this picture, along 2D and 3D seismic via the Isle of Wight to the Weald confirms that the micrites at depth in the Weald are essentially the same as shown here. Photo © Ian West 2011.

Acidising – ugly sister of fracking

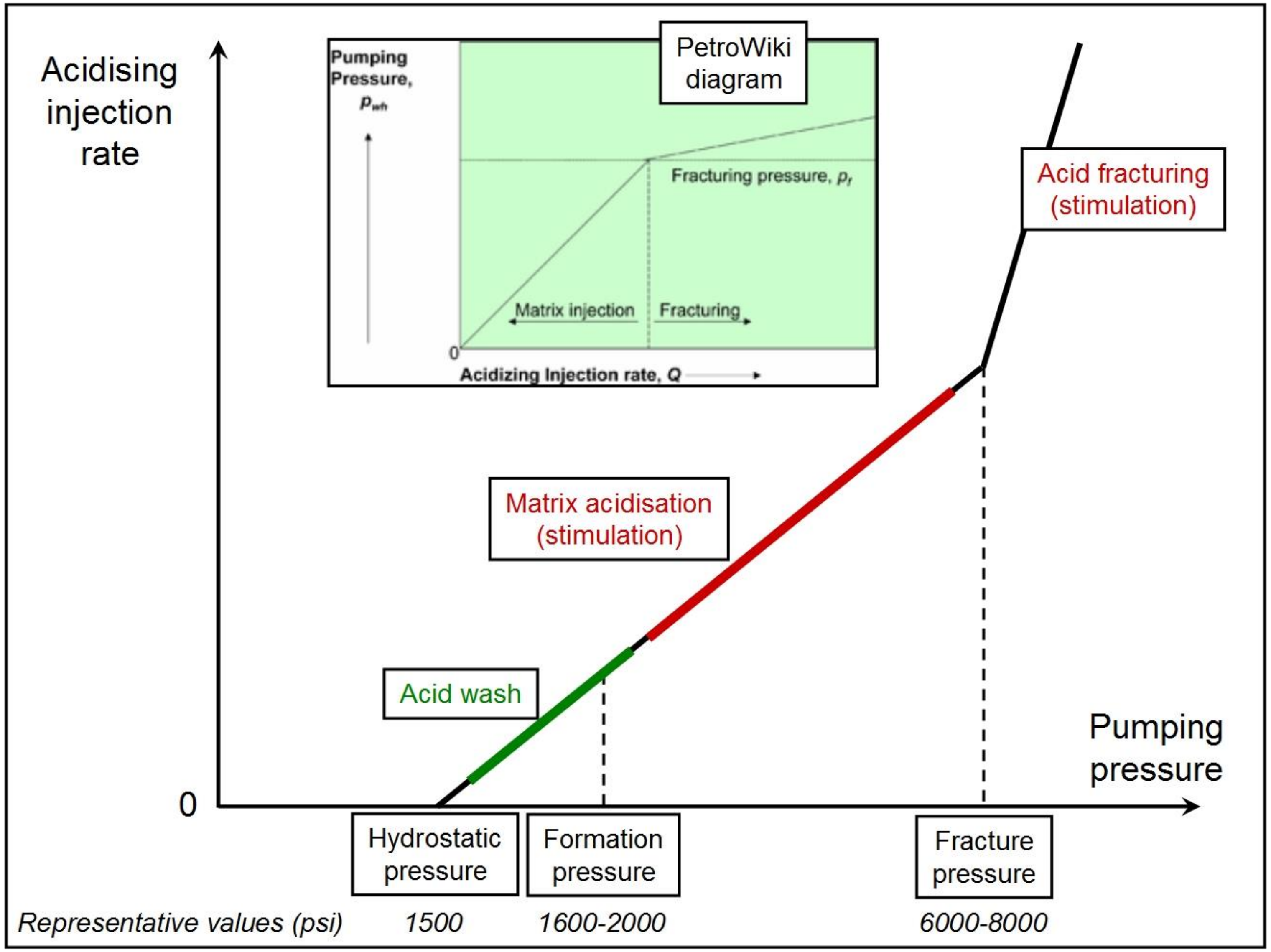
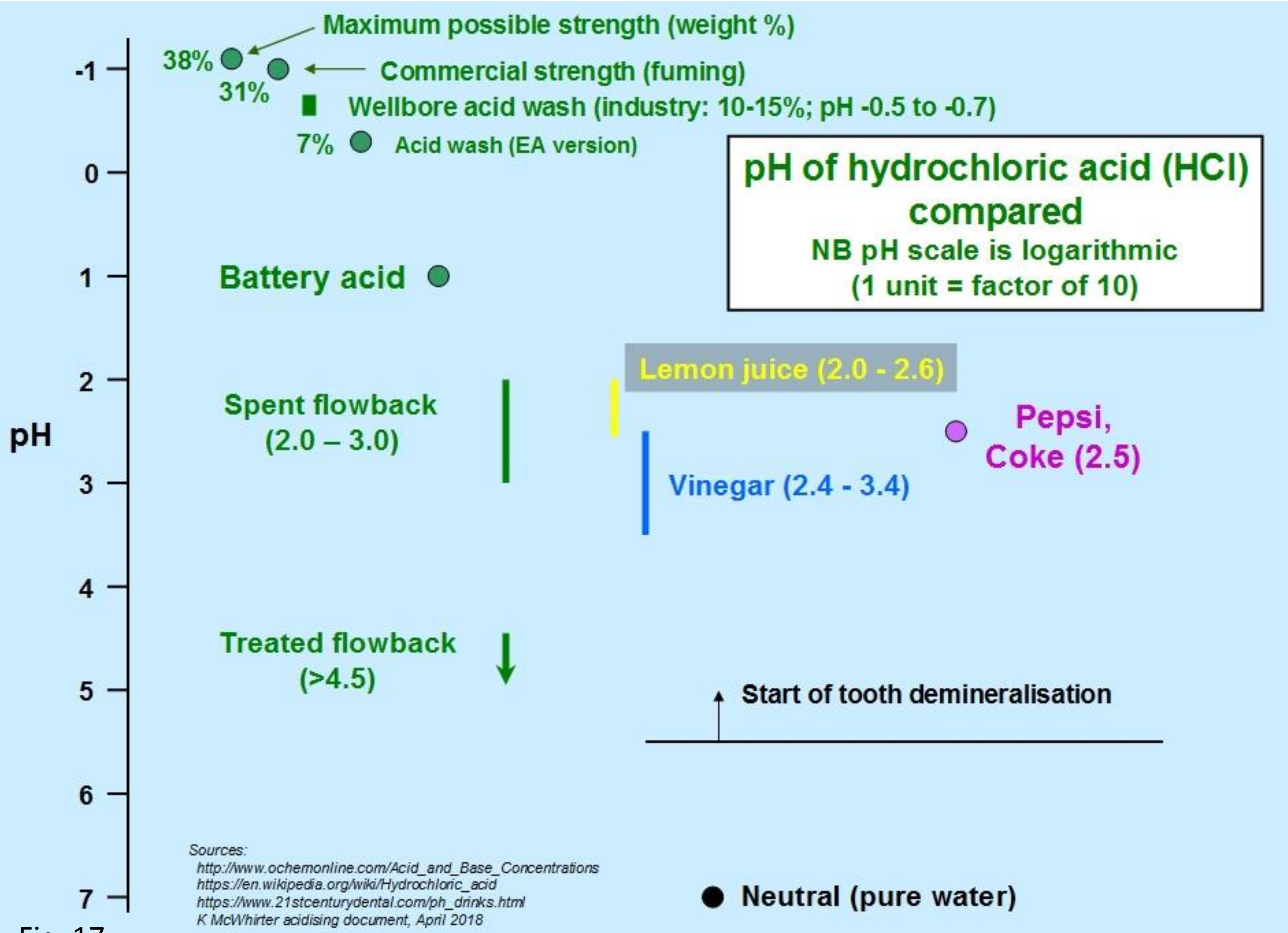


