Planning application no. SDNP/1305896/CM

by Celtique Energie to drill at

Fernhurst, West Sussex:

Critique of environmental statement in the context

of relevant geology and hydrogeology

By

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NON-TECHNICAL EXECUTIVE SUMMARY

I have been asked by Lynchmere Parish Council to supply it with information. This paper is both an appendix to its submission, but is also being submitted in its own right as an **OBJECTION** to the development.

The present application to drill a test vertical well, followed by a contingent horizontally deviated well along an unspecified geological formation, is the first stage of a progression towards hydraulic fracturing ('fracking') of shales for oil or gas. The target for the horizontal drilling (and hence any future fracking) is the Middle and Lower Lias shale. There is no other possible outcome to this initial exploration phase, apart from withdrawal from the site after this stage. *Therefore the application must be considered in the context of the intention to frack.*

Celtique Energie claims that the well is 'conventional', but the target oil (or gas) is held in an 'unconventional' rock formation; it is not 'conventional', as claimed. By 'unconventional' we mean a geological formation which will require horizontally directed wells, fracked to release the oil or gas. There is no finite prospect of the exploration resulting in conventional (orthodox) oil or gas production, that is, fluid which would flow of its own accord.

Assertions that fracking has been going on for many years, including in the UK, are misleading, because the scale of this historical fracking is tiny in comparison to what is envisaged in the exploitation of shale gas (by 'scale' I include length drilled, fracking pressures and volumes of fracking fluid). The 200 or so onshore wells that have been fracked on this small scale before 2012 are all vertical; the Wytch Farm oilfield (Dorset) has horizontal wells, but none were fracked, as has been claimed by some.

The crucial question of faulting has been ignored by advisory committees in the UK, including the Royal Society. In addition, the reports from such committees have accepted uncritically the results of a US industry-funded study, based on confidential data, purporting to show that fracking is safe. I have shown by an extensive review of the four principal shale gas basins in the USA used by the American study that, in effect, *there are no faults in these basins which connect the fracked shale to the surface*. The opposite is the case in the Weald, where a myriad of near-vertical faults cut through from the surface (or within 300-400 m of the surface in the case of the PEDL231 licence area containing the present application) to depths much greater than the shale deposits. No such faulted basin has ever been fracked before; therefore the Weald would be a guinea-pig for testing the safety (or otherwise) of such operations.

Faults are complex and unpredictable structures. In the absence of strong evidence to the contrary, faults at depth are assumed to be leaky. In Sussex it is likely that some faults will leak fracking fluids and/or methane both to groundwater resources and to the biosphere. Evidence of oil and gas seeps at the surface of the Earth in East Sussex suggests that faults are leaky.

Although the groundwater resources below the licence area are minor, they are not negligible. Even where faults are absent there is the possibility of upward leakage from depth, because the cover rocks above the shale layers do not form a good seal, or 'cap'. This is proven by the abundant natural issues of water onto the surface from depth in the area around the proposed well. Recommended baseline studies of groundwater, natural gas emissions and seismicity should be undertaken before any drilling.

In addition to the finite risk of severe environmental pollution as a result of fracking, there is the risk of earthquake damage, from:

- The fracking process,
- Subsequent production of oil or gas,
- Injection of waste fracking fluid back underground.

All three cases have been demonstrated in the USA, and the first of these also in Lancashire.

A large German study of the environmental risks of fracking advises that the method be banned from any area which is faulted. This supports my view that any application which is aimed at fracking should not be permitted in geological structures such as the Weald Basin.

Therefore on technical and environmental safety grounds:

the application should be refused.

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1 INTRODUCTION

1.1 Relevant personal details from my 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.

Prior to my taking up the Chair of Geophysics at the University of Glasgow in 1988 I was employed by the British Geological Survey (BGS) in Edinburgh, from 1973 to 1987. I was a research scientist, rising to the post of Principal Scientific Officer. My work in the BGS from 1973 to 1986 was funded by the UK Department of Energy as part of a Commissioned Research programme on the geology of the offshore UK region. I also gave geological advice to the Foreign & Commonwealth Office on matters pertaining to UK territorial claims offshore. This was during the exciting phase of early discoveries and development of the North Sea. I headed a team of seismic interpreters working mainly on the prospectivity of the western margins of the UK, using the industry seismic and well data supplied to the Department of Energy. As a result I became the UK's leading expert on the deep geology of the continental margin west of the British Isles. Although our interpretation groups in the BGS were never able to commission our own wildcat wells, we had many 'virtual successes', where our independent interpretations were confirmed by subsequent drilling, and where the industry operator was proved spectacularly off-course.

