Geological objections to

Surrey County Council planning application no. 2018/0152

by

UK Oil & Gas for hydrocarbon developments at Horse Hill

by

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Executive summary

The 1980s 2D seismic database used by 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 drilling at Broadford Bridge.

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

- The location of the Collendean Farm-1 (CF-1) well used by UKOG is 150 m NW of its true position.
- It is placed on the wrong (northerly) side of a large fault, the Collendean Farm Fault.
- UKOG's attempt to explain the resulting mismatch of well tops (geological layers) appeals to a highly unlikely shallow velocity anomaly.
- The UKOG interpretation of a single fault with a sharp bend and changing sense of throw 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, I have re-interpreted the geology to resolve these fundamental problems:

- There are two separate *en echelon* faults in the vicinity of HH-1 and CF-1, the Collendean Farm and the Horse Hill Faults.
- An accurate and simple well tie from CF-1 to HH-1 can be made without errors or recourse to velocity anomalies.
- HH-1 has been drilled into the HH Fault damage zone, and possibly intersects the fault itself. This accounts for the temporary high, but rapidly declining, Kimmeridge oil flow.

It is not clear whether UKOG has revised its geology in the light of my previous published critiques (a non-technical blog and a technical analysis). Some of the planning application diagrams imply two 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. UKOG's own submissions are inconsistent on this matter.

The 3D cartoon perspective views of actual and proposed drilling submitted by UKOG are inadequate for a proper scrutiny of the planning application. The application should be supported by internally consistent structure contour maps of the several horizons which it is proposed to develop, together with illustrative properly-scaled cross-sections. No such maps and cross-sections have been submitted.

Several of the proposed wells, to be deviated due south, stray outside the defined development deviation area.

The supposed target 'limestones' are in fact micrites, which are calcareous mudstone layers. UKOG purports to recognise six such layers, but the BGS recognises only three micrites in the Weald Basin. One of the additional layers is an existing layer repeated by faulting, but mis-diagnosed by UKOG as a new layer. UKOG 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 UKOG 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.

UKOG misleadingly cites historical earthquakes from outside the Weald Basin in support of its view that the Newdigate swarm of 2018-19 is not unusual. My analysis shows that earthquakes above local magnitude 2.0, had they occurred within the last few hundred years, would have been documented, but records of these do not exist; therefore the recent swarm is highly unusual. UKOG also supplies diagrams which misleadingly seek to minimise any link from faulting and well operations at Horse Hill to the Newdigate swarm.

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 such a development.

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

Contents

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 has been prepared 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. Inadequacy of the seismic database

UKOG is using a database of 2D seismic lines dating from the 1960s to the 1980s. Figure 1.1 illustrates the density of the lines (shown in brown) available over various oil and gas structures in the Weald Basin. These structures 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 within the last decade frequently involves highly deviated wells (up to 30-40° from the vertical). The problem now 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 problems such as at Brockham (operator Angus Energy) and at Broadford Bridge (operator UKOG).

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

2. UKOG errors in well location

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 Libraray (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 coordinate (lat/lon) 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 presented by Hicks et al. (2019; in review) concerning the Newdigate earthquakes. Here the UKOGL seismic database is located on a Mercator projection map (typically that used by seismologists) about 130 m NW of the correct position. The implications of that error will not be discussed further here.

The maps of UKOG (and its predecessor/partner Magellan) do not suffer from the problem of misplaced seismic data, however there is severe error in the placement of the Collendean Farm-1 (CF-1) well, a vertical well drilled by Esso in 1964.

Figure 2.1 shows a detail of the Top Great Oolite depth structure map, submitted in application by UKOG in May 2019. The digital seismic overlay (black lines) matches the underlying colour image well, suggesting an error of under 10 m in the registration of the image within the Kingdom v8.8. seismic interpretation package. However, the well locations are in error. Figure

2.2 shows a close-up of the map. Collendean Farm-1 (yellow disc) is about 130 m NW of its correct location shown in small print. A tabulation of the grid coordinates for this well and for Horse Hill-1 (HH-1) is given in Figure 2.3. The erroneous UKOG location for CF-1 is shown in blue. The correct location, given by Esso in its composite well log header, is shown in Figure 2.4 (BNG = British National Grid). It is in a large field, which I have personally viewed from the road to the east. In contrast, all the UKOG 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 (Fig. 2.4 inset) and, indeed, back at for least 100 years, as shown by archived OS maps.

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.

Figures 2.1 and 2.2 also show that the surface location of HH-1 (southerly yellow disc) is in error. The erroneous location is shown in red in the table of Figure 2.3. I have checked the correct location of HH-1 by overlaying the wellpad plan on the database. This is shown in Figure 2.5. Here it can be seen that my positions for the well track (blue line) and for the wellhead (oil well symbol) are within 2 m of the correct location.

In Figure 2.2. the toe of HH-1 (crimson disc) is in the correct location.

In conclusion, UKOG appears to be unable even to position its own and another well correctly on the map. This has implications for the resulting interpretations.

3. UKOG inconsistencies in fault intepretation

The errors in mapping of the Collendean - Horse Hill area go back to 2009. But after HH-1 was drilled in 2014, UKOG merely made minor cosmetic alterations to the structure maps. The main fault running E-W through the centre of Figure 3.1 (dating from February 2015) corresponds approximately to the Collendean Farm Fault in the west, and the Horse Hill Fault in the east. Both these faults have a downthrow to the north. But in UKOG's interpretation they are marked as a single fault (more recently called by UKOG the Horse Hill Fault), with a downthrow predominantly to the south. This contradicts its own seismic section interpretations from that era, so is internally inconsistent. The fault is on the south side of CF-1. That error is mainly due, as we have seen above, to the mis-positioning of CF-1 too far to the NW.

Figure 3.2 shows the image of UKOG's Top Portland Prospect (February 2015) as an underlay to the database. HH-1 and the deviated well track are in approximately the correct location; CF-1 (green disc) is in the wrong location (cf. Fig. 2.4). The dotted orange line in the top left-hand corner is the edge of the structure, as outlined by the orange hatching in Figure 3.1. Note that the offsets at the faults show that the downthrows are to the south.

Figure 3.3 shows the whole Top Portland prospect map. The 'Horse Hill Fault' is now marked with a thick lilac line. Black arrows show local dips. The red arrows along the fault show the throw across the fault in feet, read off from the contours on either side. The downthrow is predominantly southwards-facing, but locally NE of HH-1 the throw is down to the north. Such a sense of changing throw direction is highly unlikely in the Weald, although it is technically possible in basins with a pronounced strike-slip fault geometry. There is no evidence for such geometry in the Weald. Here it is an artefact of poor seismic interpretation.

Figure 3.4 summarises the UKOG fault mapping (upper map) compared with my version (lower map). The UKOG version forces fault traces through even where the seismic data confirm a lack of faults with a discernible vertical offset. In contrast, my version honours the data, placing a fault only where seismic evidence exists for one.

Detail in UKOG's proposals is woefully inadequate. Consider firstly an example 'well plat' from Pennsylvania (Figure 3.5). This is a detailed surveyor's plan for just one 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, UKOG sees fit to supply merely a couple of cartoon perspective views of the geology and the proposed development drilling. Figure 3.6 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 3.7, this absence implies that there are two separate faults, conforming to my Collendean Farm and Horse Hill Faults, respectively. If the UKOG interpretation of the Top Portland Sandstone shown in Figure 3.3 is correct, there should be the single 'Horse Hill Fault' cutting face B. Note that both the faults in the cartoon of Figure 3.6 displace the Top Portland down to the north. So UKOG's maps and cartoons are internally inconsistent.

The location of CF-1 in relation to the major nearby fault is also internally inconsistent. In Figure 3.6 the well lies to the *south* of the major fault, but in the even more recent structural map of the deeper Great Oolite horizon (Fig. 2.1) the well is positioned by UKOG to the *north* of the major fault. If the correct location for CF-1 is taken into account, the vertical well intersects the fault at Top Great Oolite level.

The second cartoon submitted by UKOG shows the proposed development (Figure 3.8). 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. But the more easterly of the two subsurface deviation sectors specified by UKOG (Figure 3.9) does not allow for wells from the wellpad to deviate initially southward, viz. HH-1z, HH-1z "producer" (which should be labelled more correctly as HH-1y), HH-5 , HH-6, HH-2, and the "Water re-injector" well.

The geology in the two cartoons is depicted as essentially flat, disturbed only by the one (or is it two?) faults at depth. Such an assumption is simplistic, and too optimistic for 'blind' drilling. The lack of adequate seismic data, especially in the easterly deviation sector, implies that these wells will be drilled up to several hundred metres from any seismic control.

4. Micrites misleadingly labelled as limestones

UKOG's production plans are targeting two so-called 'limestones' within the Kimmeridge Clay Formation, labelled KL #3 and KL #4, respectively. 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 calcareous layer (low 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, as I have demonstrated to be the case with UKOG's drilling fiasco 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 4.1). 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 (Fig. 4.2) accurately fixes the tops and bottoms the 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 terminology these are numbers 3 and 4, with a locally recognised number 2. The micrites depicted in the application documents by UKOG labelled 0, 1, and 5 have never been documented by any non-UKOG earth scientists. UKOG's understanding of the geology falls woefully short of the professional standards of the hydrocarbon industry.

The methods proposed by UKOG 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 mendaciously refer to the micrites as 'limestones', when they are no such thing. They are merely thin (<30 m) layers of calcareous mudstone. 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 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 avoids the Purbeck-Isle of Wight Fault Zone.

This study confirms that the exposures of the lower main micrite (KL2 in UKOG parlance) as seen at Horse Hill are the very same rock as seen in the cliffs (Fig. 4.3). 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 (and other Weald licensees) call it.

5. Exploitation of the Kimmeridge Clay Formation

5.1 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 UKOG, 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 and Horse Hill sites, now asserts 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. It now states 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 5.1. 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 5.2. The scale is logarithmic, so that acetic acid (e.g. lemon juice) with a pH of around 2.3, is around 1000 times weaker than 15% hydrochloric acid commonly used by the industry for a wellbore wash (pH -0.7).

If UKOG 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.

5.2 Drilling into the fault damage zone

I first pointed out in August 2017 that UKOG 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 (Fig. 5.3) suggests that the Horse Hill fault extends almost to the track of HH-1. This seismic section display has been stretched somewhat horizontally to clarify the intersection of HH-1 at depth with the possible westward end of the Horse Hill Fault. CF-1, shown as a vertical dashed green line, is projected from about 300 m to the west.

A contour map of the fault is shown in Figure 5.4. The fault may splay into two or more parts as it dies out westwards. My version of the fault has some similarity to part of UKOG's version as seen on the Top Great Oolite structure map used as an underlay to Figure 5.4 (see also Figure 3.3). But the crucial difference between the two interpretations is that in my version the Collendean Farm and the Horse Hill Faults are separate structures. This is illustrated in Figure 5.5. They form part of a pattern of *en echelon* faults within the Mesozoic sediments. In Figure 5.5 the traces of the various faults at approximately Top Portland level are shown by the toothed lines.

The Newdigate Fault (green), near which the earthquakes have been located, is shown extending eastwards in Figure 5.5 as a dashed line where it is present at greater depth. However it does not extend any further eastwards than the meridian of Horse Hill, as proposed by Hicks et al. (2019).

An isometric cartoon of the intersection of HH-1 with the Horse Hill Fault is shown in Figure 5.6. This demonstrates that the wellbore will have penetrated the damage zone extending for about 50 m on either side of the fault surface. The damage zone cartoon is from Johri et al. (2014). My inference accounts successfully for the temporary high flow rates encountered within the Kimmeridgian (the infamous 'Gatwick Gusher'). This inference is supported by the rapid decline of the flow rate (as I predicted in 2017), shown in the inset to Figure 5.6. Such a decline is to be expected from drilling into a fault zone.

6. Possible link between Horse Hill and the Newdigate earthquake swarm

6.1 Introduction

UKOG has submitted to SCC a document entitled '*Why Earth Tremors in Surrey Should* <u>*Not*</u> *be Blamed on Oil Exploration*'. It is an attack on the hypothesis devised by a group of earth scientists at Edinburgh University. 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.

6.2 Faulting at Horse Hill

UKOG depicts part of an interpreted seismic line (its figure E) which I reproduce here in the upper part of Figure 6.1. The biggest fault in the centre of the section is evidently the Collendean Farm Fault, which I have labelled as such, although UKOG calls it the Horse Hill Fault. Note that the downthrow is to the north, which is correct. Contrast that with the downthrow to the south shown in Figure 3.3. The seismic section is a reprocessed and migrated version of C79-36. UKOG has projected onto this section the deviated HH-1 well from 1000 m to the ENE, stating in its figure D that "*the Horse Hill-1 well does not intersect a fault (see also Figure E)"*. The map of the locality reproduced in the lower part of Figure 6.1 shows that this projection is spurious, in that UKOG has chosen a seismic line far away from the local complexity of the faulting in the area of the two wells.

In contrast, as I have shown above, the deviated HH-1 either passes very close to, or even penetrates, the western tip of the Horse Hill Fault.

One of the lessons to be learned here is that the density of the existing 2D seismic coverage is not up to the task of properly interpreting the fault structure.

6.3 Historical seismicity

The UKOG submission deals with historical seismicity in the Weald. It quotes the Edinburgh report (Cavanagh et al. 2019) 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:

> "*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 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), reproduced here as Figure 6.2. 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 one can 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 6.3, on which the earthquakes resulting from the search 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 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 geographically within the Weald Basin.

The Three Billingshurst events are plotted on a regional seismic cross-section shown in Figure 6.4 (the same line used as the basis for the geological cross-section of Figure 6.2). 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 varying from 1.5 to 3.0 km (Hicks et al. 2019; 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 will not have 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 on 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 earthquakes, the East Grinstead and the Scaynes Hill events, which have hypocentres within the Weald Basin sedimentary fill.

6.4 Completeness of the earthquake catalogue

UKOG claims that the BGS catalogue is incomplete; that is, many historical events may be missing. The BGS states (Musson 1994) 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=2.3 km Newdigate earthquake was felt out to about 15 km away. This range is plotted in Figure 6.5 (blue circle). The 19 Feb 2019, M_L=2.0, depth=2.5 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 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 Musson catalogue. 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. The statement quoted above by Cavanagh et al. is therefore not only valid, but is rather conservative.

6.5 Possible permeable fluid pressure link from Horse Hill to Newdigate

UKOG has presented an interpreted seismic line (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 6.6. 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 6.6. 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. The earthquake has been projected along the strike of the fault, which dies out eastwards, and does not cut the micrite. I disagree with the Hicks et al. geological mapping here, in not extending the fault further to the ENE.

The interpreted cross-section of Figure 6.6 shows that there is a plausible physical link between the Horse Hill Fault and the Newdigate Fault. Pressure changes at the well, caused, for example by releasing shut-in, could pass down the Horse Hill Fault and/or its damage zone, and thence along permeable horizons such as the Great Oolite (not mapped) at ~1 s TWT, to reach the earthquake zone.

In conclusion, UKOG's attempts to dissociate its activity from a possible temporal and causal link to the earthquake swarm are erroneous and disingenuous. 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.

7. 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 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. 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 a new 3D seismic survey of around 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 less than 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.

The extended well test of the Portland at HH-1, currently underway, is due to be swapped over again to return to testing the Kimmeridgian. It will be interesting to see whether such activity, involving depressurising the Portland interval, might correlate with any new phase of seismicity.

References

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.

Hicks, S.P. et al. 2019. A shallow earthquake swarm close to hydrocarbon activities: discriminating between natural and induced causes for the 2018–19 Surrey, UK earthquake sequence. Submitted to *Seismological Research Letters*, in review.