Fig. 16 Difference between an acid wash (green) and matrix acidisation (red), depending on the pumping pressure.



Maximum possible strength (weight %)
38%
Commercial strength (fuming)
31%
Wellbore acid wash (industry: 10-15%; pH -0.5 to -0.7)
7%
Acid wash (EA version)
pH of hydrochloric acid (HCl) compared
NB pH scale is logarithmic
(1 unit = factor of 10)
-1
0
1
2
3
4
5
6
7
pH
Battery acid
Lemon juice (2.0 - 2.6)
Spent flowback
(2.0 – 3.0)
Pepsi,
Coke (2.5)
Vinegar (2.4 - 3.4)
Treated flowback
(>4.5)
Start of tooth demineralisation
Sources:
http://www.ochemonline.com/Acid_and_Base_Concentrations
https://en.wikipedia.org/wiki/Hydrochloric_acid
https://www.21stcenturydental.com/ph_drinks.html
K McWhirter acidising document, April 2018
Neutral (pure water)

Fig. 17

Interpretation of line ESO-021(1), suggesting that the Horse Hill Fault intersects the lower deviated portion of HH-1 (green line). The fault may splay into two or more parts as it dies out westwards.

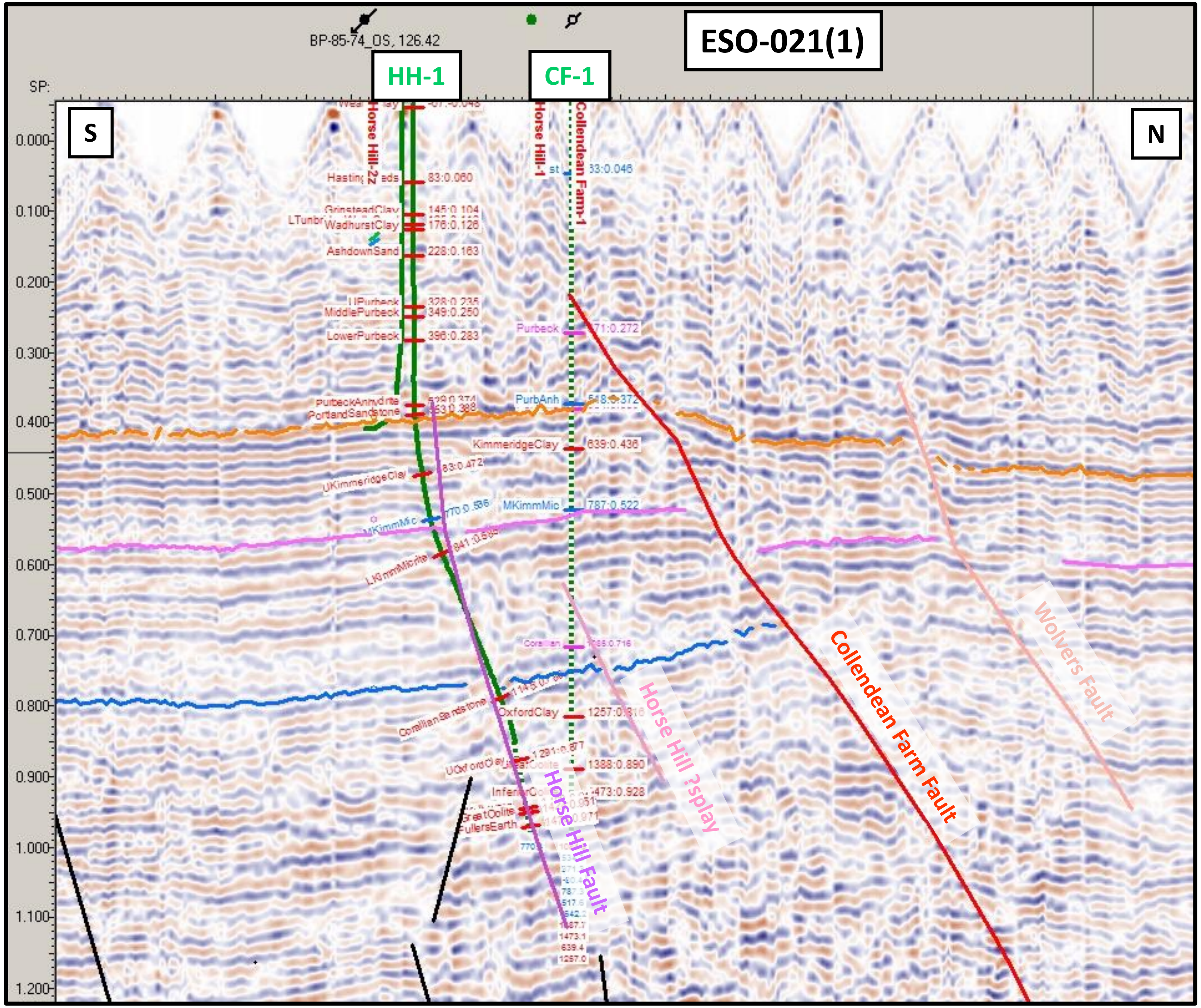


Fig. 18

Contours (TWT in seconds) on the Horse Hill Fault. It terminates in the vicinity of line ESO-021(1) shown in Fig. 18, and here may splay into two or more strands. The portion of ESO-021(1) shown in Figure 18 is highlighted in blue.

The inset shows proposed HH-3, from HHDL's Top Portland structure contour map. The shaded fan-shaped sector shows the possible azimuthal range.