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

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

Since my retirement from the university in 1998 I have carried out private research, acted as a consultant to the oil industry, and maintained an interest in the geological problems raised by nuclear waste disposal, shale gas exploration and coal-bed methane exploration. My tools for this work are up-to-date; I have my own licence for ProMAX 3D on a Linux workstation (seismic data processing), and currently hold on loan industry-owned licences for SMT Kingdom (seismic and well interpretation) and ModelVision (gravity/magnetic modelling including tensor fields).

1.2 Declaration of interest and non-liability

I have no interests to declare. This document was requested by Lynchmere Parish Council, which is paying me a modest honorarium. I am not connected to, nor am I a member of any activist group, political party, or other organisation. I am solely responsible for its contents. It is supplied in good faith, but I can accept no liability resulting from any errors or omissions.

2 GEOLOGY OF THE FERNHURST SITE

2.1 The geology database

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

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

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

All the released 2D seismic data are available in preview form online via the UK Onshore Geophysical Library. This dataset excludes seismic data recently acquired by the Applicant, Celtique Energie Weald Ltd, hereinafter referred to as 'Celtique'.

2.2 Relevant aspects of the geology

The geology of the site and its environs out to a radius of 10 km comprises flat-lying layers of sediments of Jurassic to Tertiary age, cut by minor faults. The density of faults varies throughout the PEDL231 and PEDL234 licence area (Fig. 1). The intensity of surface-mapped faults dies off progressively from east to west, and there are just three such faults in PEDL231. Two of these lie about 600 m and 100 m respectively east of the wellsite, and trend north-south. Figure 2 shows these faults in the context of available seismic reflection lines, shown in green with numbered shot-points. There is a large data gap south and SW of the well. It is not known whether this has been infilled by recent Celtique Energie confidential data; however, it is very unlikely that new seismic was acquired around Fernhurst because according to Celtique, in 2011 the *"National Trust'"*refused permission for a seismic survey to enter its property. All the lines of the 2011 survey, which was undertaken in July and August, stop at the Park boundary. The National Trust may have been confused here with the SDNP.

The short red lines show where faults at depth can be recognised from the seismic images. No attempt has been made to correlate these with one another, although it is probable that their general trend is east-west.

Figure 3 shows a detail from a regional study of the hydrocarbon potential of the Weald Basin by Butler and Pullan (1990). Although this paper is based on work of 25 years ago it remains the latest published synthesis of information on the region. It is not too out-dated, because thereafter the area went through a fallow period for more than twenty years during which there was little or no exploration activity. One of the authors, Dr. Chris Pullan, is currently the Exploration Manager of Celtique Energie.

Figure 3 shows that there is a strong set of E-W trending normal faults at depth traversing the Weald, even though few of them have a surface expression. Both of the proposed Celtique wells lie in the area where the Jurassic basin is deepest. The green line in Figure 3 shows the location of a north-south geological cross-section drawn by Butler and Pullan. The central part of this section is depicted in Figure 4, with the two wells projected onto the section.

Celtique's recent geological studies in the SE corner of PEDL 234 have identified a conventional oil prospect named Willow. The Top Triassic map of this area is equivalent to the Base Jurassic map of Figure 3. In this area more E-W trending faults than previously recognised have now been mapped. The structural cross-section for this prospect is shown in Figure 5. It shows faults extending from Palaeozoic (Carboniferous) up to the Ashdown Beds of the Lower Cretaceous, about 300 m below the surface. This illustrates that the western Weald is, in general, cut by many such faults which do not break the surface and cannot therefore be mapped by surface geology.

2.3 What are Celtique's ultimate targets?

It is difficult to discern the purpose of the proposed Fernhurst-1 well, because the application documents are either opaque or vague regarding the geological targets. This leads us to question:

1. Why is Celtique now choosing to drill within the South Downs National Park when it was apparently refused planning permission to enter the Park in 2011 for the purpose of seismic survey?
2. What are the criteria for the Primary and Secondary search areas within PEDL231?

3. How does Celtique propose to drill a lateral well both here and at Wisborough Green, when neither of the operations can be guided by a seismic profile?
4. Why is Celtique choosing to drill Fernhurst-1 within the National Park, when all the answers to its preliminary exploration questions can be answered by the proposed work at Wisborough Green, some 16 km to the east.
5. How can the Primary and Secondary search areas for the wellsite selection exercise within PEDL231 be objectively evaluated when no criteria have been supplied as to how these areas have been selected?