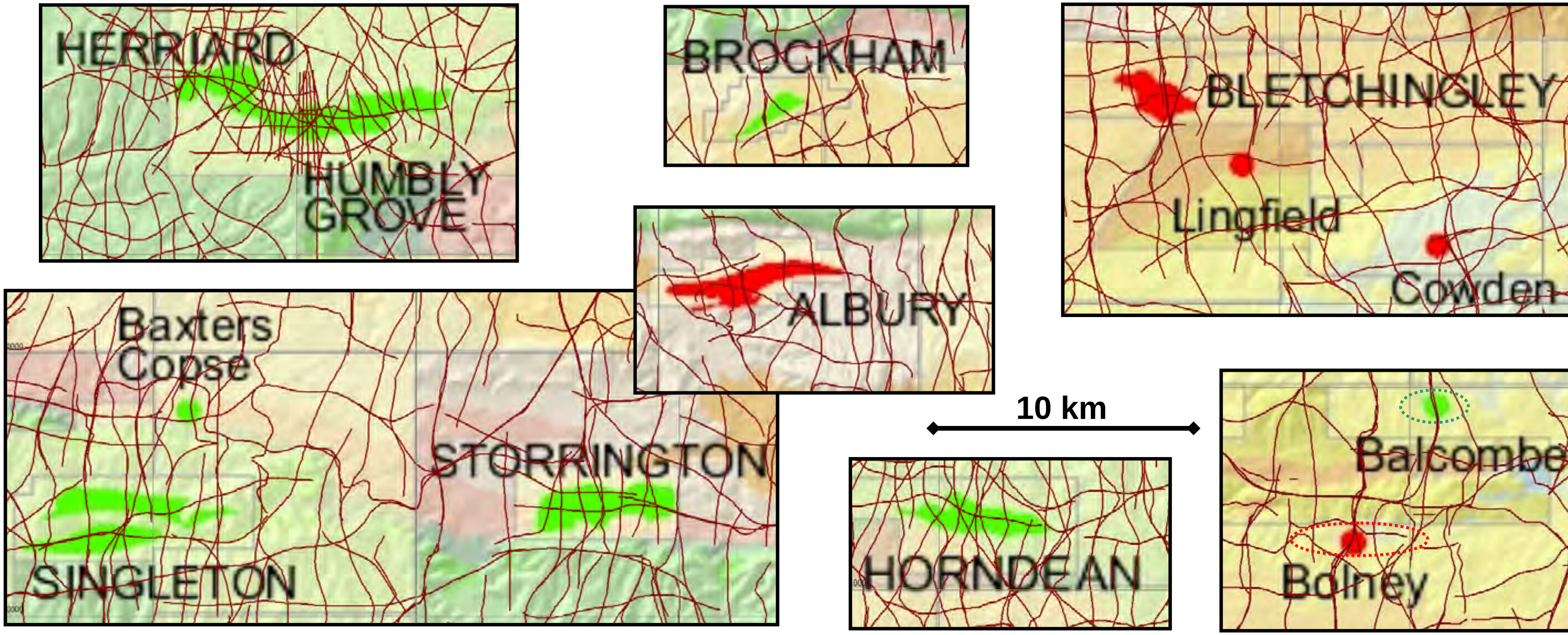
Johri, M., Zoback, M.D. and Hennings, P. 2014. A scaling law to characterize fault-damage zones at reservoir depths. *AAPG Bulletin*, v. 98, no. 10 (October 2014), pp. 2057–2079.

Musson, R.W. 1994. *A catalogue of British earthquakes*. BGS Technical report WL/94/04.

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

UKOG 2019. *Why Earth Tremors in Surrey Should Not be Blamed on Oil Exploration*. Document submitted to SCC, May 2019, 10 pp.

Weald oil and gas fields



The conventional structures are typically 2-6 km long and 1-3 km wide

They are defined by seismic lines at 1-3 km spacing

They were then drilled with vertical or deviated wells by the majors.

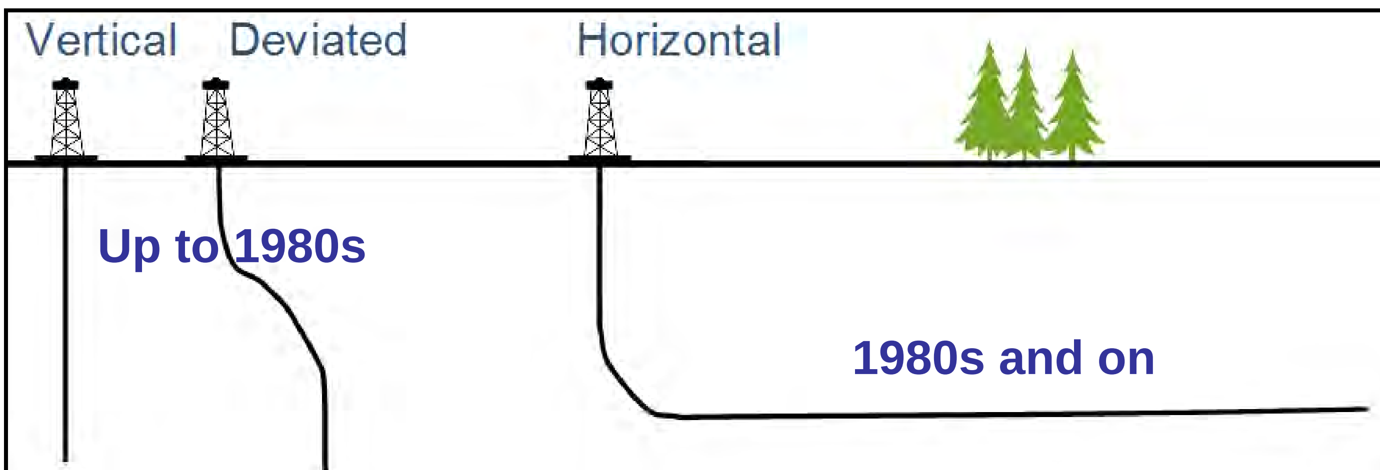


Fig. 1.1

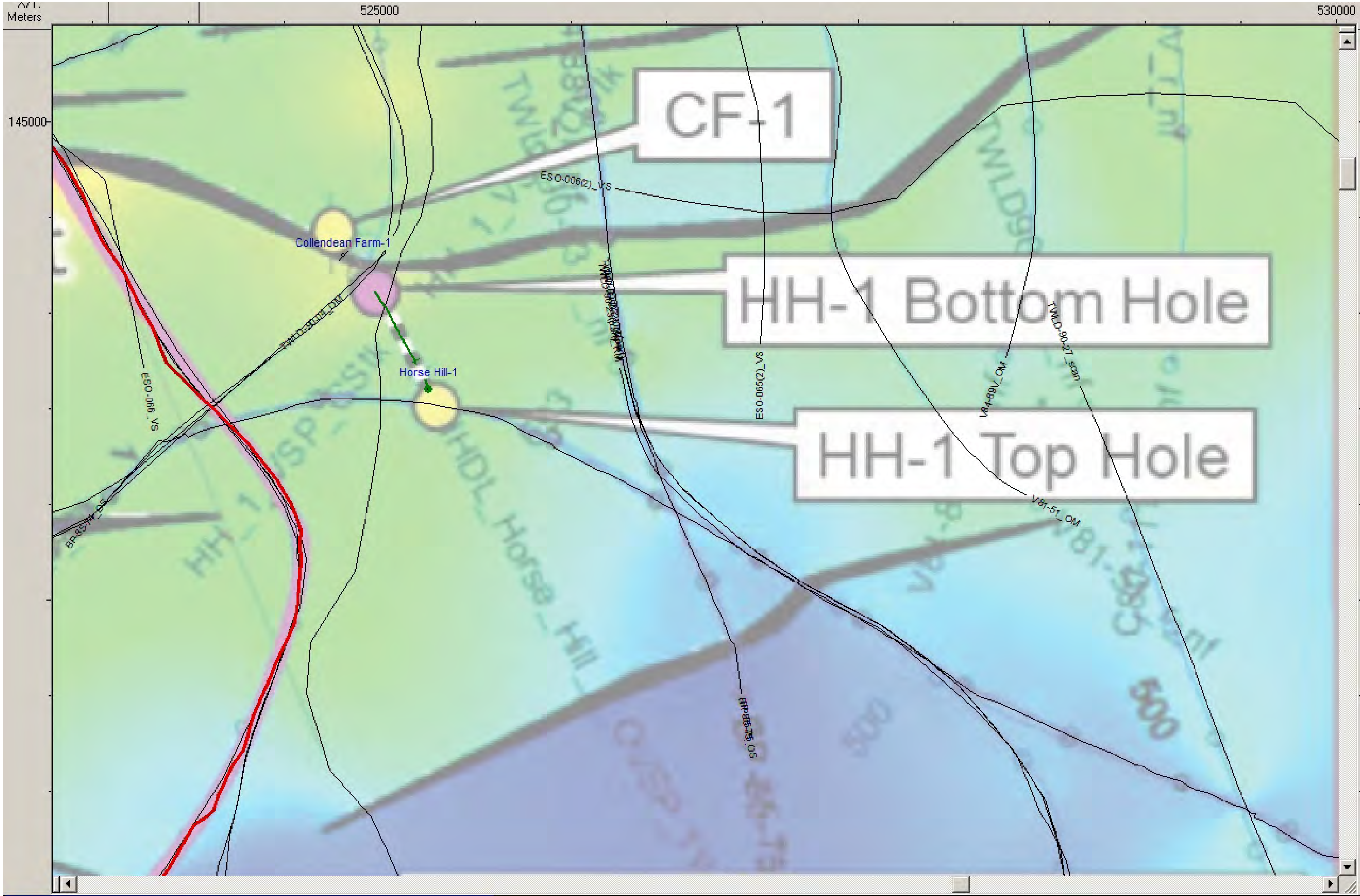


Fig. 2.1 Detail of the Top Great Oolite depth structure map, submitted in application by UKOG in May 2019. Note the location errors of CF-1 and HH-1.

Close-up view of the map shown in Fig. 2.1. Collendean Farm-1 (yellow disc) is about 130 m NW of its correct location shown in small print.

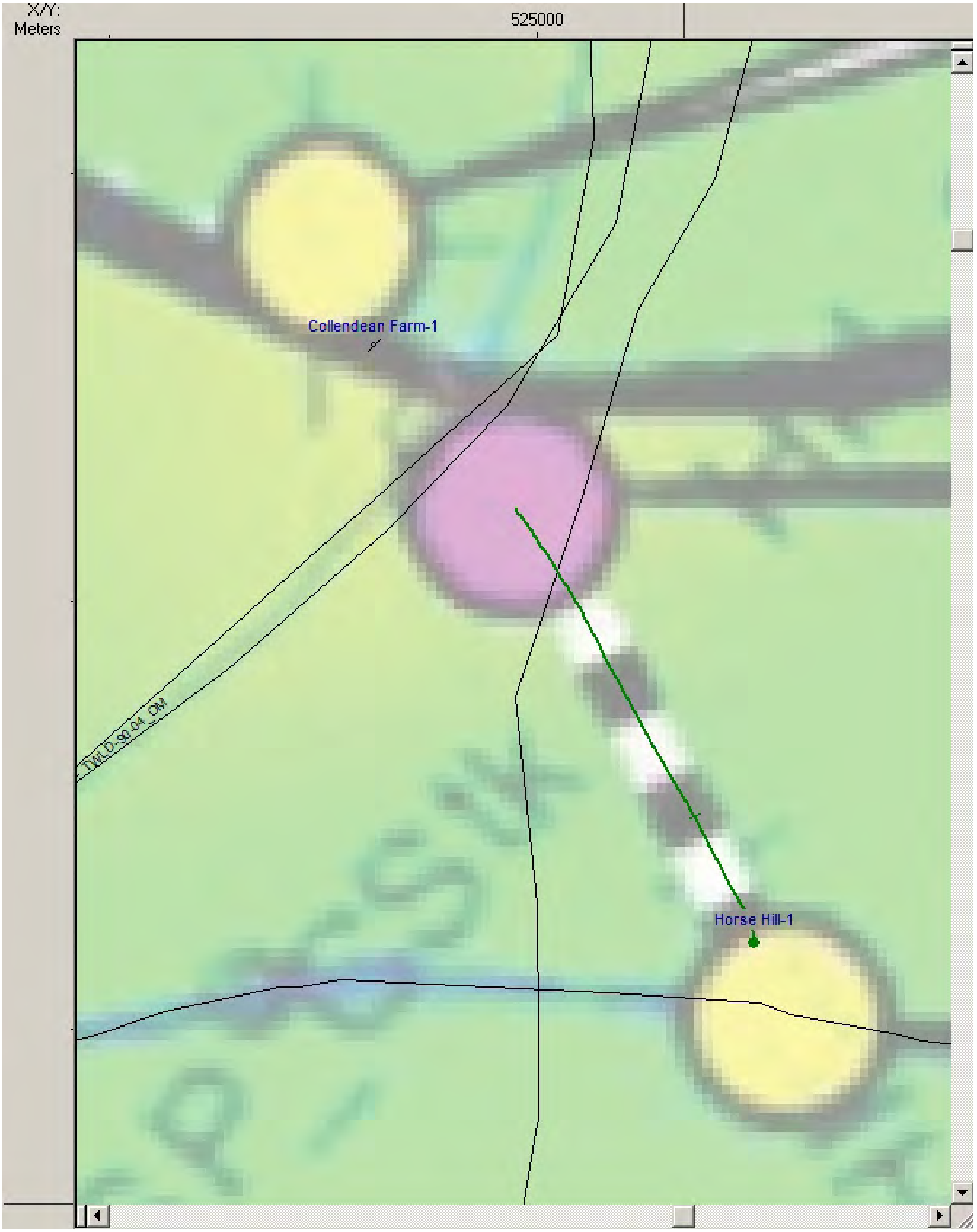


Fig. 2.2

Well	East	North	Source of coordinates	Notes
HH-1	525254	143600	DECC	
	525307	143514	UKOG map June 2019	
CF-1	524811	144300	DECC	
	524800	144290	Esso composite log header	10 m precision
	524752	144418	UKOG map June 2019	
Distances		**m**		
CF-1 to HH-1		828	DECC	measured
		1064	UKOG map June 2019	measured
CF-1 to HH-1		828.4	DECC	calculated
		1060.8	UKOG map June 2019	calculated

Tabulation of the grid coordinates for Collendean Farm-1 (CF-1) and for Horse Hill-1 (HH-1) The UKOG plotted distance between the wellheads is about 70 m greater than the true distance.