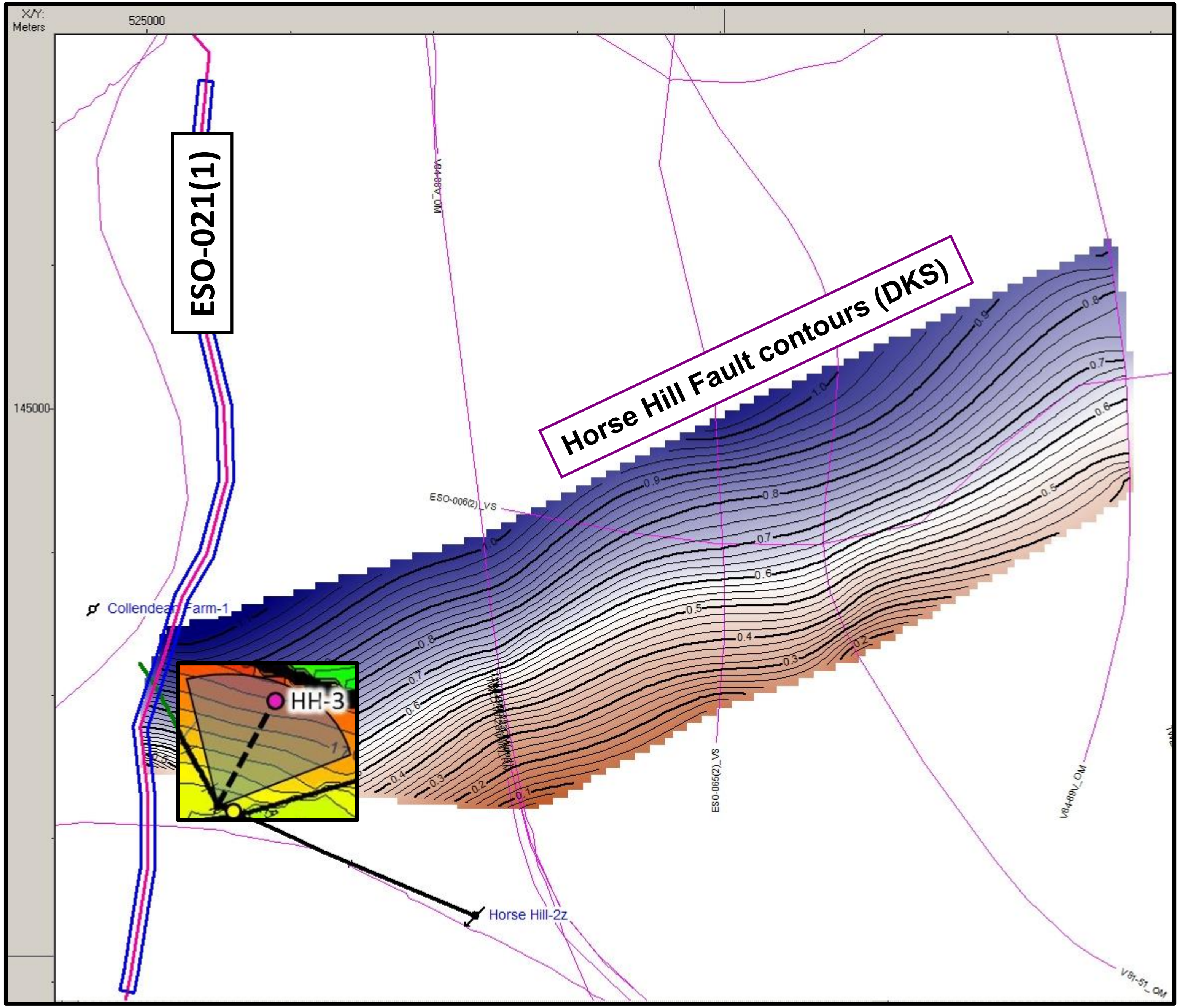
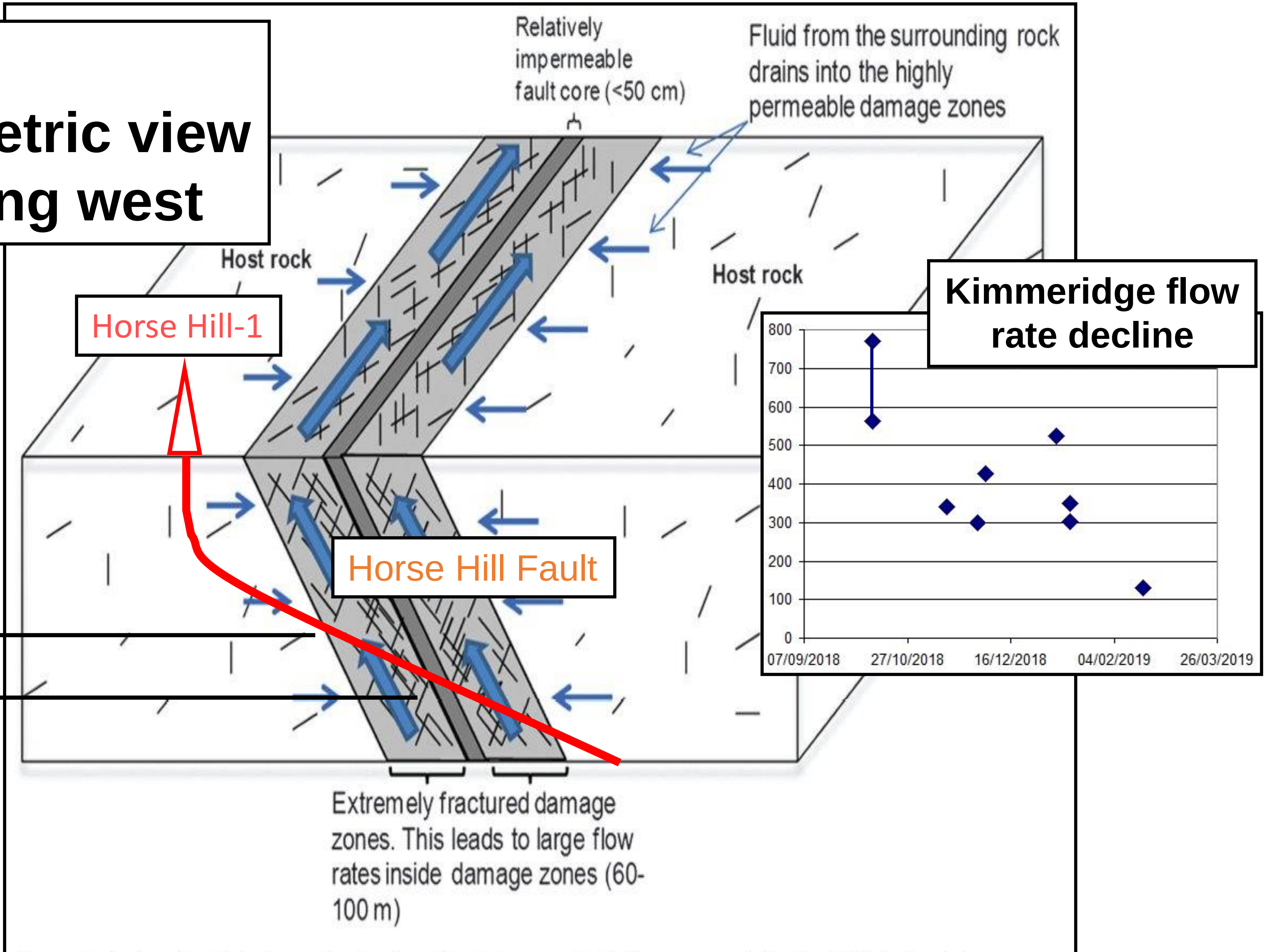