The only semblance of any geological detail is provided in Celtique's planning application, chapter 4:

> *"4.53 ... the 8½" hole is drilled with some* ***coring in the Kimmeridge Clay and Kimmeridge Limestone****, to the top of the Upper Lias at which point 7" casing is then run and cemented to surface to isolate the Kimmeridge, Corallian and Oxford Clays. Finally, a 6" hole is drilled to the* ***target Middle Lias, and cores taken****."* [my emboldening]

Coring (the taking of solid rock cylinders) is normally done only at the layers of interest. Although the application mentions a contingent deviated well, nowhere is it stated what geological layer this will be targeted on. There is a map (application drawing no. 1 (3624 P 01)) of which the central portion is reproduced as Figure 6. It shows a deviation path of just 260 m to the SW. This is too large to be a normal deviation of a vertical well in terrain such as this where the layers are supposed to be flat-lying. On the other hand it fits the preferred direction of horizontal drilling in this region for a wellbore designed to be fracked. Its length is only 260 m, which seems rather short for a horizontal side-track. In practice this horizontal distance is about equal to the radius of curvature of the hole to bring it from vertical to horizontal, so little or no actual horizontal drilling would be done if this published plan is adhered to.

Regionally, the well area lies in the centre of a large geological depression or syncline, as illustrated by Celtique and reproduced here as Figure 7. The syncline also coincides with the region of thickest Kimmeridge Clay as mapped by DECC (2010). However, the diagram, although schematic, is misleading, because the central area of the Weald at depth is practically flat-lying and not synclinal (bowed downwards) in shape. This is demonstrated as follows:

1. The regional cross-section shown in Figure 4 shows that the central deepest part of the basin is flat.

2. The regional seismic section published on exhibition boards by Celtique shows a similar flat central area.
3. The detailed seismic section shown on the exhibition boards by Celtique shows planar flat-lying layers.

The deepest part of the Jurassic-Cretaceous Weald basin owes as much or more to down-faulting as to down-folding.

It is clear from Figure 2 that the nearest seismic data to the propose wellsite lie 500 m to the north. A single detailed sample of flat-lying seismic data has been used both for the Wisborough Green-1 proposal and for the current Fernhurst-1 proposal. It is not evident, therefore, whether this sample of seismic data relates closely (or at all) to either well. It can hardly be construed as being 'close' to both wells. It appears to be the western half of an east-west line TER-91-06, reprocessed, which runs in a wavy line from east to west (Fig. 8). If so, it is misleading to use the line as being relevant either to Fernhurst-1 or to Wisborough Green-1. It is also disingenuous to use an 8 km long sample of a seismic line, entirely within PEDL234, to illustrate the prospect in PEDL231. Best practice, in contrast, is to illustrate the proposed well by a seismic line running *through* the well.

The seismic line sample as used by Celtique is reproduced in Figure 9. It was recorded in 1991 by Geco-Prakla using a group of four vibroseis trucks as the seismic source. In Figure 10 I have compressed it horizontally and displayed it side by side with the original image of the relevant part of TER-91-06. Both versions of the line are *migrated*, which means a better image than a more basic *stacked* section. The vertical offset between on and the other of about 220 ms is due to a different *static correction* having been applied in each case. The original version was obtained for Teredo Petroleum PLC and processed locally by Digital Exploration Ltd of East Grinstead.

In my view the original version of TER-91-06 is better than the reprocessed version used by Celtique, because it shows the faulting that is present. The reprocessed version used by Celtique has a smeared-out quality; the fine detail of the faulting has been obliterated. Figure 11 shows a fault (red curve) that can be interpreted on the original version, cutting very obliquely through the section between 1600 and 1900 ms. The fault is probably planar; it is the seismic line that is curved and hence intersects the fault-plane twice. The central part above the 'smile' is the upthrown side. Detail within the black rectangle is shown in Figure 12. There are two faults in the Middle Jurassic and Lower Cretaceous, extending upwards at least in one case into the

Weald Clay. This is important evidence, because the Weald Clay is supposed to act as the impermeable cover-rock layer to prevent any upward migration. The problem of faults, sealing of hydrocarbons, and seepages of hydrocarbons are discussed in subsequent sections.