Fig. 2.3

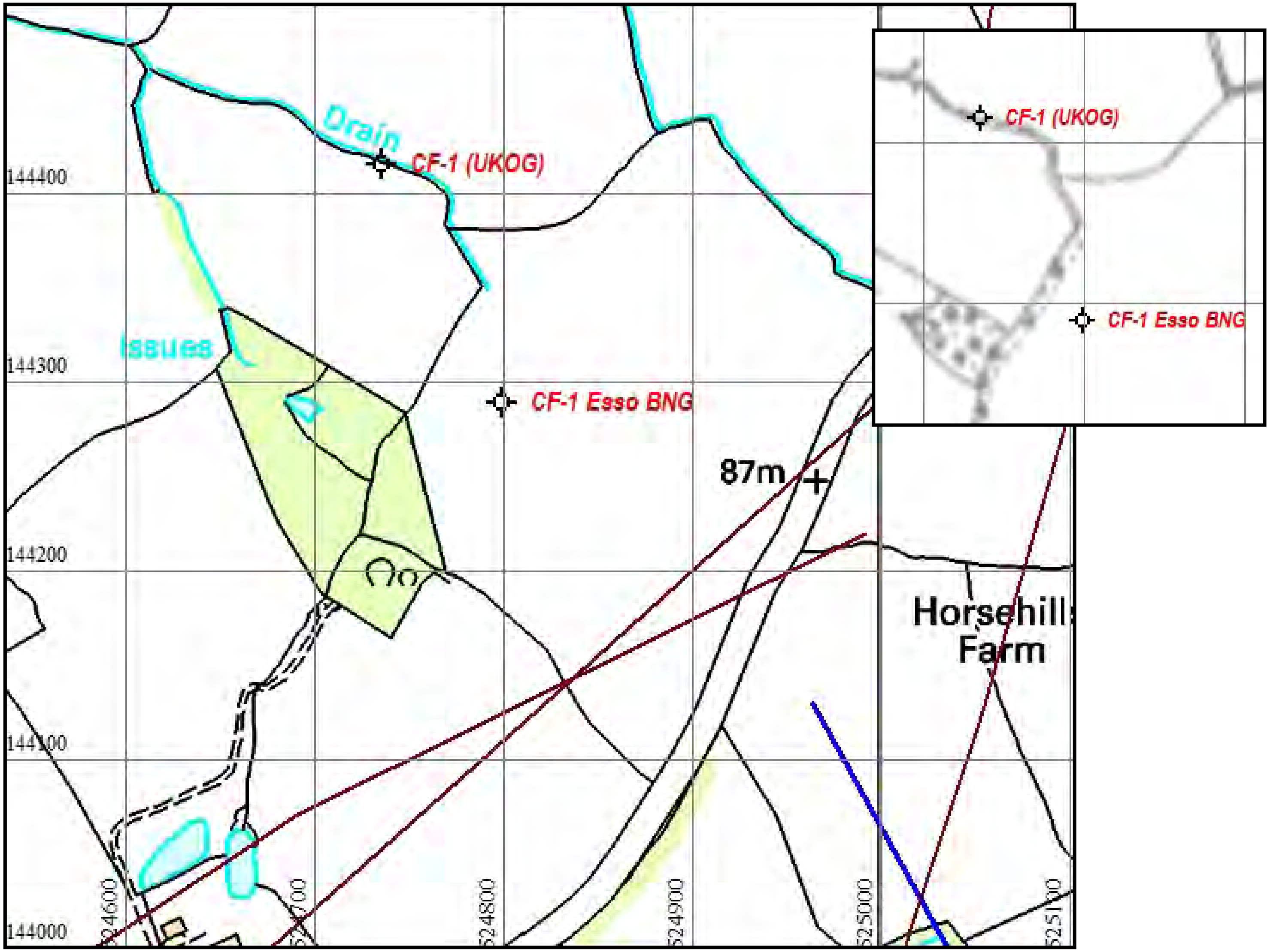
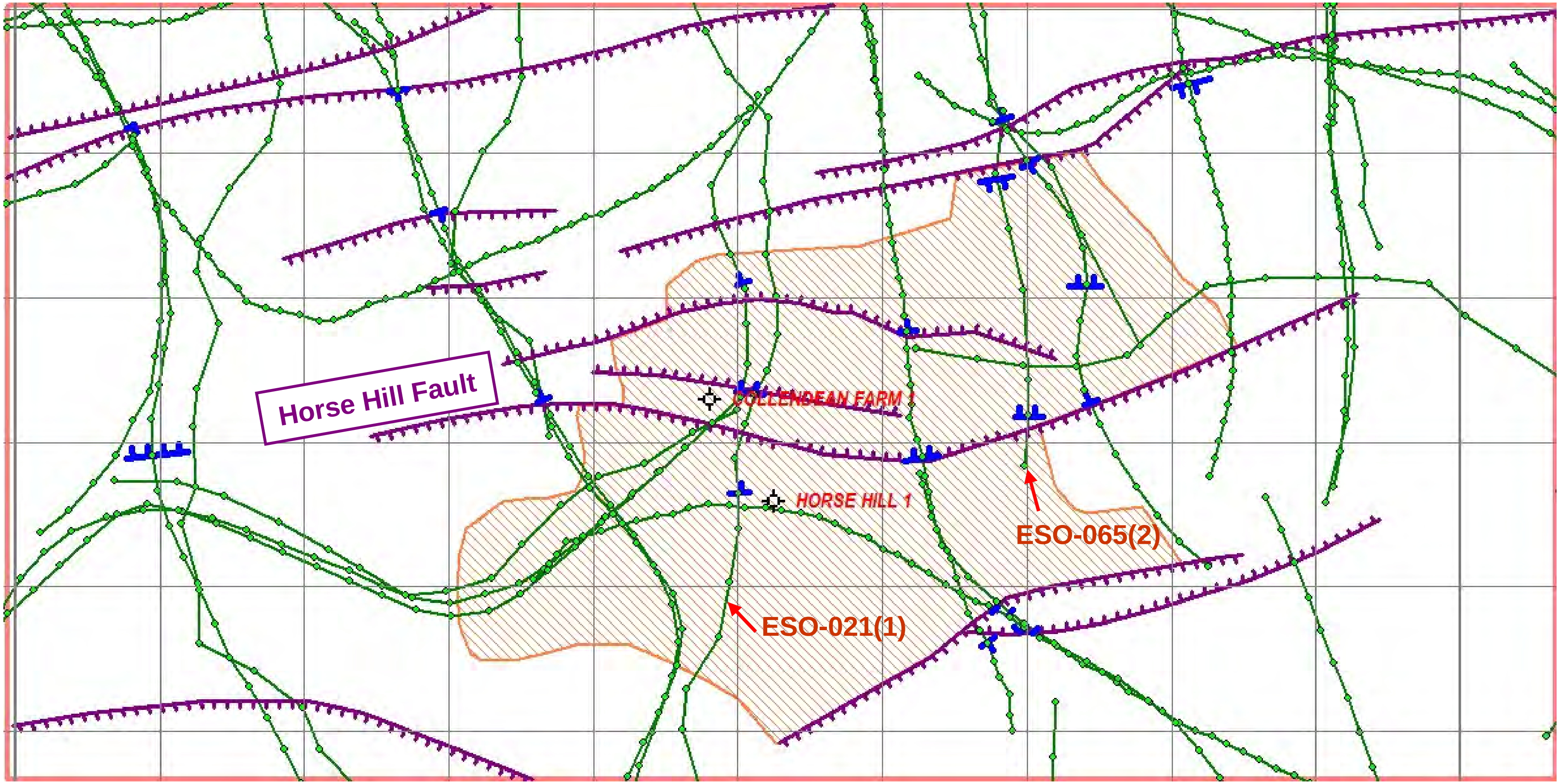


Fig. 2.4

Erroneous location of CF-1 by UKOG in a stream. The inset shows the OS map from the 1960s, demonstrating that the stream existed then. The correct location, defined by the operator Esso in 1964, is shown, specified in British National Grid (BNG) coordinates.

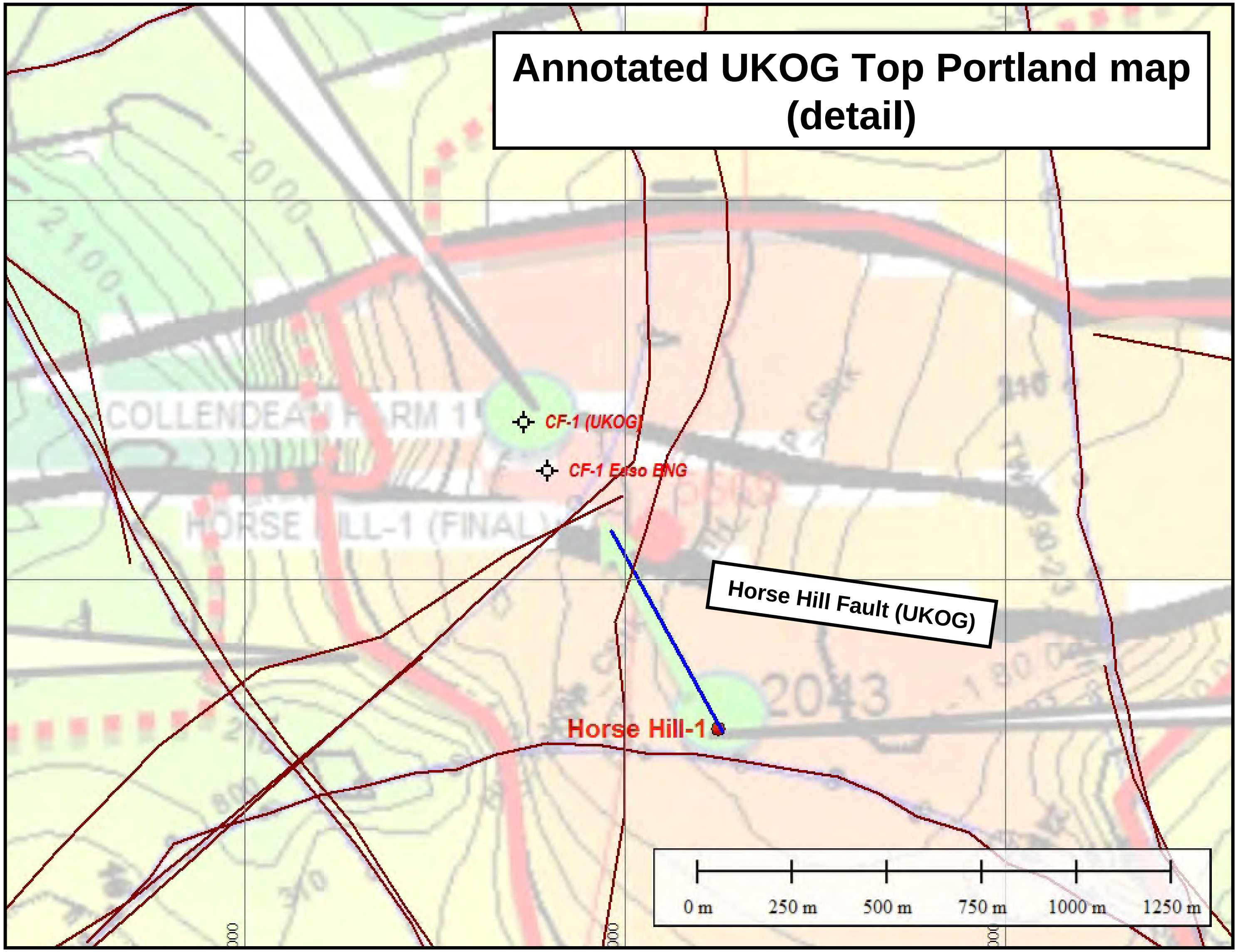
Check map of the location of HH-1 by overlaying the wellpad plan on the database. The blue line is the deviation well track. Location errors are less than 2 m.

Fig. 2.5



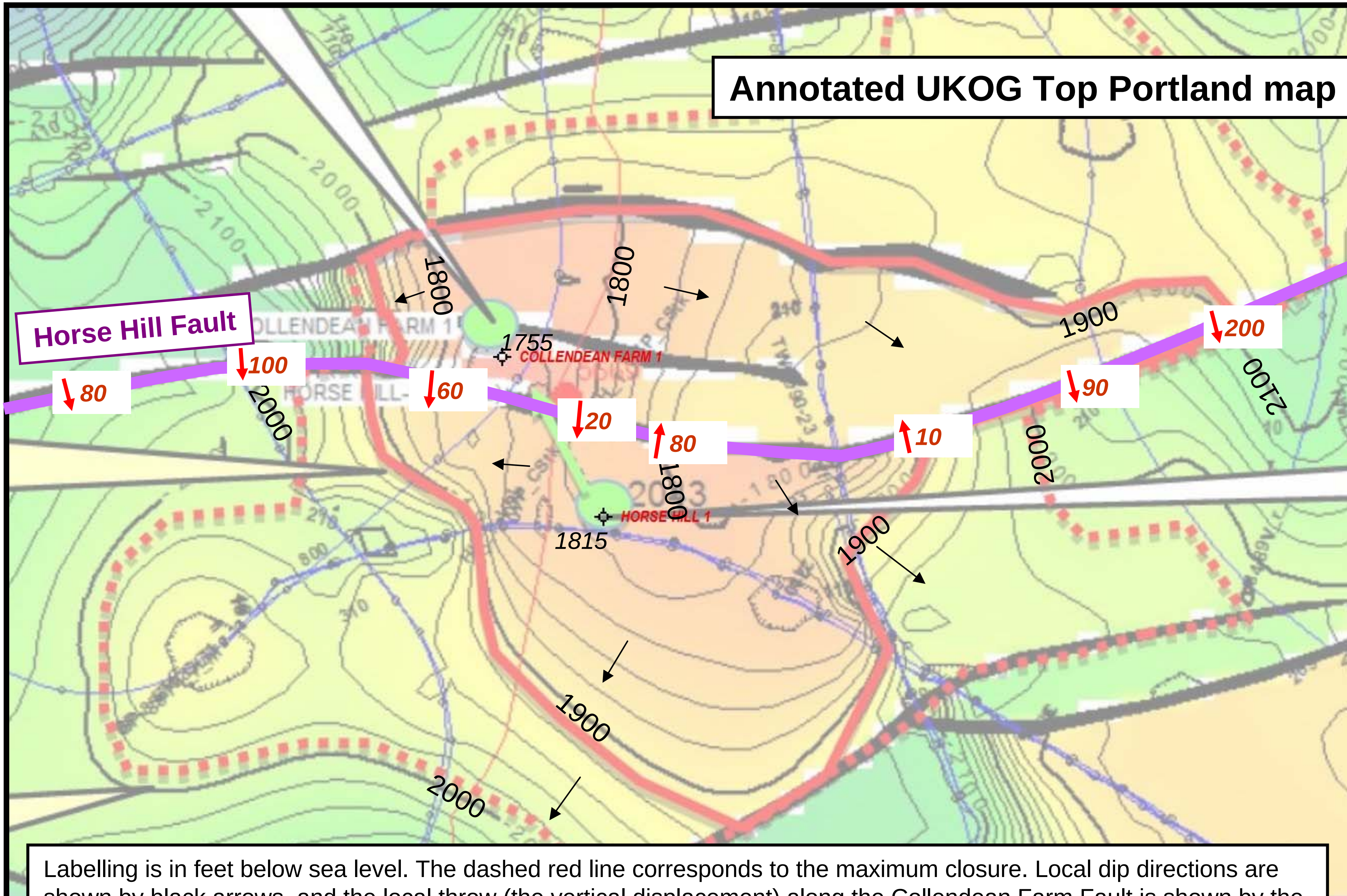
This is the UKOG maximum Top Portland prospect (orange) with the available seismic data (green lines with shot-points marked). Not all of these lines were used in the UKOG interpretation of faults, shown by purple toothed lines. I have marked with short blue toothed lines my version of the locations of faults at around 400 ms depth, at approximately the Top Portland. Two very old Esso seismic lines dating from 1962 are labelled (prefixed ESO-); they were not used by Magellan/UKOG.

Fig. 3.1



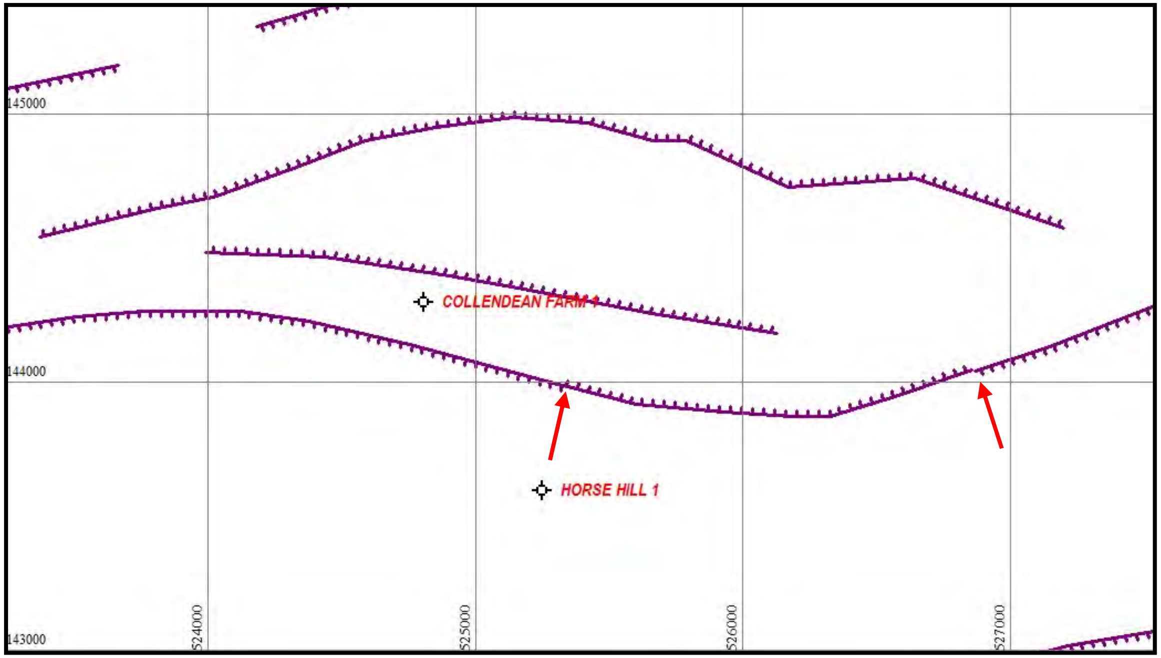
Annotated UKOG Top Portland map (detail)
COLLENDEAN FARM 1
CF-1 (UKOG)
CF-1 Esso BNG
HORSE HILL-1 (FINAL)
Horse Hill Fault (UKOG)
Horse Hill-1
2043
0 m
250 m
500 m
750 m
1000 m
1250 m

Fig. 3.2

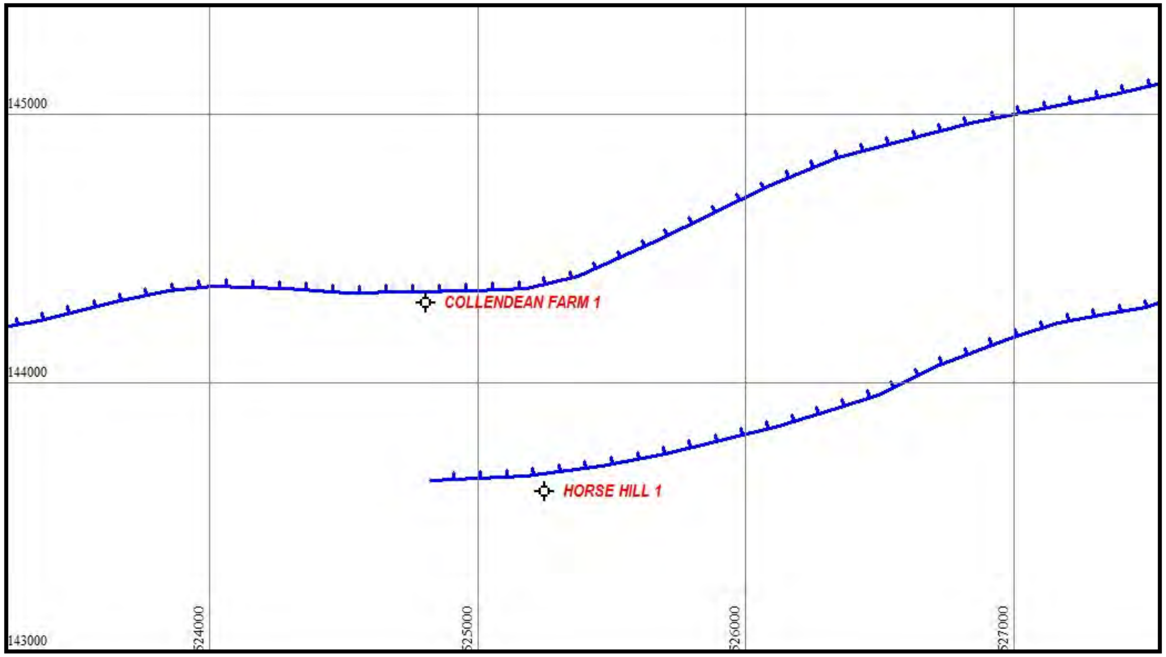


Labelling is in feet below sea level. The dashed red line corresponds to the maximum closure. Local dip directions are shown by black arrows, and the local throw (the vertical displacement) along the Collendean Farm Fault is shown by the red arrows pointing to the downthrown side. Note the local change of sense of throw, NE of HH-1. The depth at the two wells is marked. Note that the Top Portland at HH-1 is <u>deeper</u> than at CF-1 (drilled by Esso in 1964) by 60 ft (18 m).