Fig. 19

HH-1 Isometric view looking west



Approximate depths:

Mid Kimm micrite

Corallian

Fig. 20

HH-1 was drilled c. 200 m south of the Horse Hill Fault, and deviated north into fault damage zone, accounting for the temporary high flow in the Kimmeridge Clay Formation, as predicted by myself in August 2017. Similarly, the high flow was predicted to be of short duration. The rapid decline in flow of the Extended Well Test is shown in the inset, again, to be expected from drilling a fault zone.

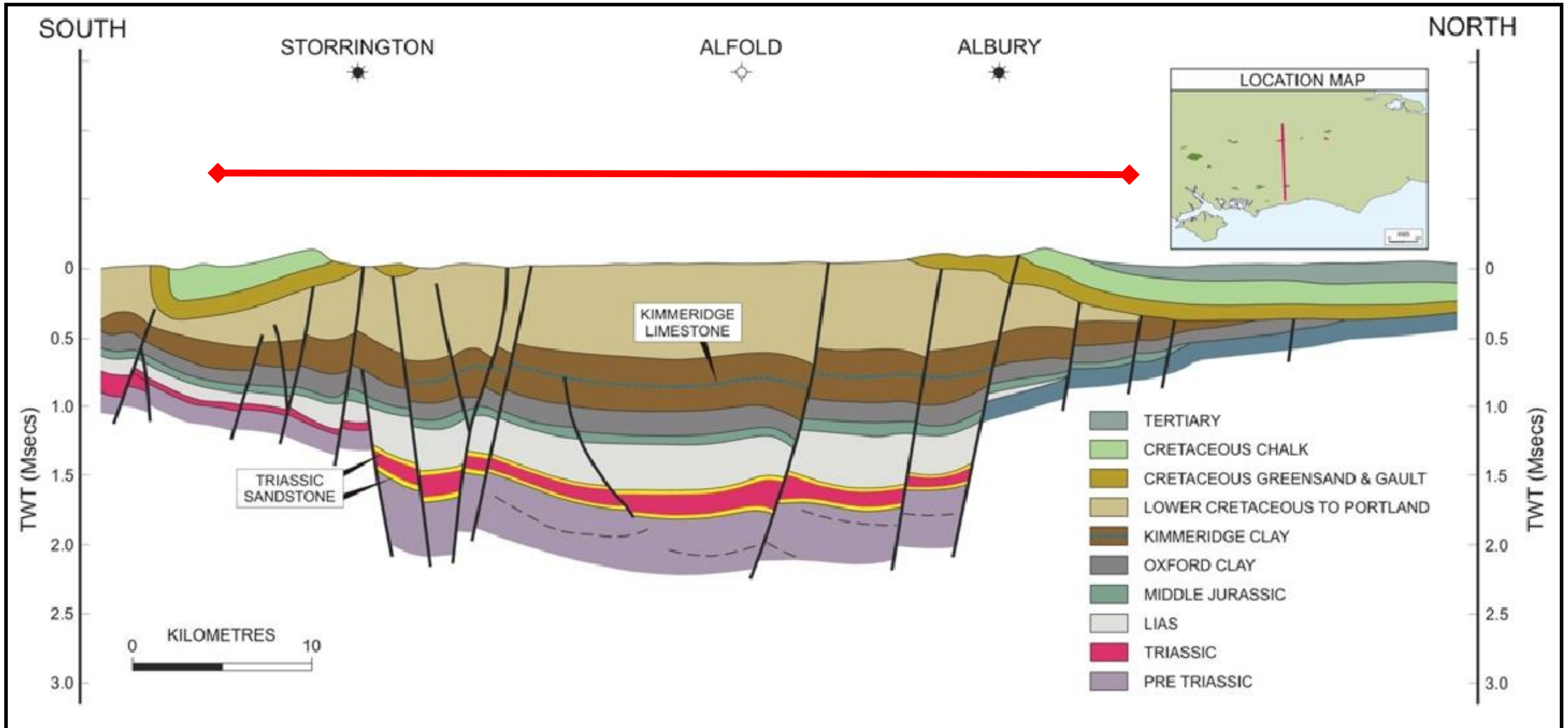
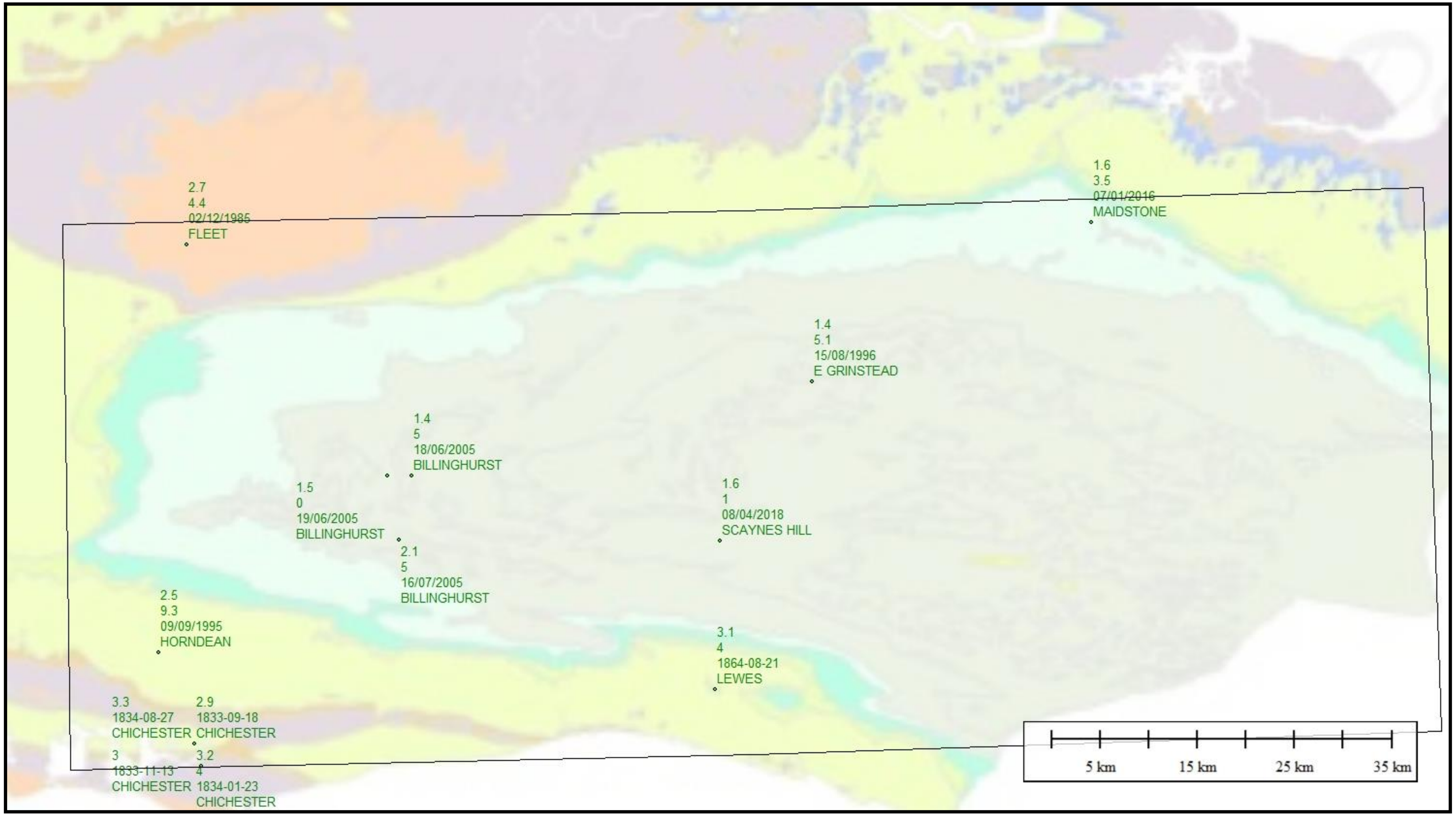