2.4 Unconventional nature of the exploration

It is my view that Celtique's opacity concerning what resource it intends to exploit at Fernhurst is designed to shield from view the fact that the company is seeking to exploit the unconventional shale gas (or oil) resource of the Weald. This will ultimately require fracking, even though the two exploratory well drilling applications state explicitly that fracking will not be carried out in the current applications.

Celtique has presented exhibition boards for public consultation with reasonable definitions of 'conventional' or 'unconventional' oil or gas fields, below the heading *"So, is this well Conventional or Unconventional?"* [my underlining]. Note that whereas Celtique defines the two terms in the context of fields, it refers to the well which is the subject of the planning application, and claims that the well is conventional technology. This is correct as far as it goes.

There are a variety of discussions and definitions of what is meant by 'conventional' and 'unconventional'. IHS, a major oil information management company, stresses that the meaning of the terms may evolve (Chungkham 2011) – exploitation techniques that were once termed unconventional may later become commonplace, or conventional. Matt Hall (2011), an industry geologist, shows that the terms vary depending upon which class of expert is defining them – geologist, geophysicist, economist, etc. Cander (2012) of BP shows that unconventionals can be clearly defined if one plots viscosity of the oil or gas against permeability of the host rock. The two classes of resource lie on different areas of the graph.

Celtique's map of its licences in relation to existing discoveries (Fig. 13) shows why the proposed development is different. All the existing discoveries occur on local high spots corresponding very approximately to the elliptical shape added to the map. This is because the high structures are found around the edge of the basin. The present application is right in the centre of the basin, where the rock formations are deepest. Other wells have indeed been drilled in the deeper parts of the basin, but these were targeting true conventional resources, and all turned out to be unproductive.

If one of the two Kimmeridge Limestone layers is being targeted in the present application, then it is an **unconventional resource**, whatever flavour of definition is used. It is misleading of Celtique to label it as a 'conventional stratigraphic trap'. It will require both horizontal drilling and high-volume slickwater hydraulic fracturing ('fracking') to exploit. There is no realistic expectation that oil or gas will be discovered and produced by conventional methods – i.e. that the hydrocarbons will flow under their own pressure through rock which is adequately permeable without being fracked.

The recent report (22 January 2014) that Cuadrilla has discovered oil in the Kimmeridge Limestone in its Balcombe-2 well, and that this well will not require fracking, as stated in the current planning application to WSCC, is good news in principle. However, it does not alter the fact that Celtique is being disingeuous about what exactly it intends to do at Fernhurst, and whether or not exploration and potential oilfield development within the SDNP should be permitted or not (section 2.5 above). Cuadrilla's new planning application is merely a continuation of its proposals delayed from 2013. It remains to be seen whether or not the oil is present in commercial quantities and can be produced by conventional methods only.

However, I believe that shales, not limestones, are being targeted by the proposed drilling of Fernhurst-1. This is explained in the next section.

2.5 Evidence that Celtique is targeting shales

The exhibition boards for Fernhurst horizontal drilling show the same diagrams and montages as used for Wisborough Green. This is misleading, as it implies that the same Kimmeridge Limestone horizon will be tested. There is no rational reason or justification for re-testing a geological layer which Celtique has proposed to investigate at Wisborough Green, 16 km away. The geology is substantially identical at both sites. Therefore the real target at Fernhurst must lie elsewhere within the reach of the drill.

The Celtique statement quoted in section 2.3 above: "*a 6" hole is drilled to the target Middle Lias, and cores taken.*" is clearly a clue. If the Upper and Middle Lias shales were not of interest, money would not be wasted drilling that far down, nor would cores be taken, which is expensive. On the other hand, if the well were really designed as a so-called 'stratigraphic' test, to obtain a more regional picure of the deep part of the Weald Basin, then it would have been essential to propose drilling somewhat deeper than is actually the case, to prove the existence of the Triassic rocks (the top of which is marked in brown in Figures 9 and 10). Triassic sandstones are a target of Celtique's conventional exploration programme elsewhere in the Weald.