Fig. 3.3



UKOG fault interpretation. Fault changes sense of displacement (arrows)



DKS fault interpretation; there are two separate faults

Fig. 3.4

HH development plans

Compare UKOG's planning application cartoons with this typical US 'well plat'.

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

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

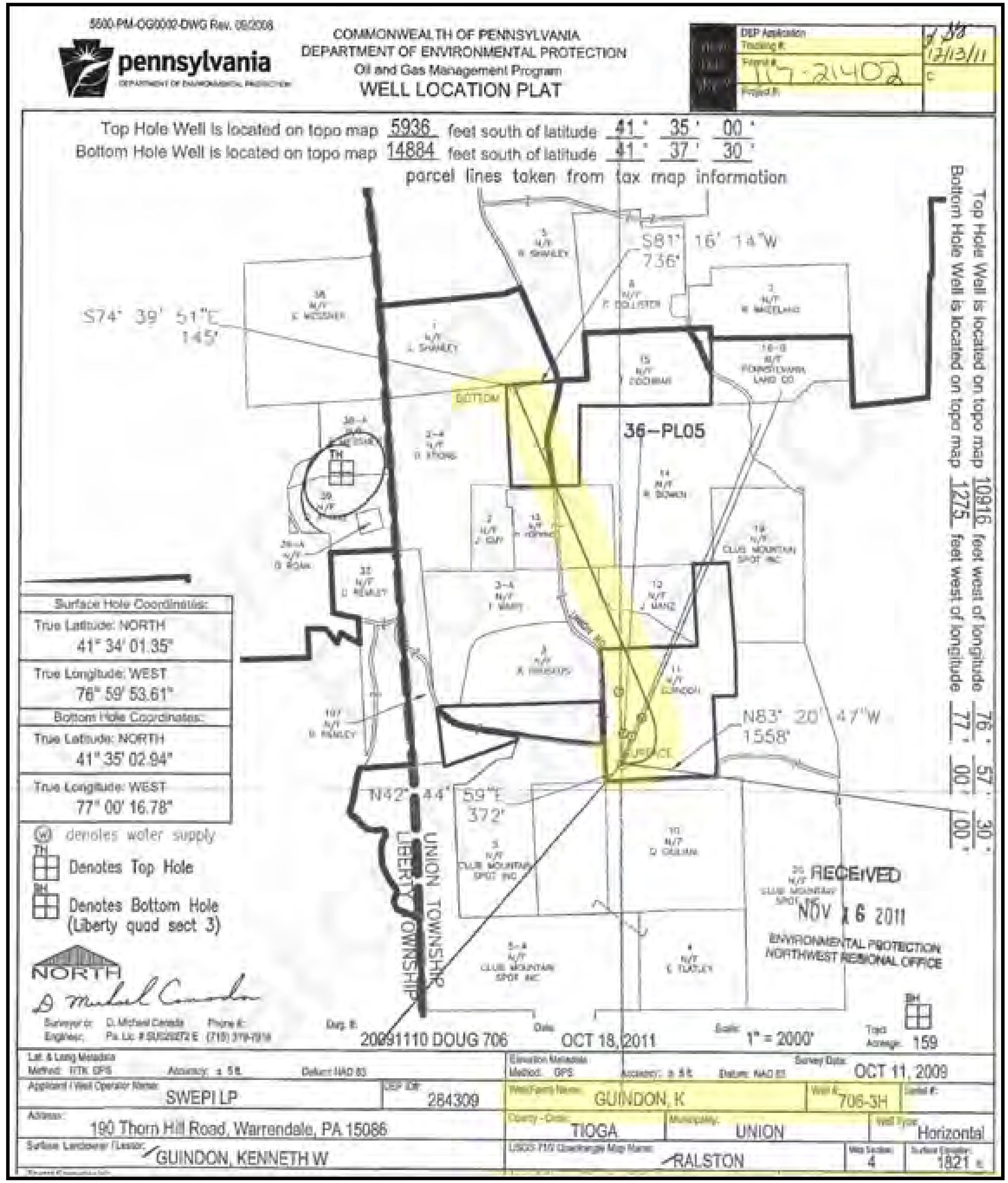
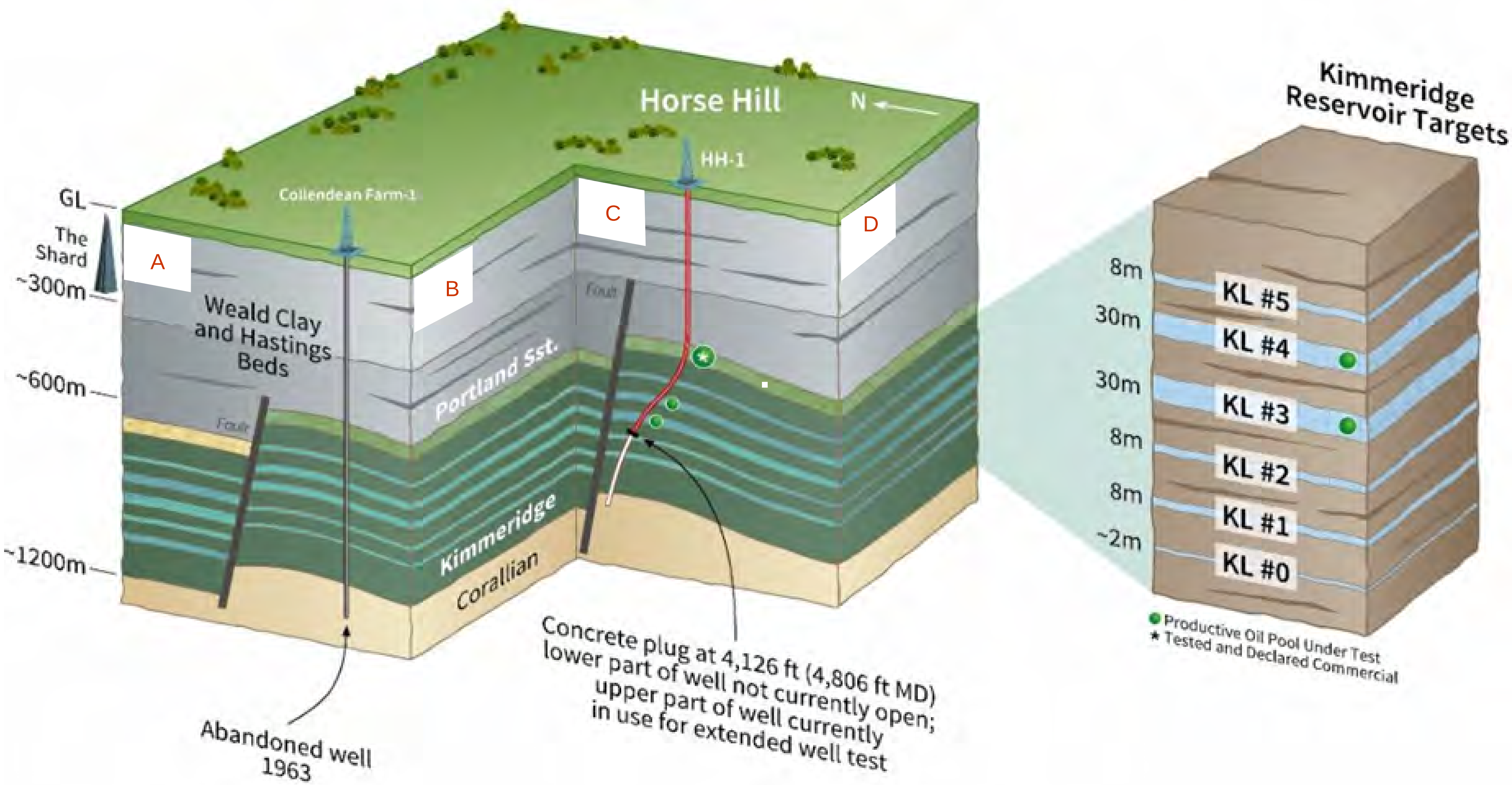


Fig. 3.5

HH development plans

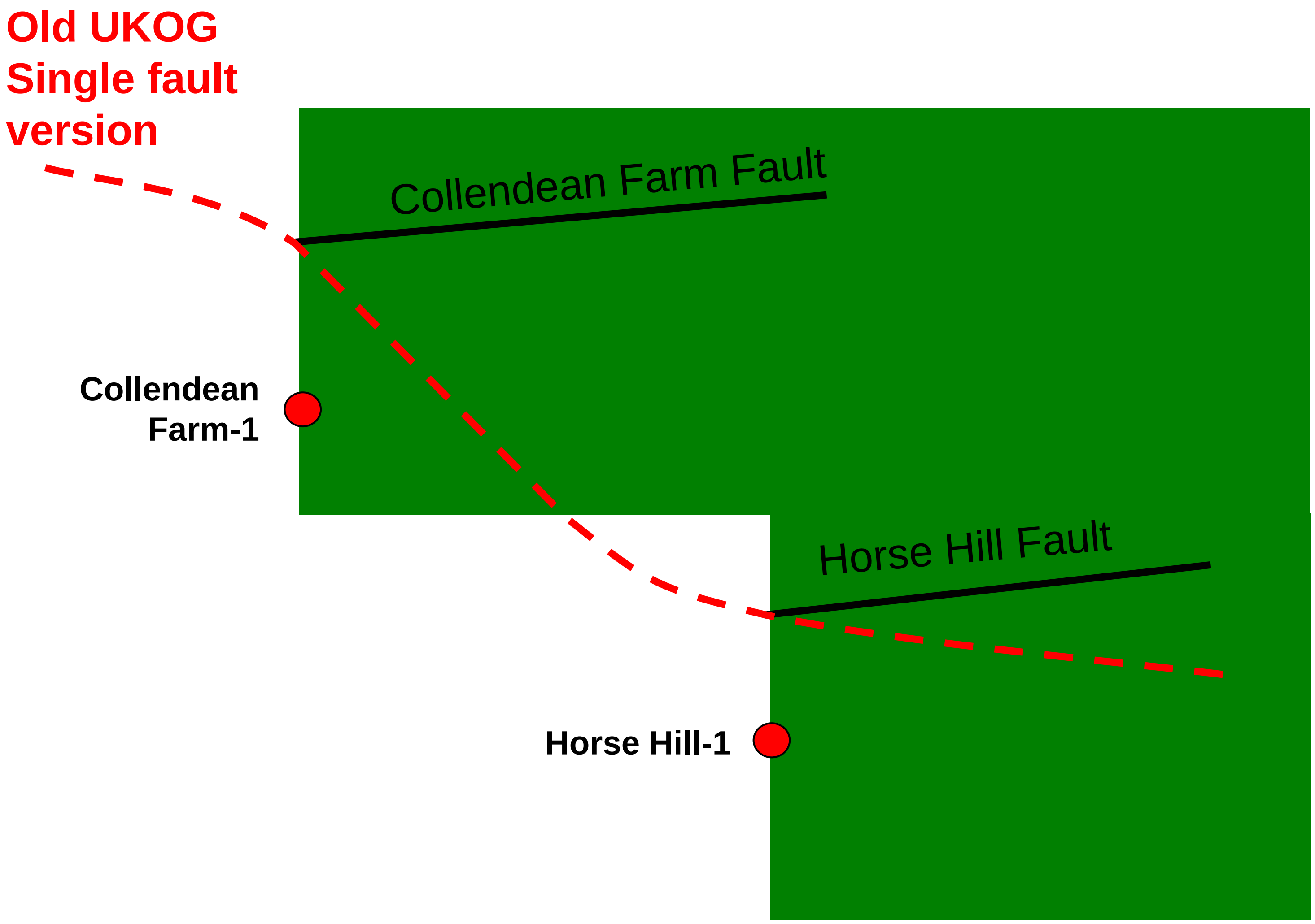
ES Figure 1: Current Status of Horse Hill Well Site[12]



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

Fig. 3.6

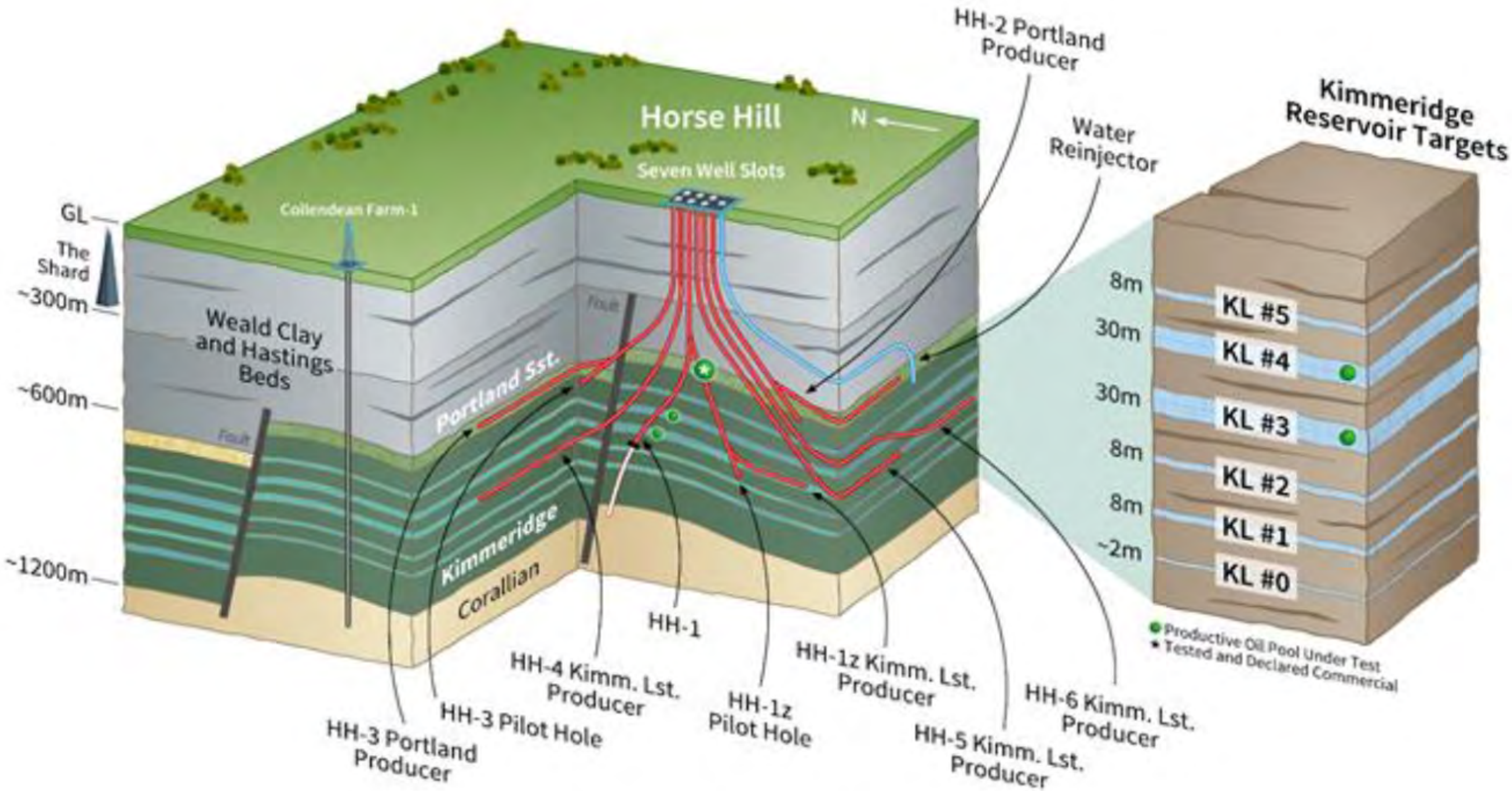
HH development plans



Plan view of Figure 3.6, demonstrating that the previous UKOG single fault version is no longer current. Note also that CF-1 is now on the south side of the Collendean Farm Fault.