Fig. 2. Geological cross-section of the Weald Basin. After Butler & Jamieson (2013, plate 1).

Regional seismic profile across the Weald depicted by Pullan and Butler (2018). The N-S geological limit of the Weald Basin is shown approximately by the red line.

Fig. 21



Results of search of the BGS catalogue for all earthquakes since 1700 (green annotated dots) within the bounding rectangle, superimposed upon the solid geology map of the Weald. The 2018-20 Newdigate events have been omitted.

Fig. 22

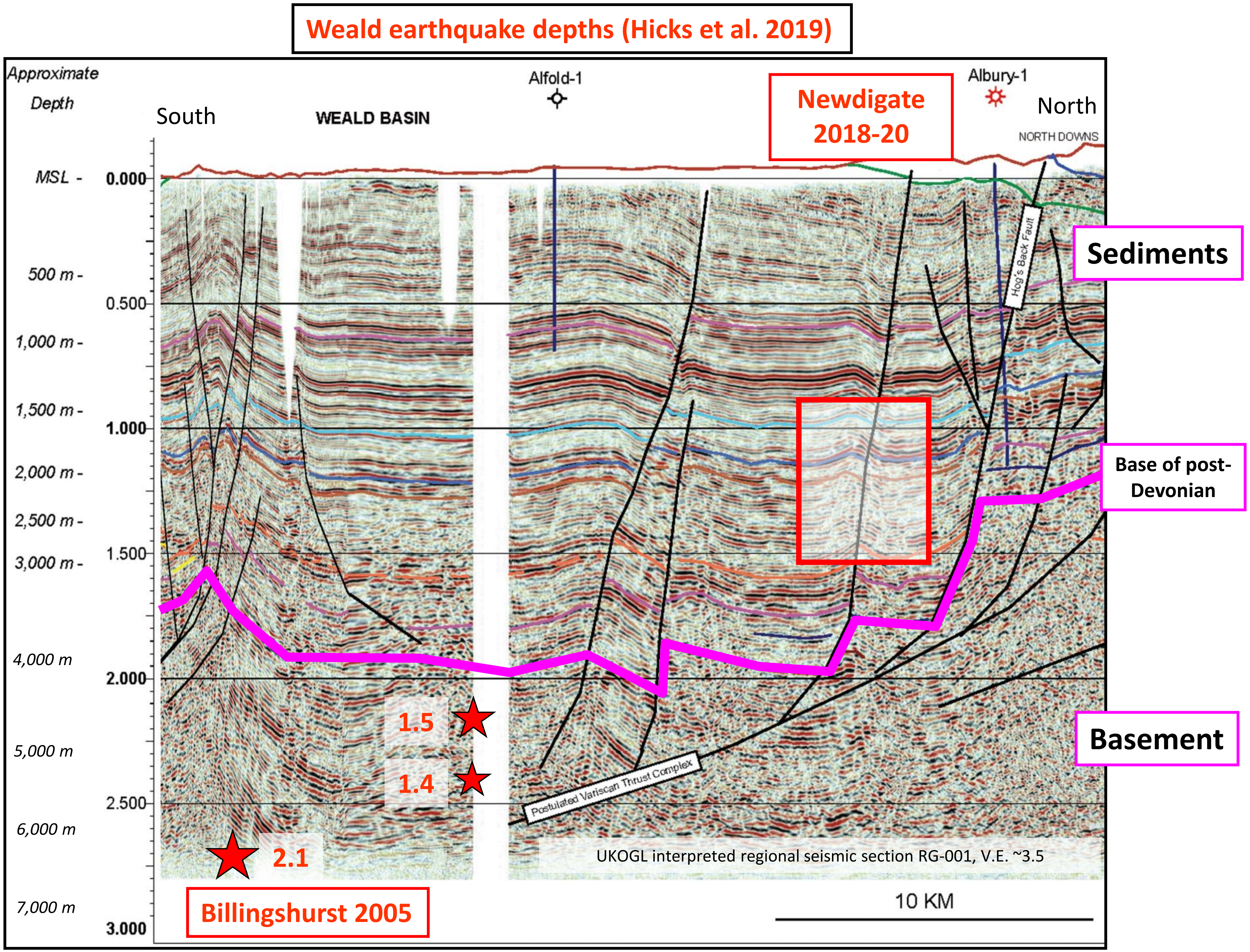

Weald earthquake depths (Hicks et al. 2019)
Approximate Depth
South
WEALD BASIN
Alfold-1
Newdigate 2018-20
Albury-1
North
NORTH DOWNS
MSL -
500 m -
1,000 m -
1,500 m -
2,000 m -
2,500 m -
3,000 m -
4,000 m
5,000 m
6,000 m
7,000 m
0.000
0.500
1.000
1.500
2.000
2.500
3.000
Hog's Back Fault
Sediments
Base of post-Devonian
Basement
1.5
1.4
2.1
Postulated Variscan Thrust Complex
UKOGL interpreted regional seismic section RG-001, V.E. ~3.5
Billingshurst 2005
10 KM

Fig. 23

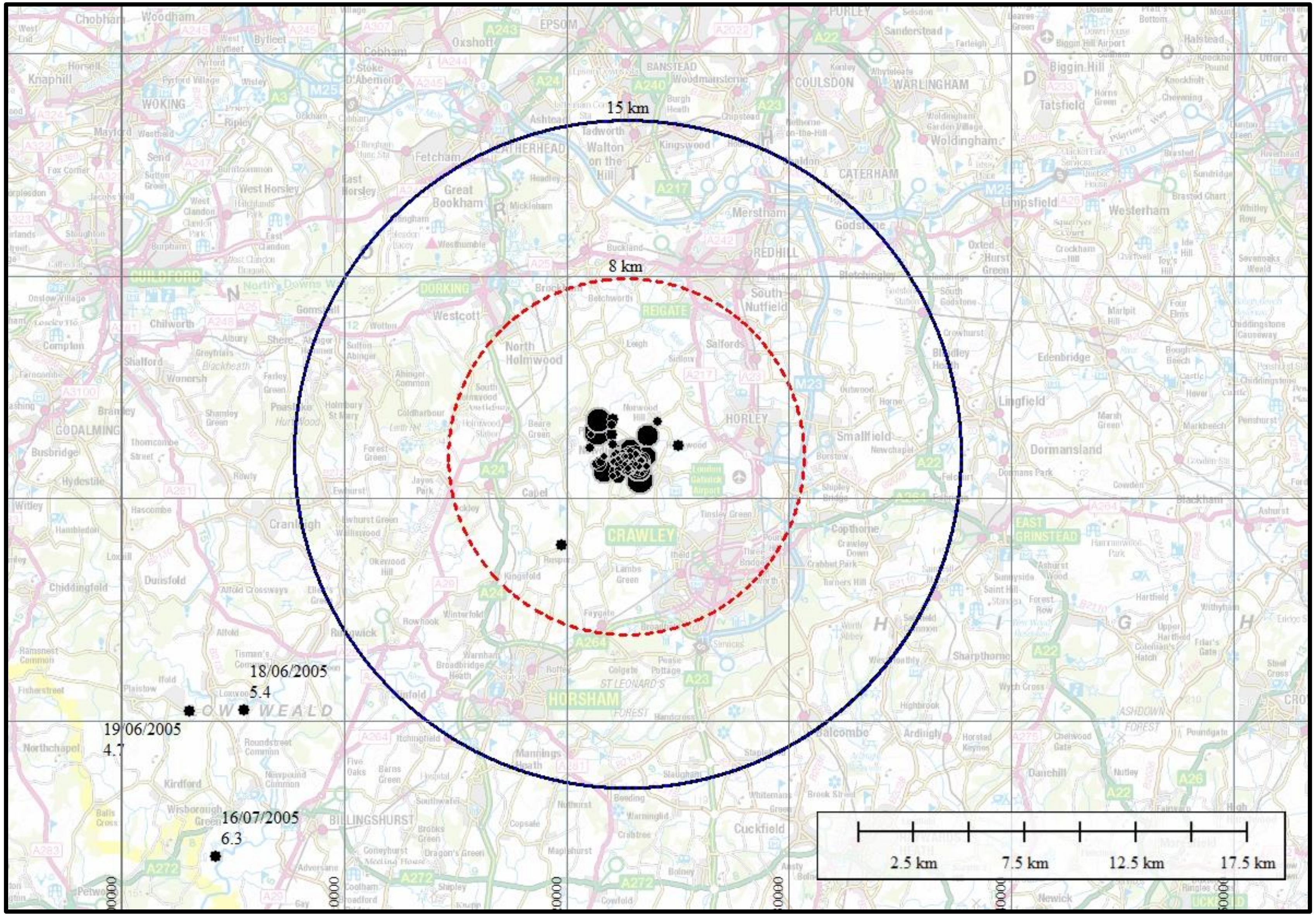
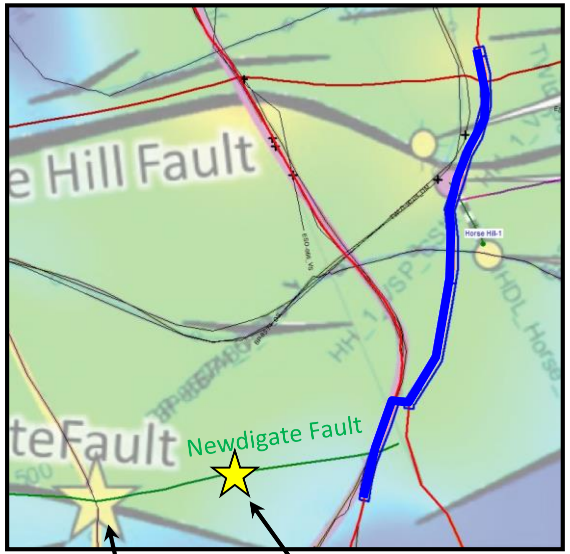