Fig. 3.7

HH development plans, late 2018



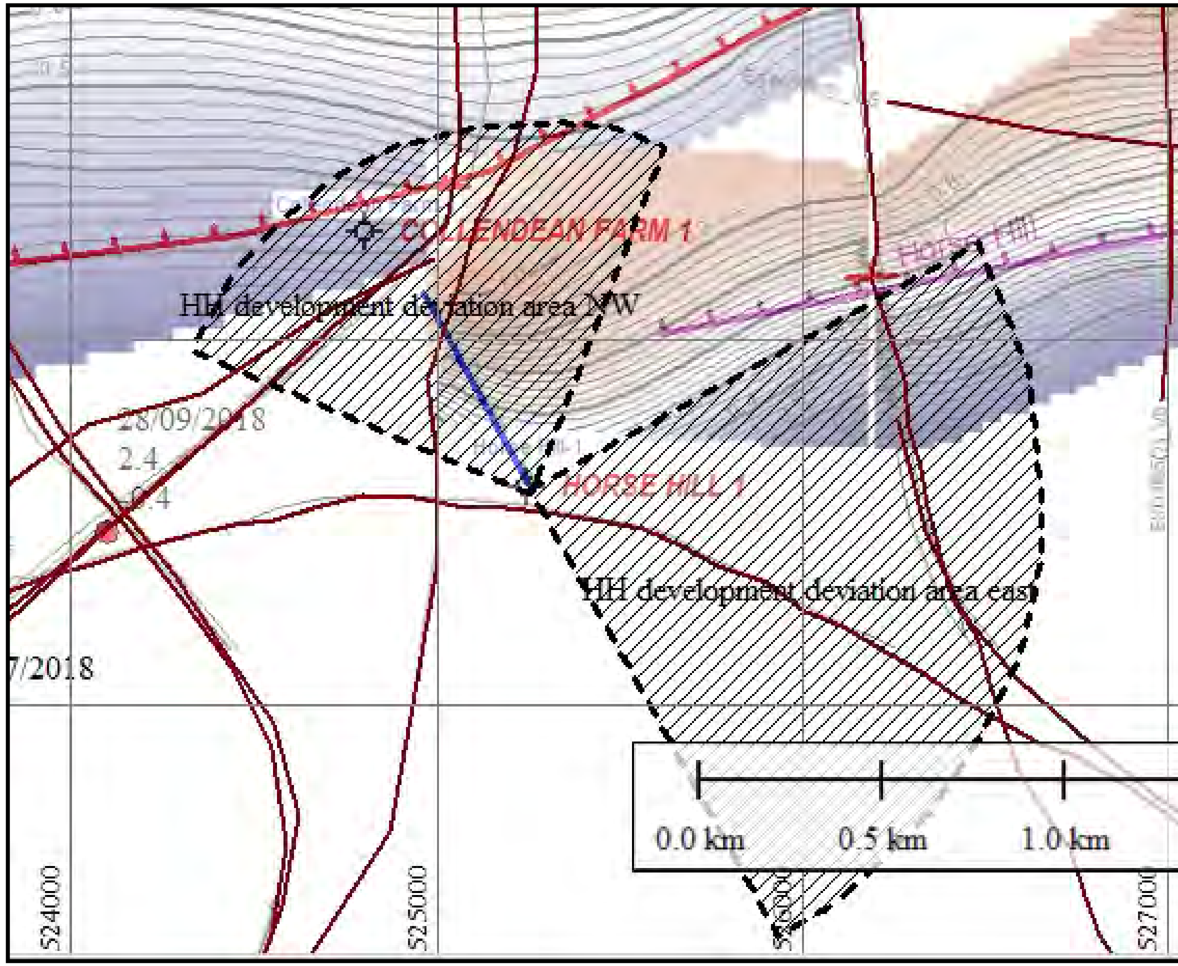
ES Figure 5: Proposed Development at Horse Hill Well Site[12]

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

Fig. 3.8

Comments on development plans

- Plans submitted are mere sketches.
- Wells have inadequate seismic (structural) control.
- Geology assumed flat, no faults.
- Wells deviating south go outside specified deviation sector.
- 3D seismic volume needed before drilling permitted.
- Geology needs to be re-interpreted from scratch.
- Learn from BB-1 fiasco.
- UKOG now claims neither fracking nor acidisation needed.



Horse Hill development deviation sectors (hatched).

2D seismic lines – brown.
HH-1 – blue line.
Collendean Farm Fault at c. Top Portland – red toothed line.
Horse Hill Fault at c. Top Portland – mauve toothed line.
Contours on fault surfaces blue (shallow) to red (deep).

Fig. 3.9

Broadford Bridge

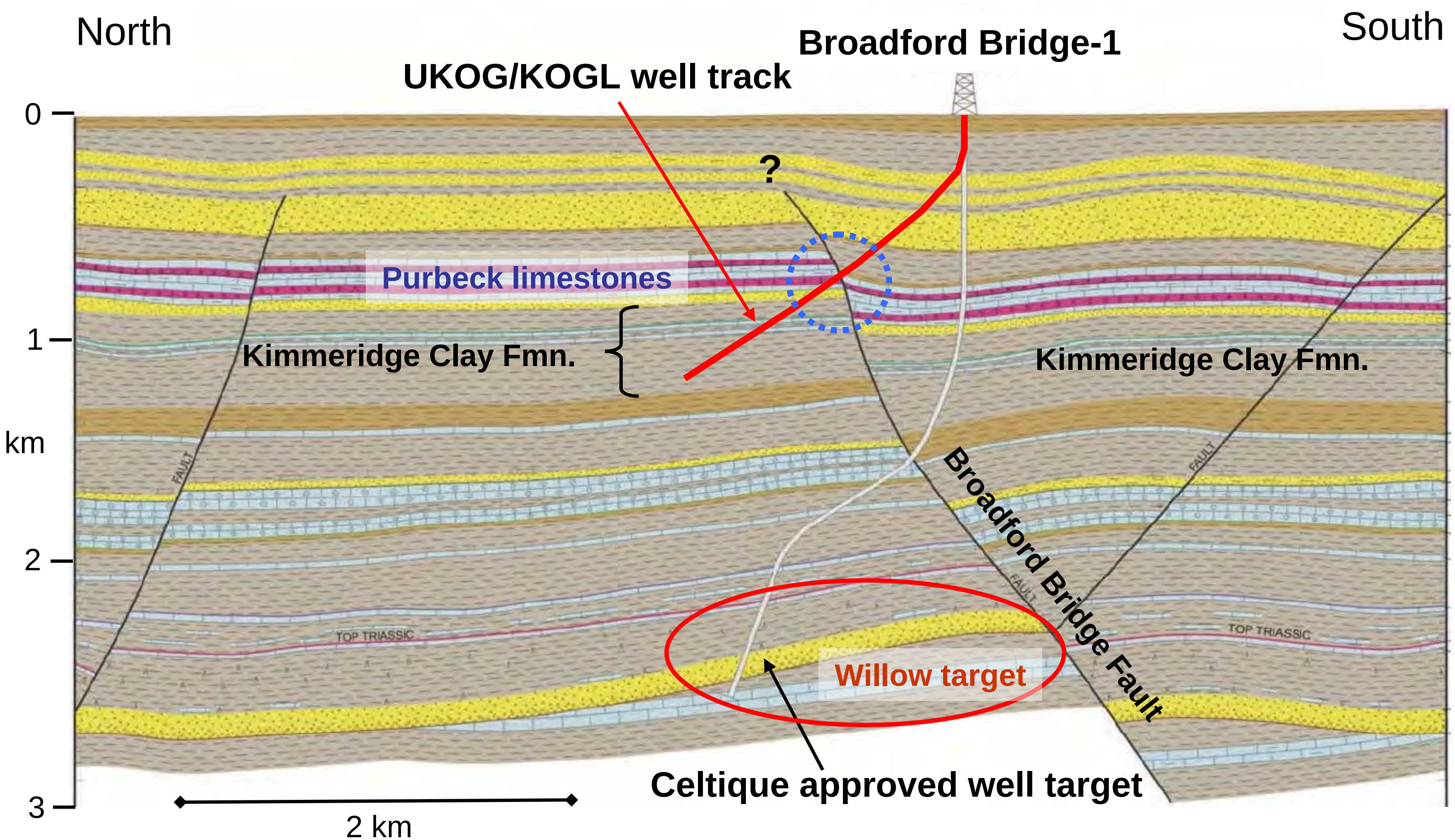
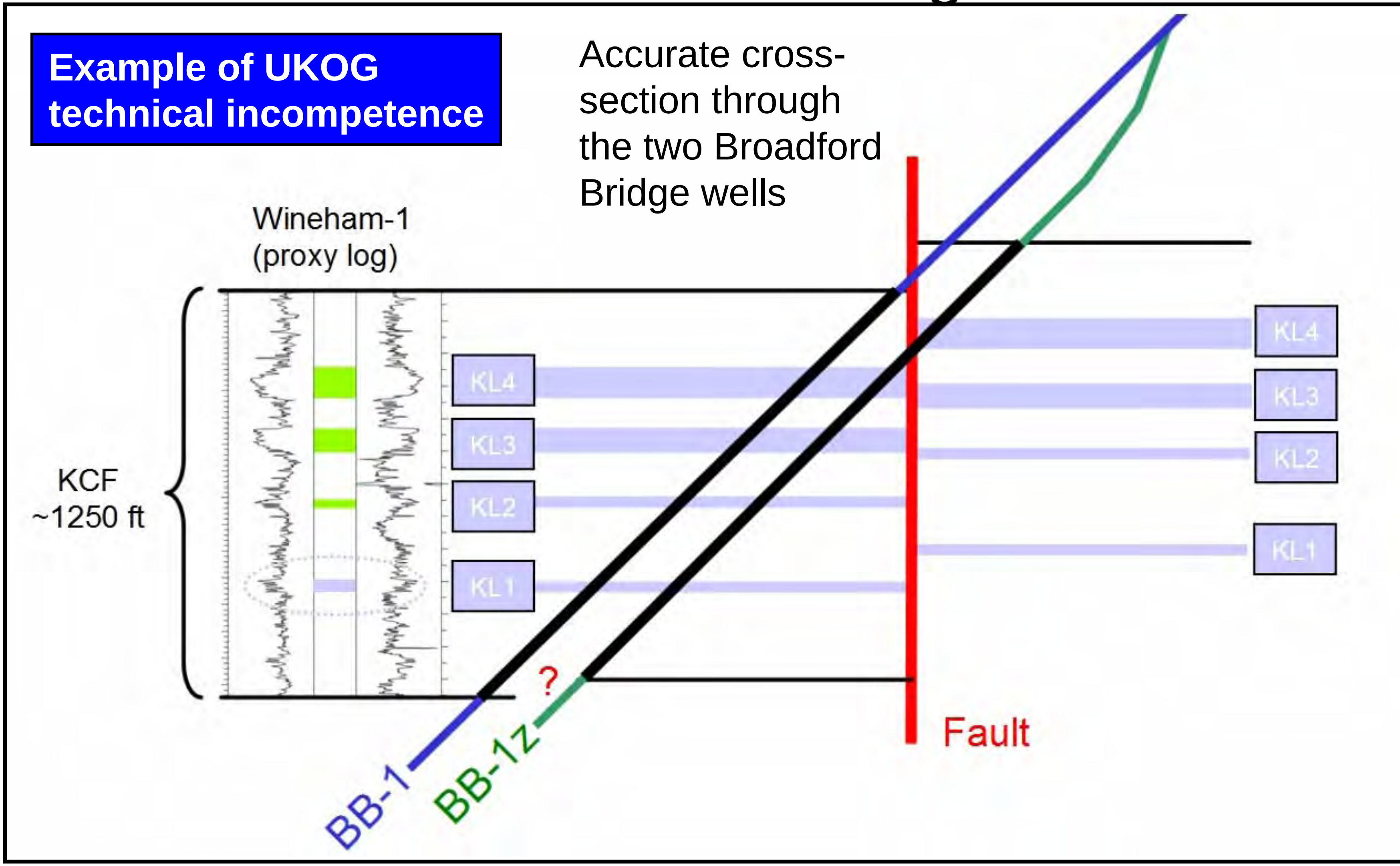


Fig. 4.1 UKOG subsidiary KOGL illegally flouted the permit conditions, drilling a very steeply inclined well at a different azimuth to test the Kimmeridge Clay Formation and not the permitted 'Willow' conventional target. In doing so it encountered borehole washout problems because they were crossing 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



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.