Fig. 24

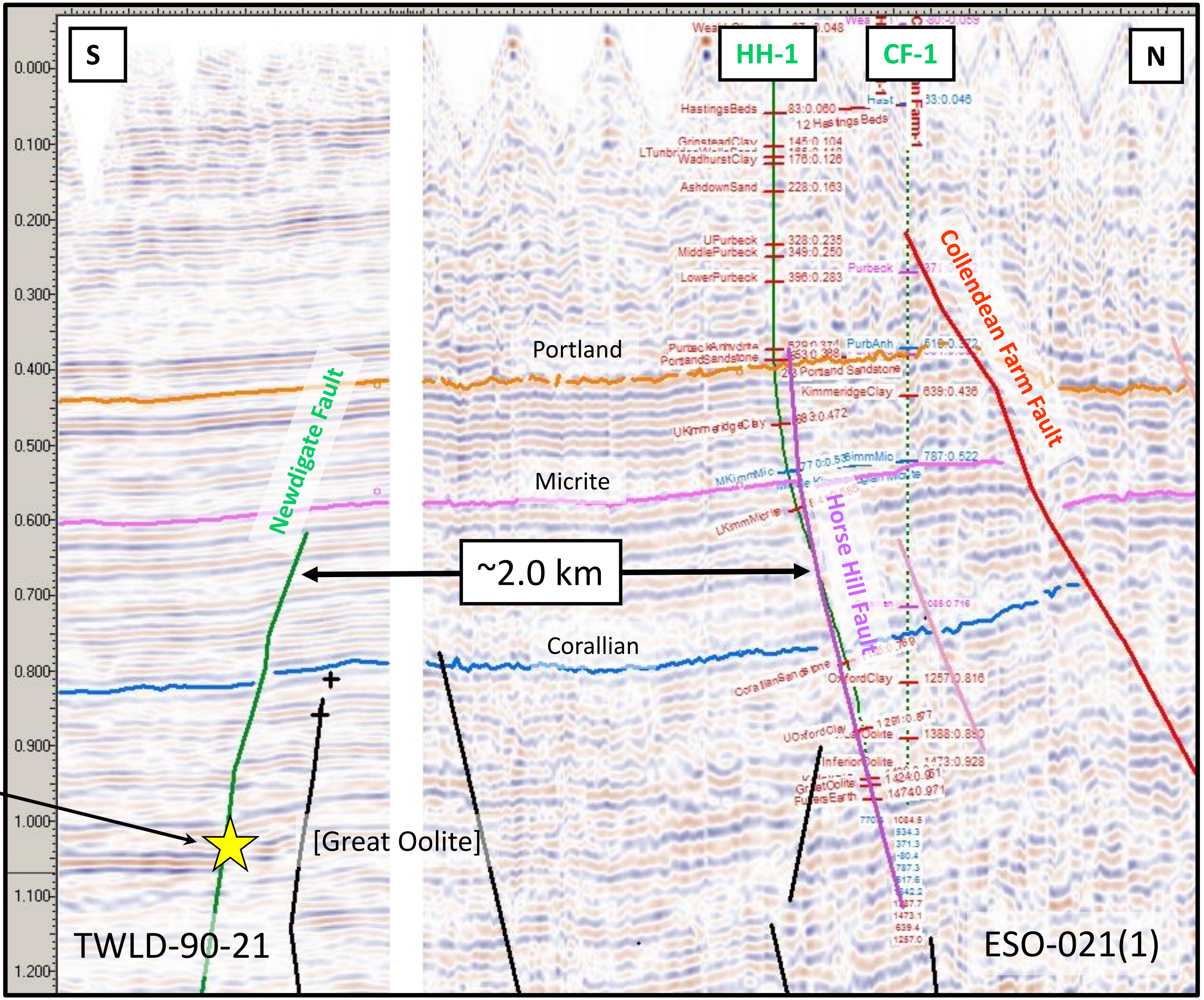
Newdigate earthquake swarm 2018-20 (black discs scaled by magnitude). Range rings of felt seismicity are drawn around the 27 Feb 2019 ML=3.1, depth=2.4 km (15 km radius, blue) and the 19 Feb 2019, ML=2.0, depth=2.4 km (8 km radius, red) Newdigate events. The three 2005 Billingshurst events are shown in black.

UKOG (2019) Top Great Oolite depth structure map



Wrong (UKOG) and correct location of 27 February 2019 earthquake

Tie-line (blue on map) from Newdigate Fault to Horse Hill along TWLD-90-21 and ESO-021(1)



Earthquake hypocentre projected east along Newdigate Fault ~1 km

Geological link from Newdigate earthquakes to Horse Hill

Fig. 25

Aerial view looking NE, 1 April 2018

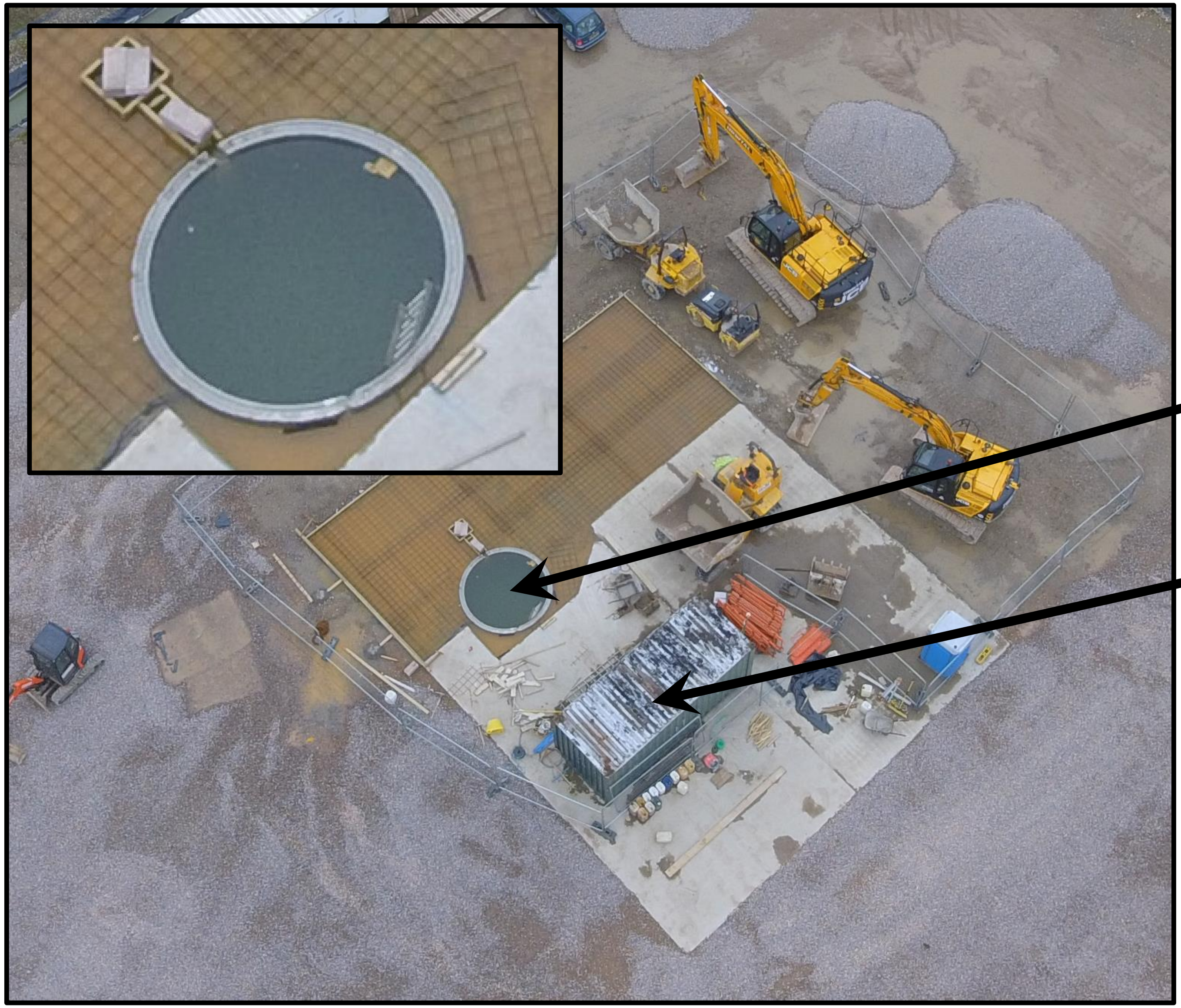
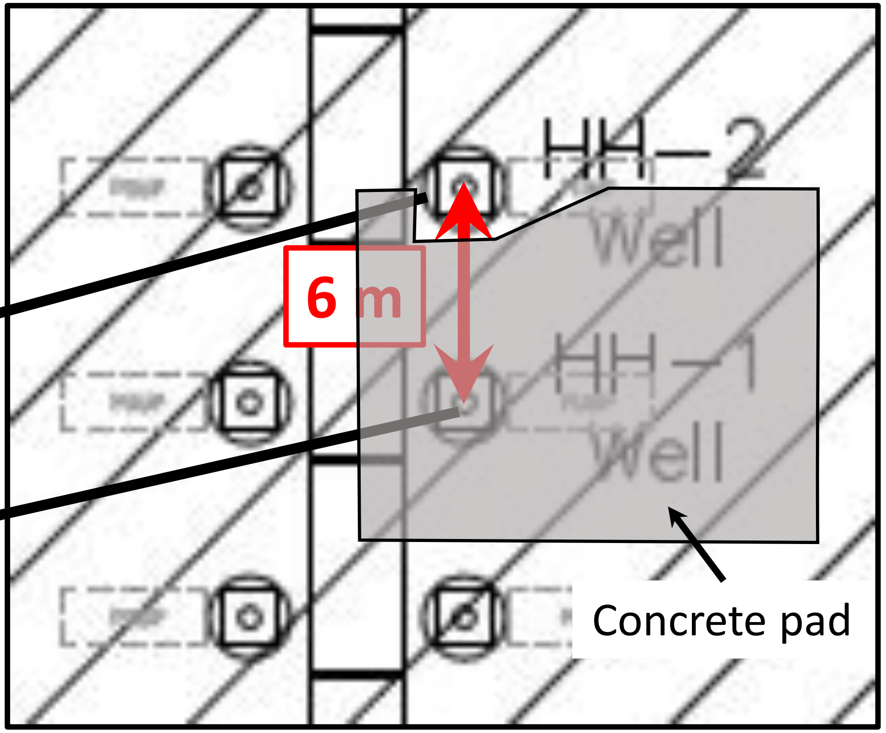