Fig. 4.2

Cliffs at Kimmeridge Bay, Dorset

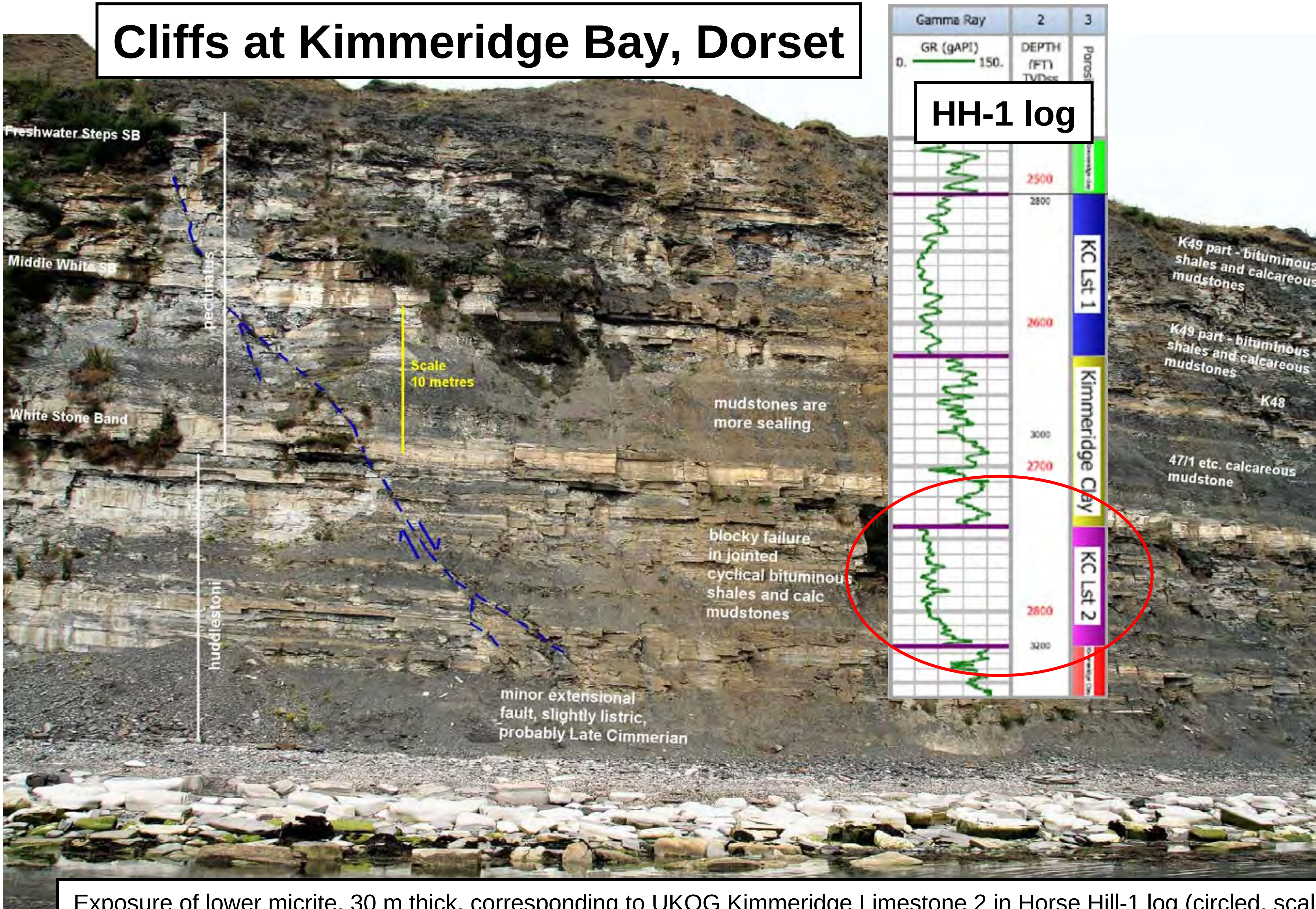


Fig. 4.3

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

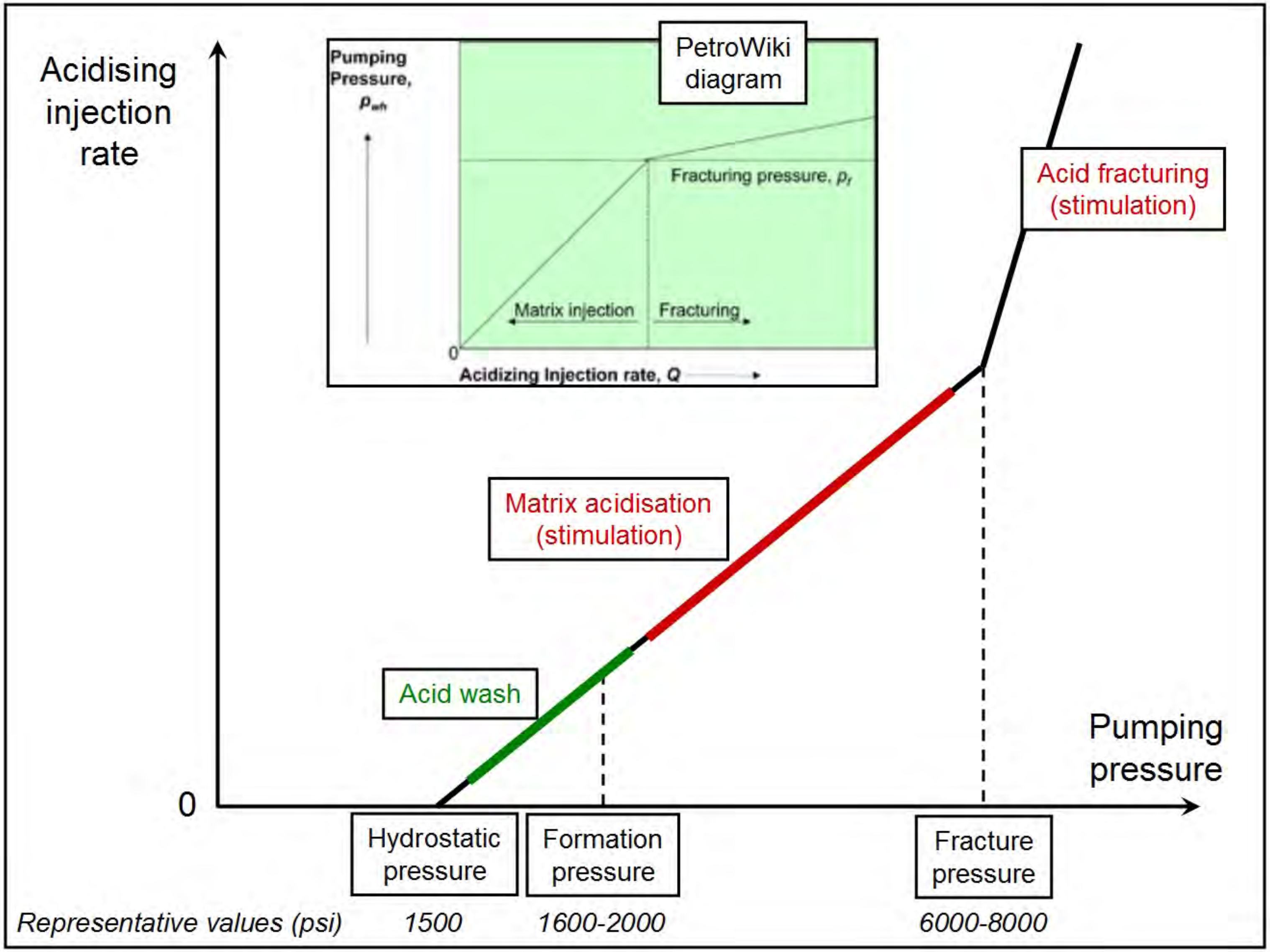


Fig. 5.1 Difference between an acid wash (green) and matrix acidisation (red), depending on the pumping pressure.

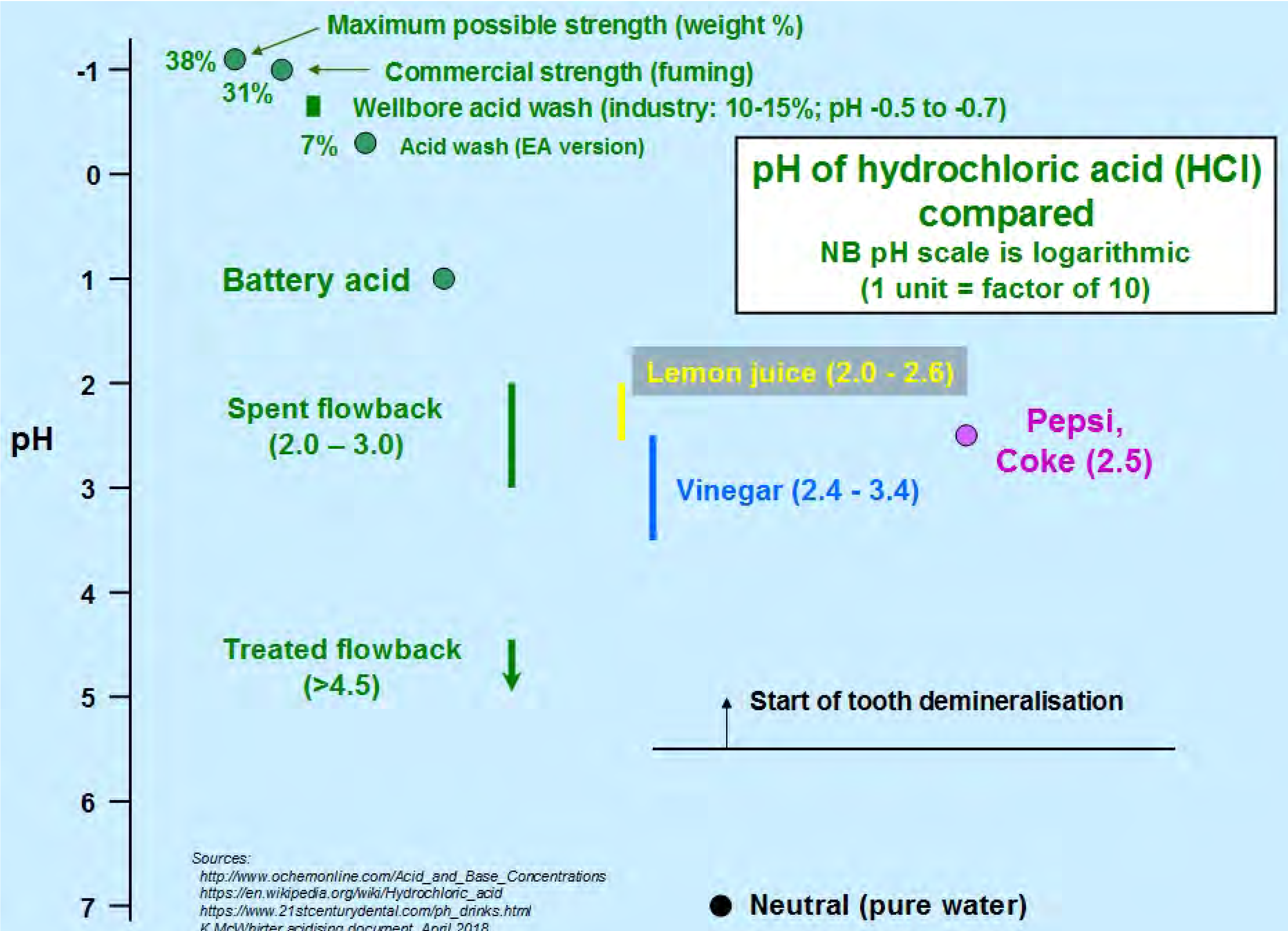
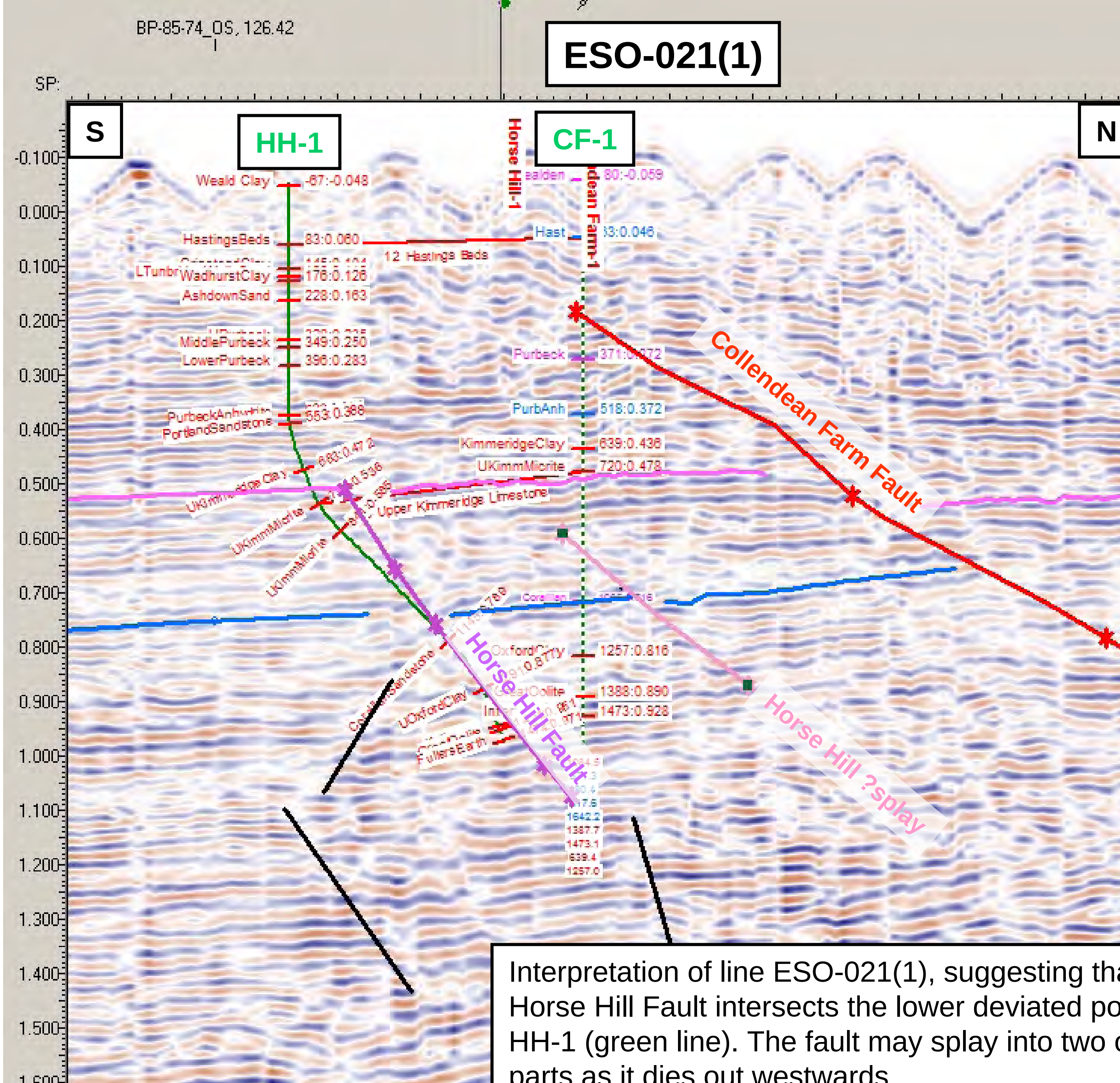
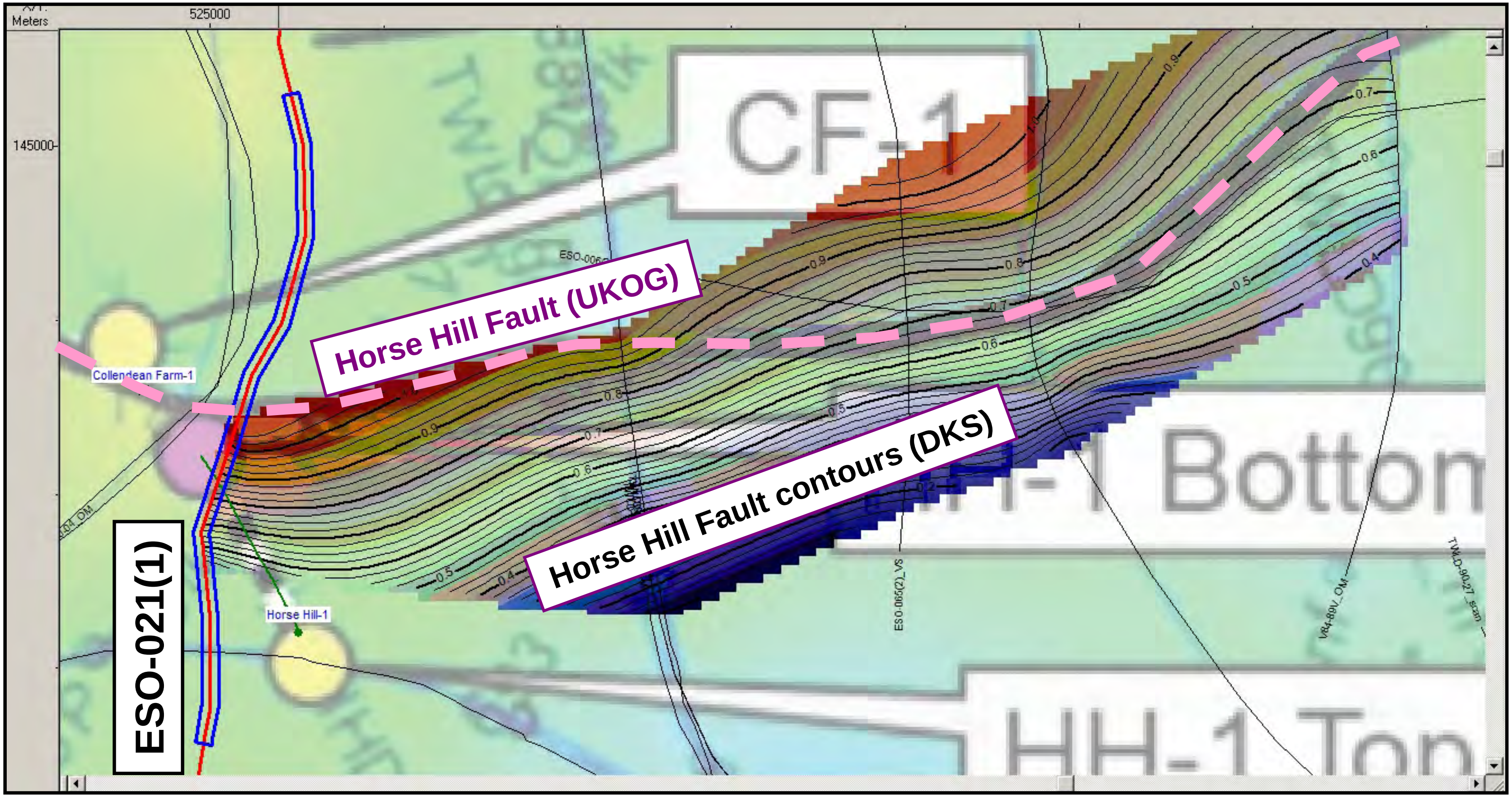

Maximum possible strength (weight %)
38%
31%
Commercial strength (fuming)
Wellbore acid wash (industry: 10-15%; pH -0.5 to -0.7)
7%
Acid wash (EA version)
pH of hydrochloric acid (HCl) compared
NB pH scale is logarithmic
(1 unit = factor of 10)
-1
0
1
2
3
4
5
6
7
pH
Battery acid
Spent flowback (2.0 – 3.0)
Lemon juice (2.0 - 2.6)
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. 5.2



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.