Fig. 26. Aerial view and plan of Horse Hill drill pad 2018



Extract of site plan (north up) showing locations of HH-1 and HH-2 wells. The cut-away existing pad has been added from the aerial viw.

The new cellar is full of greenish water. A ladder projects from the cellar (inset). The HH-1 wellhead is inside the cabin. The concrete pad has been cut back to make way for the new cellar. Note the reinforced wire mesh (visible in the inset) laid out prior to pouring concrete for extension of the pad to the north

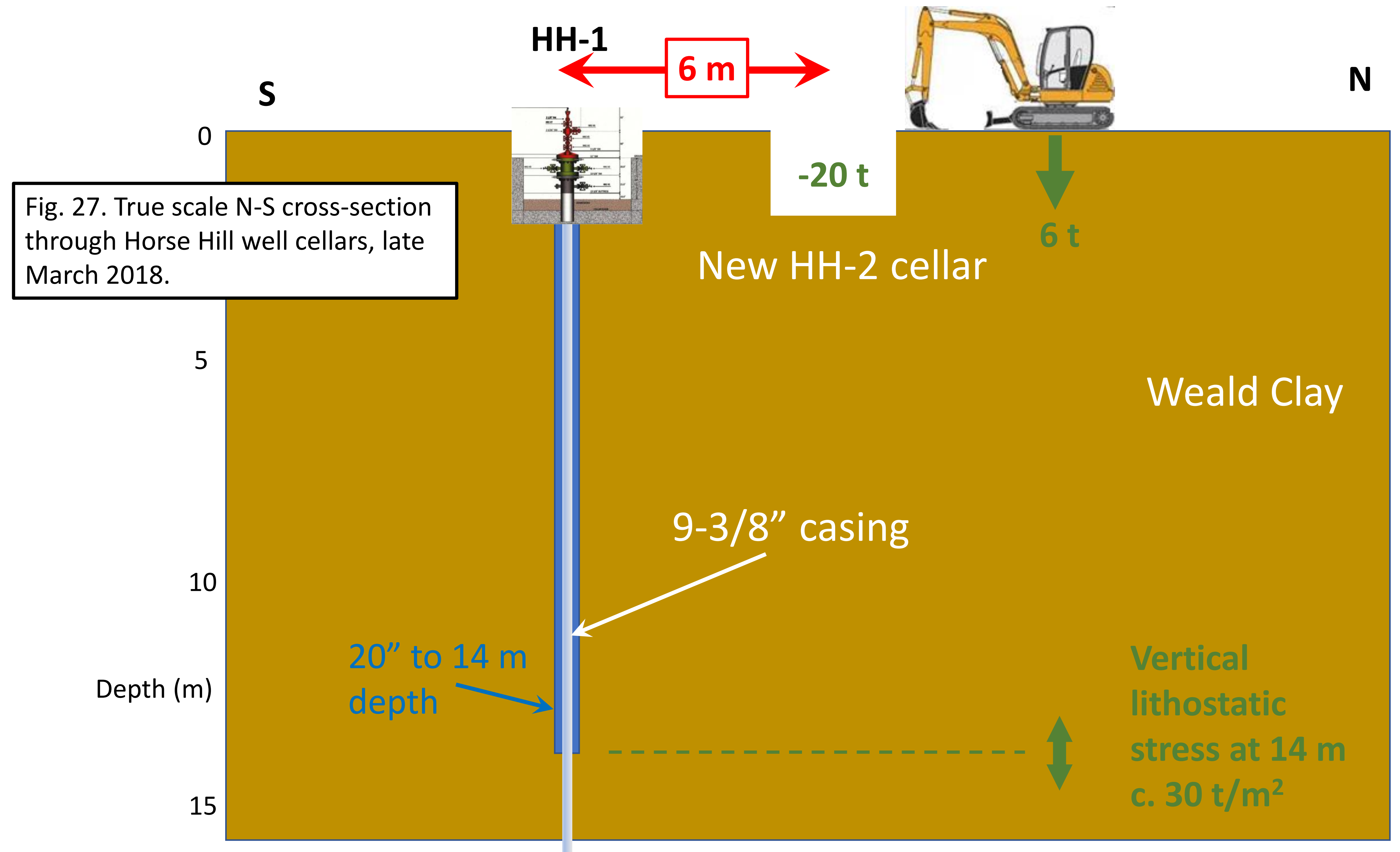


Fig. 27. True scale N-S cross-section through Horse Hill well cellars, late March 2018.