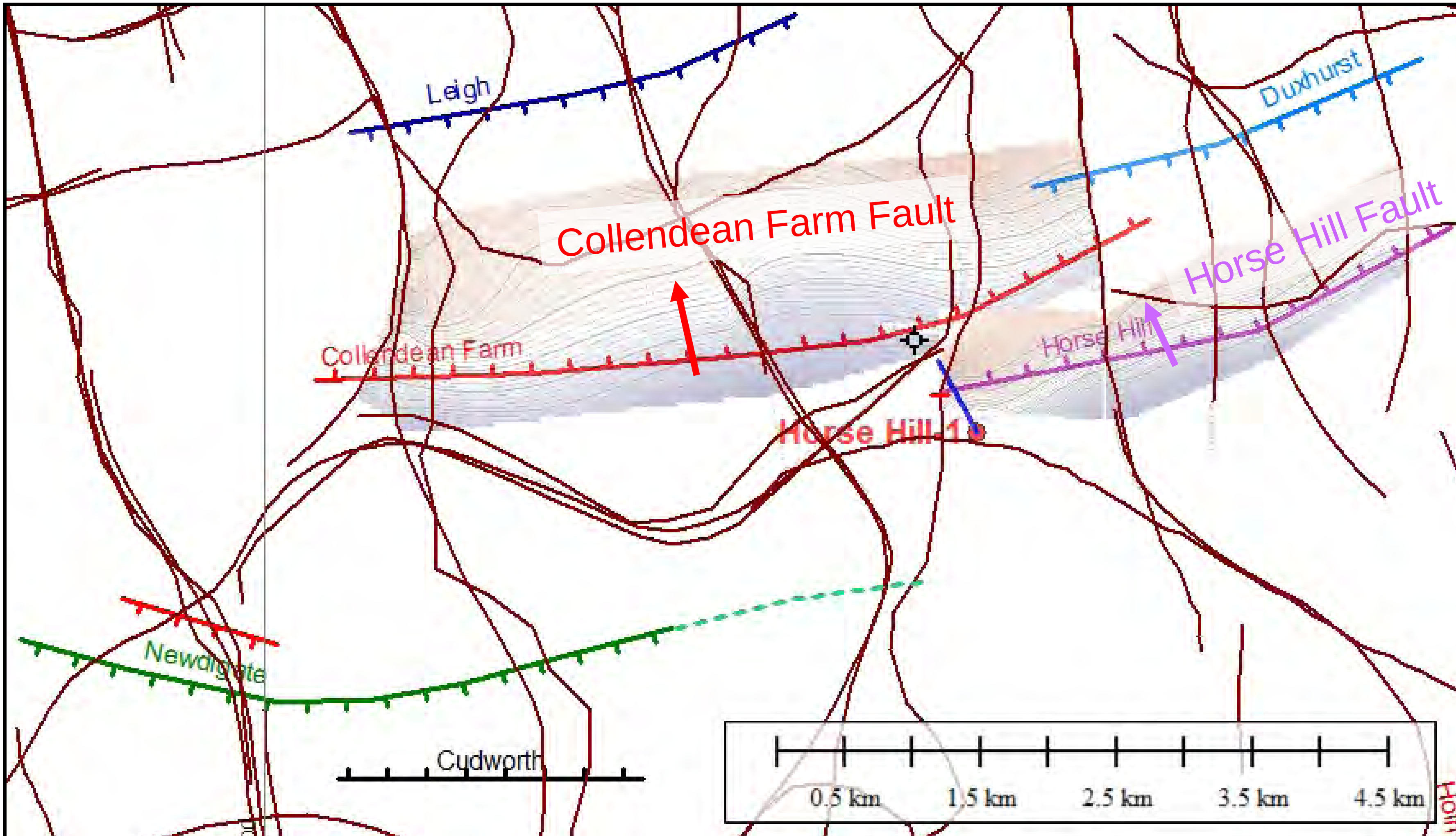
Fig. 5.3



Contours (TWT in seconds) on the Horse Hill Fault. It terminates in the vicinity of line ESO-021(1) shown in Fig. 5.3, and here may splay into two or more strands. The underlay is the UKOG Top Great Oolite map, with its location of the Horse Hill Fault highlighted in pink. The portion of ESO-021(1) shown in Figure 5.3 is highlighted in blue.

Fig. 5.4

Fault surface maps



In my interpretation the Collendean Farm and Horse Hill Faults are clearly separate structures. Horse Hill-1 was drilled into the Horse Hill Fault. The coloured surfaces are the respective two faults, contoured, with arrows showing the dip direction of the fault surfaces.

Fig. 5.5

HH-1 Isometric view looking west

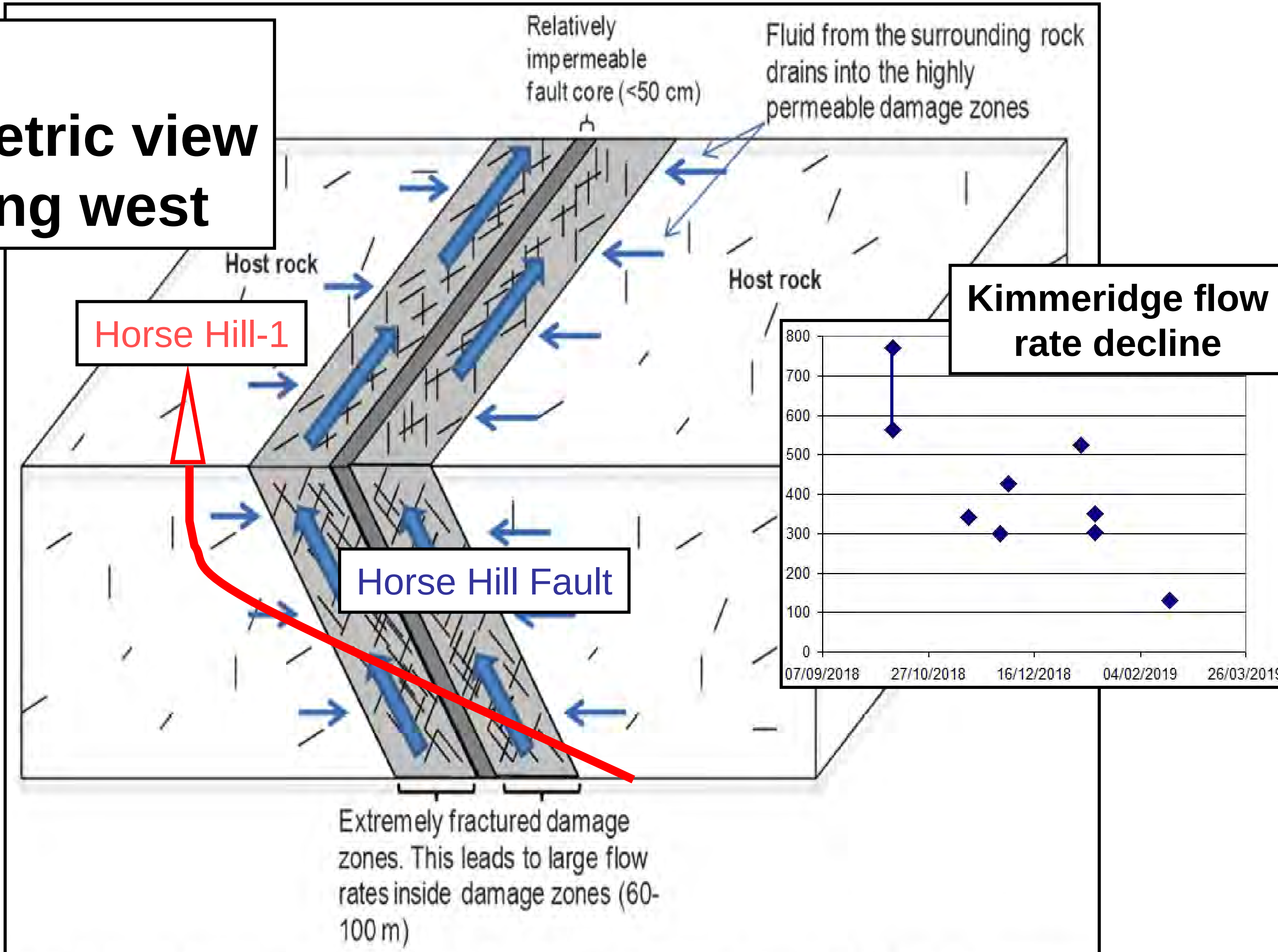
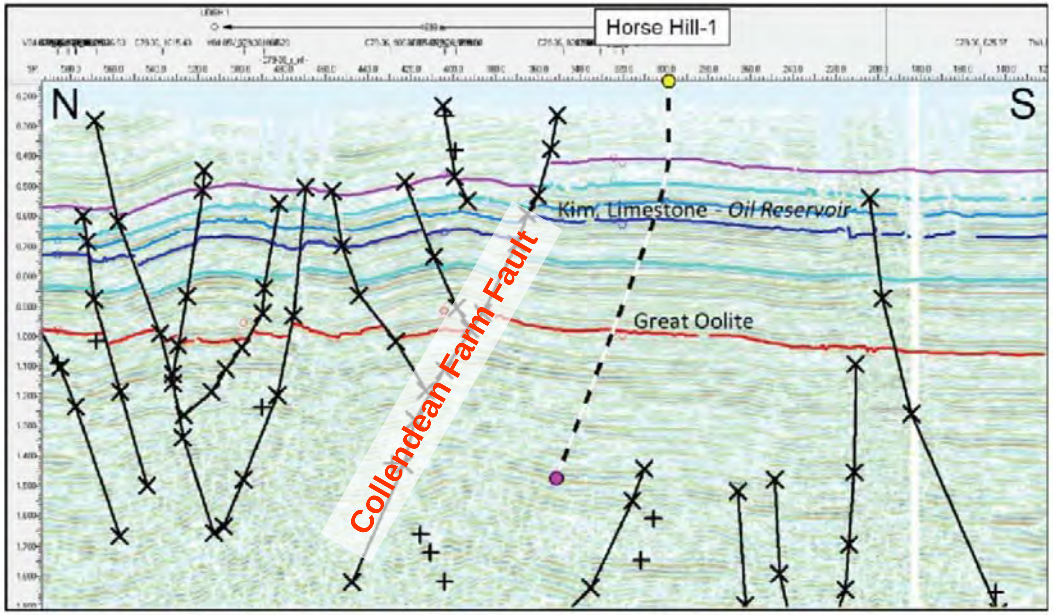


Fig. 5.6

HH-1 was drilled c. 100 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.



C79-36

UKOG interpretation of line C79-36 showing the Collendean Farm Fault and other faults. HH-1 has been projected WSW by 1000 m (black-and-white dashed line).

Figure E: Seismic line showing the Horse Hill-1 well and that it does not intersect any faults.

Location map. The offset of HH-1 from the seismic line C79-36 is about 1000 m.

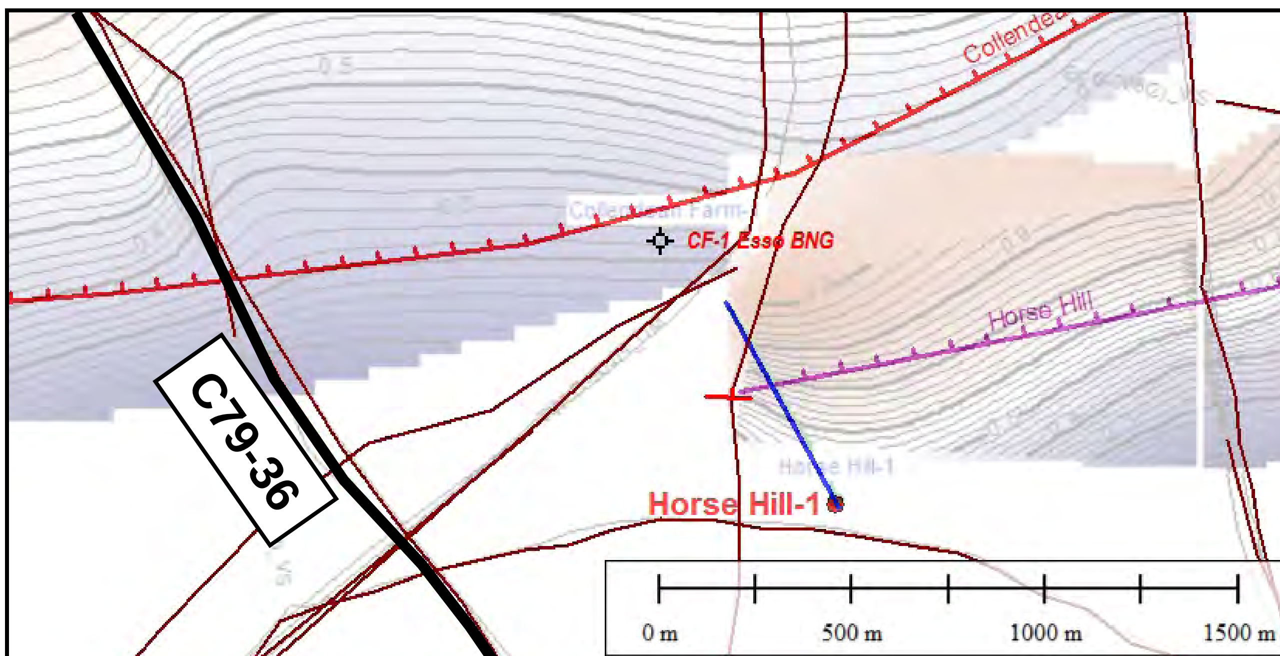


Fig. 6.1

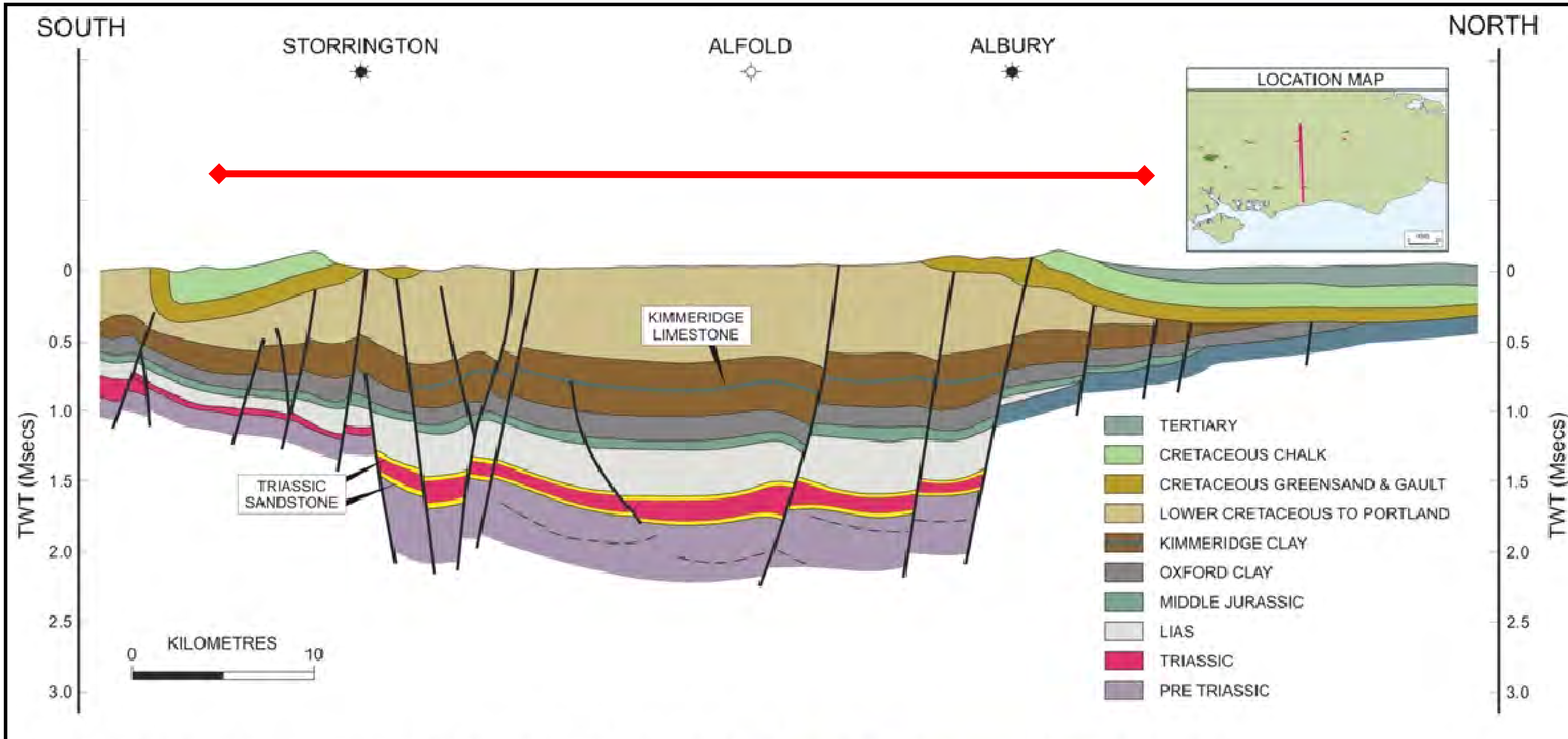
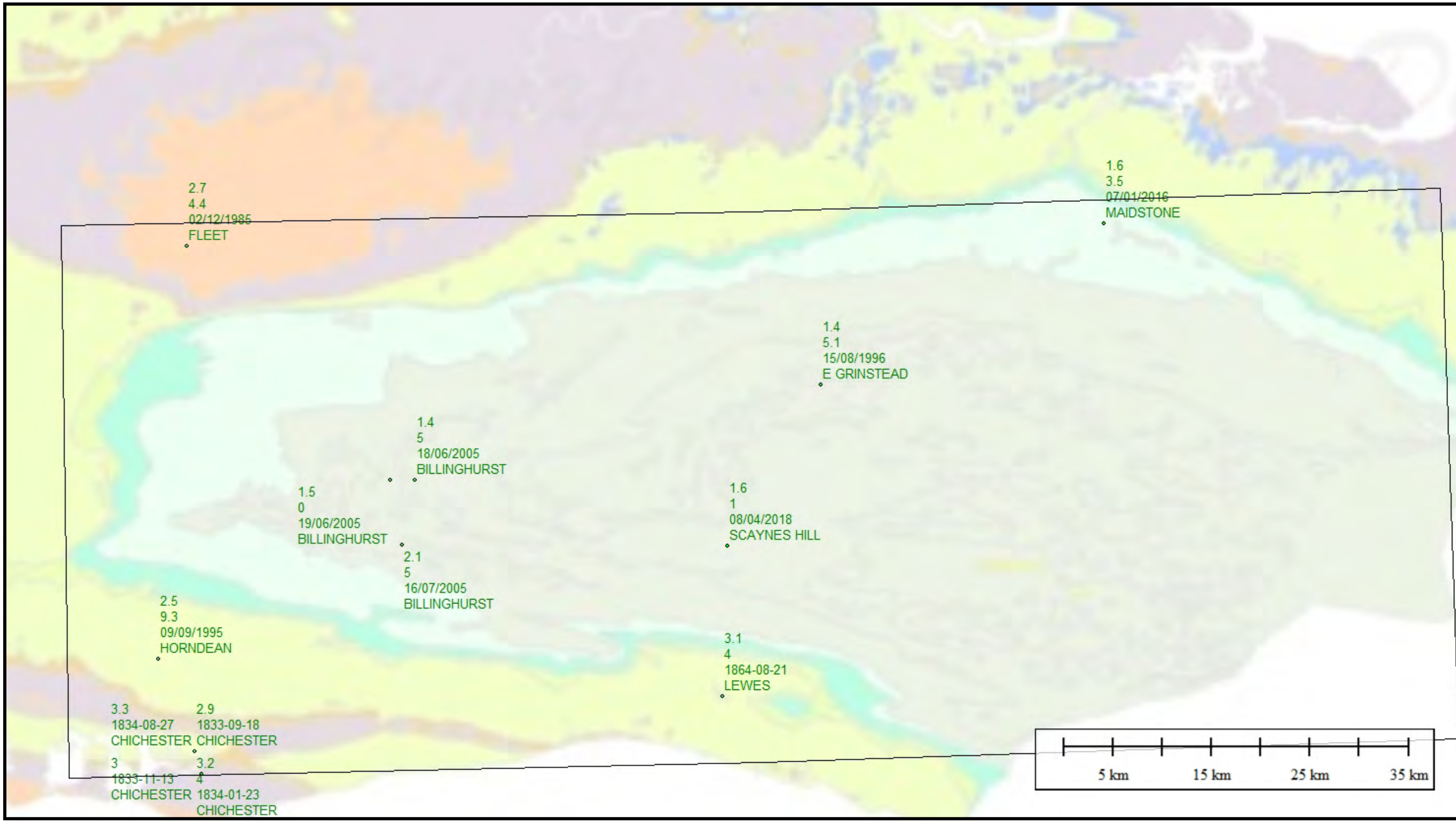


Fig. 2. Geological cross-section of the Weald Basin. After Butler & Jamieson (2013, plate 1).

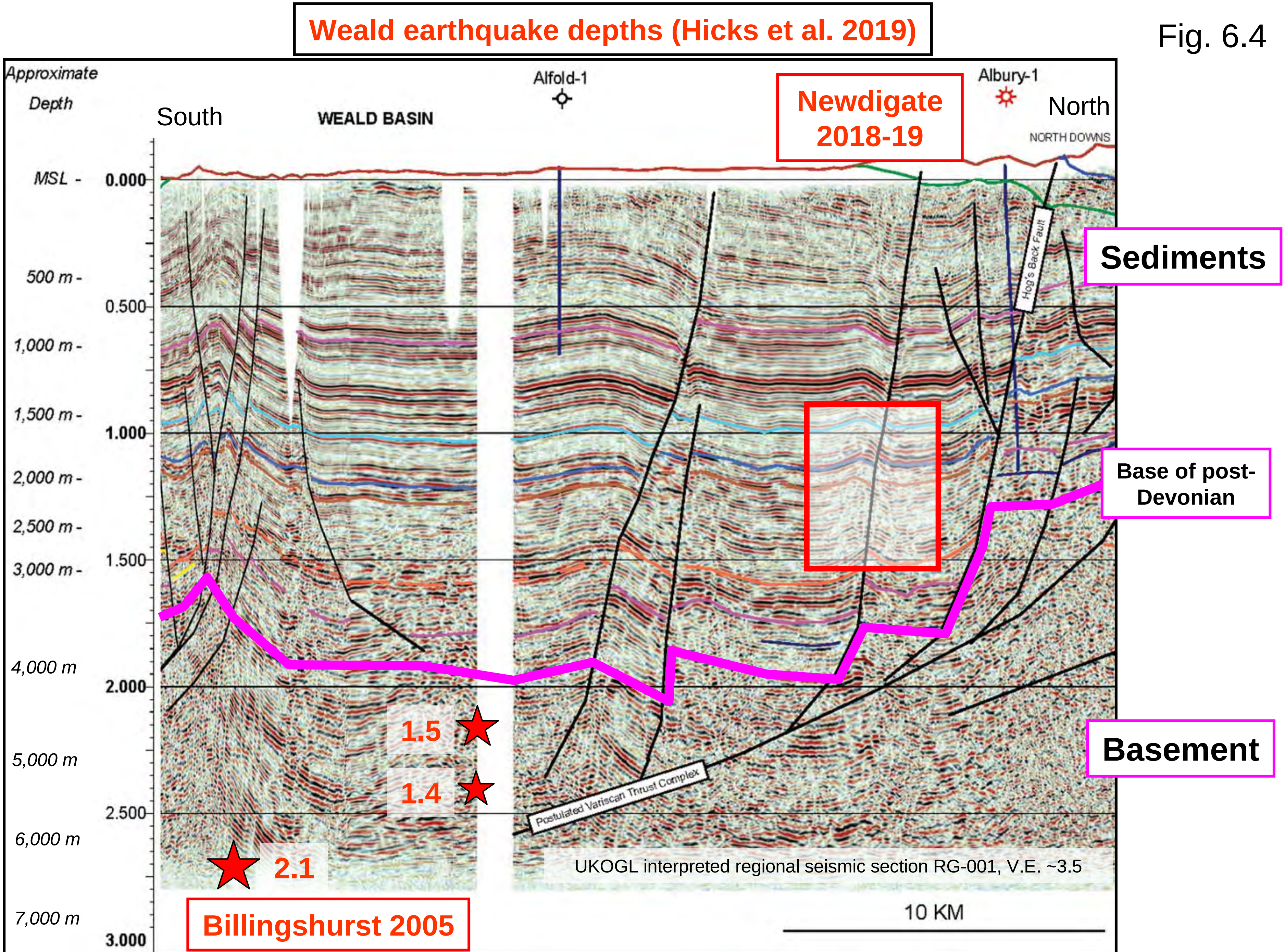
Regional seismic profile across the Weald depicted by Pullan and Butler (2018). The N-S geological limit of the Weald Basin is shown approximately by the red line.

Fig. 6.2



Results of search of the BGS catalogue for all earthquakes since 1700 within the rectangle. The 2018-19 Newdigate events have been omitted.

Fig. 6.3



Weald earthquake depths (Hicks et al. 2019)
Fig. 6.4
Approximate Depth
South
WEALD BASIN
Alfold-1
Newdigate 2018-19
Albury-1
North
NORTH DOWNS
MSL - 0.000
500 m -
0.500
1,000 m -
1,500 m -
1.000
2,000 m -
2,500 m -
1.500
3,000 m -
4,000 m
2.000
5,000 m
2.500
6,000 m
7,000 m
3.000
Hog's Back Fault
Sediments
Base of post-Devonian
Basement
Postulated Variscan Thrust Complex
1.5
1.4
2.1
UKOGL interpreted regional seismic section RG-001, V.E. ~3.5
10 KM
Billingshurst 2005

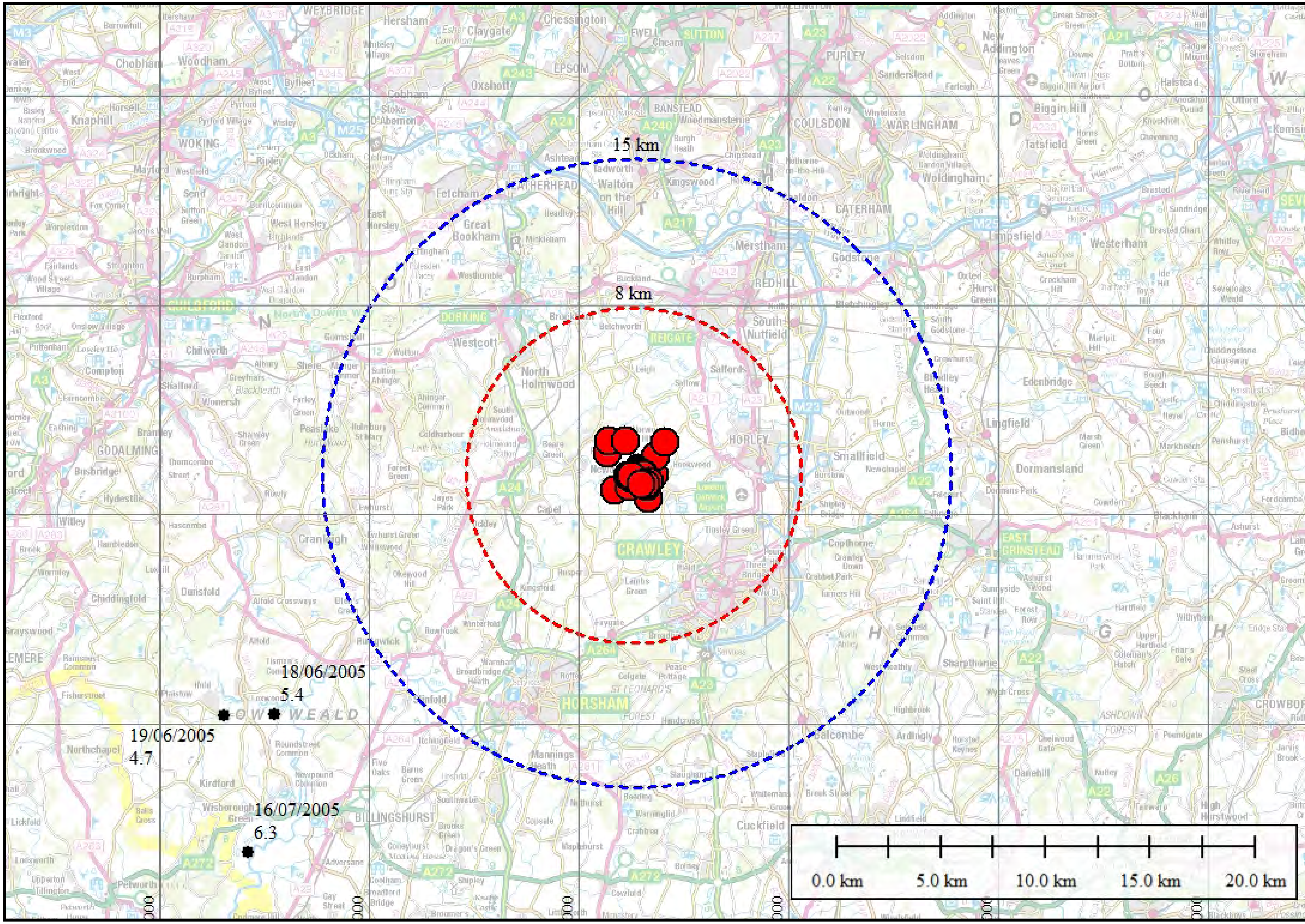
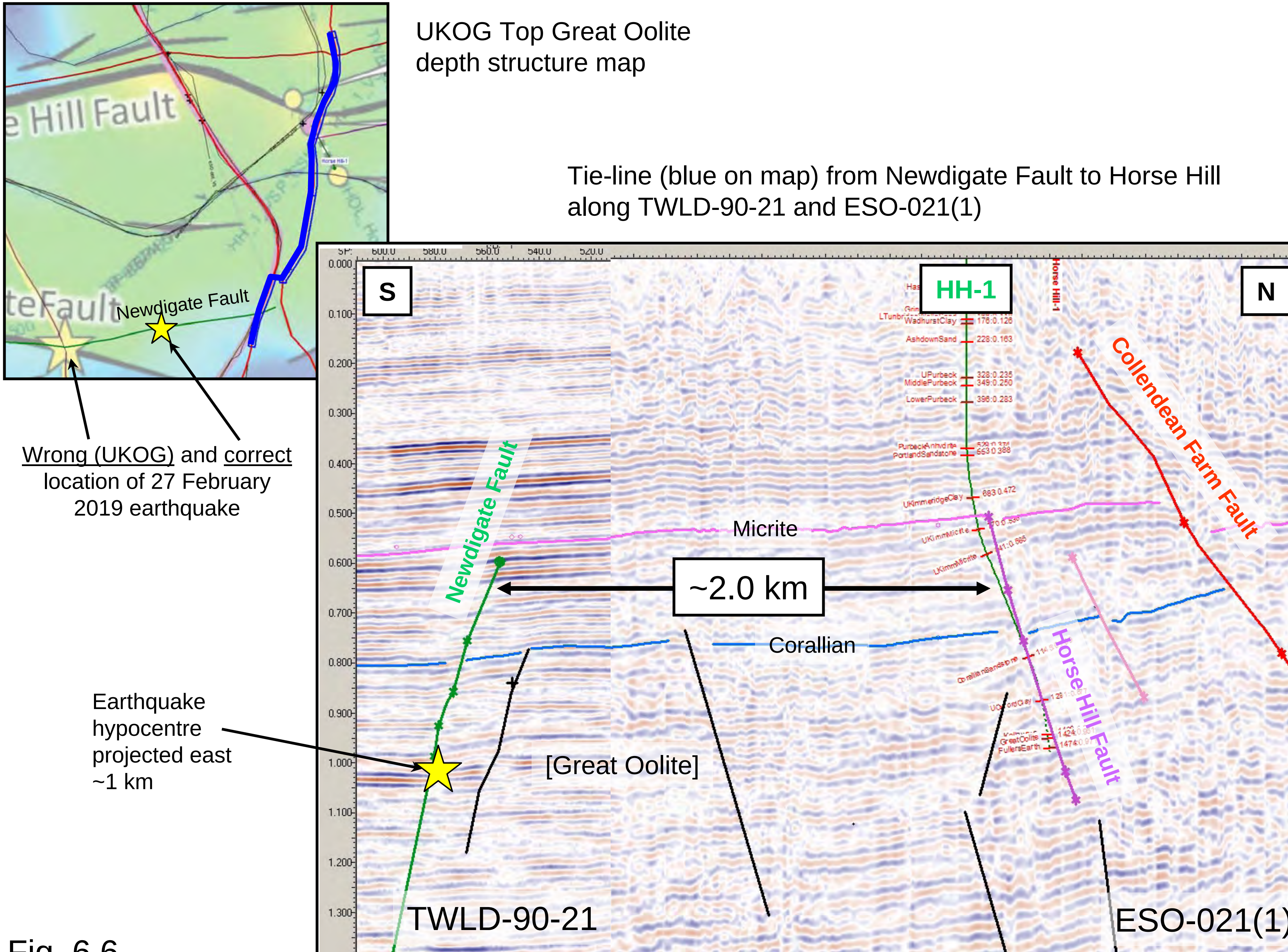


Fig. 6.5 Newdigate earthquake swarm 2018-19 (red circles). Range rings of felt seismicity are drawn around the 27 Feb 2019 ML=3.1, depth=2.3 km (15 km radius, blue) and the 19 Feb 2019, ML=2.0, depth=2.5 km (8 km radius, red) Newdigate events. The 2005 Billingshurst events are shown in black.


UKOG Top Great Oolite
depth structure map
Tie-line (blue on map) from Newdigate Fault to Horse Hill
along TWLD-90-21 and ESO-021(1)
Hill Fault
Newdigate Fault
Wrong (UKOG) and correct
location of 27 February
2019 earthquake
Earthquake
hypocentre
projected east
~1 km
S
HH-1
N
Newdigate Fault
Collendean Farm Fault
Horse Hill Fault
Micrite
~2.0 km
Corallian
[Great Oolite]
TWLD-90-21
ESO-021(1)
WadhurstClay
AshdownSand
UPurbeck
MiddlePurbeck
LowerPurbeck
PurbeckAnhydrite
PortlandSandstone
UKimmeridgeClay
0.000
0.100
0.200
0.300
0.400
0.500
0.600
0.700
0.800
0.900
1.000
1.100
1.200
1.300
Fig. 6.6