It is instructive to consider information previously published by Celtique and its partner Magellan Petroleum. Some of this information has since been withdrawn from view. Celtique's website, as of December 2012 stated:

> *"**Shale oil potential***
> *The shale oil play of the Upper and Middle Liassic in the Weald Basin is believed to be directly comparable to the Bakken and Paris Basin analogues. Both the Weald Basin and the Paris Basin are sub-basins of the Anglo-Paris Basin and the two basins have a common origin and geological history.*
> *With the emergence of horizontal drilling and multi-stage hydraulic fracturing in the US, production from the limestone layers in the Bakken shale has become highly commercially viable, opening up a recoverable resource potential of up to 4.3 bn bbls of oil according to the US Geological Survey. Oil and gas companies have also started exploring the shale oil potential at similar prospects outside of the US, and a joint venture between Hess and Toreador is currently exploring and developing the vast oil resource potential of the Liassic shales in the Paris basin."*

The thin Kimmeridge Limestone layer, embedded in the Kimmeridge Clay, was the target of Cuadrilla's well Balcombe-1, drilled in late 2013, and also of the proposed Wisborough Green-1 well. But the statement above suggests that the deeper Liassic clays are the primary target at Fernhurst-1. The same now-deleted web pages state:

> *"**Shale gas potential***
> *The seismic data and maturity modelling studies for the Weald basin also suggest that 2 shale gas resources may be located in the centre of the Weald Basin.*
> *The area of Liassic source rock within the gas window is believed to be over 467 sq.kms (115,000 acres) at exploitable drilling depths between 9,000 and 13,000 feet true vertical depth ."*

Celtique's Environmental Statement (ES) includes the following statements:

> *"2.8 ... Having evaluated seismic data of the underground rock structures in the Basin within PEDL 231, the Applicants* [sic] *geologists identified **a large structure deep** within the Basin.* [my emboldening]
> ...

2.9 This rock structure consists of Jurassic Limestones and Shales including the Kimmeridge Limestones, the Great Oolite, Kimmeridge Clay and Liassic Shales which may hold oil or gas accumulations."

2.10

There is no geological structure in the accepted sense of a target for conventional hydrocarbon exploration; the *"large structure"* referred to above is nothing more than the deeper part of the Weald Basin.

One of the shortcomings of Celtique's Environmental Statement is that we are unable to judge the validity or otherwise of the Alternative Sites Assessment, since we do not know what the targets are, and how they have been mapped. The primary search area is a mirrored D-shape or near semicircular area abutting the boundary of PEDL231 with PEDL234 to the east. Outside that there is a larger secondary search area also terminating against the licence boundary. It is remarkable that the primary search area coincides very closely to a Celtique map of 'base middle Lias limestone' maturity. The correlation is shown in Figure 14. On this map yellow indicates immature hydrocarbon content. The green area is predicted to be oil-mature, with more central contours being more mature, or favourable. Note how one contour closely matches Celtique's primary search area in PEDL231. The secondary search area appears to be a reduced-area version of the heavier outer contour.

2.6 Conclusion on Celtique's ultimate aim

Therefore the well, although 'conventional' in its technology, is merely **<u>the first step in planning for unconventional resource exploitation</u>**, and serves no other purpose. I believe that the Planning Committee of the South Downs National Park should consider this fact as germane to the determination of the application. There is no goal other than this end result. There is no alternative outcome expected such as free-flowing conventional oil or gas. The fact that fracking will necessarily be used, if this first step shows that the rock physical properties are promising, applies to all the target formations, whether they comprise a thin limestone layer sandwiched between clays or shale, or of course the Kimmeridge Clay and deeper Lias shales themselves.

An analogy might be useful here. Let us say that a planning application came forward to drill for and excavate test trenches for the foundations of a skyscraper in an area where the applicable planning policy included height restrictions on construction. The test drilling and trenching would not exceed the height restriction, but they will have no purpose other than to inform the applicant whether or not the envisaged skyscraper can technically be built. If the test results are unfavourable the site would be returned to *status quo ante*. Would such a preliminary planning development be permitted? I would think not, because there is no conceivable social or economic benefit to the community of having some boreholes drilled and trenches cut. Since the ultimate aim – the skyscraper – is *a priori* not permitted, and there are no intrinsic benefits in the excavation itself, the planning committee would therefore refuse the preliminary application.

The remainder of this document concerns the implications for the environment if and when the PEDL231 licence development is permitted to reach the stage at which fracking will prove necessary.

3 FRACKING TECHNOLOGY

3.1 Introduction

Given that the ultimate and sole purpose of Celtique's activities in here Sussex is **production of oil or gas by fracking**, it is justifiable to examine this process, and whether or not there is evidence to show that it can safely be applied in the Weald**.**

3.2 Fracking – old or new?

Proponents of fracking for hydrocarbons often claim that it is 'old' technology, and has therefore been thoroughly tried and tested over the 60 years or so since it was first developed. But this claim is a sleight of hand; modern fracking techniques are very different both qualitatively and quantitatively from those used before the 1980s. Some of the differences between modern and 'traditional' fracking include (King 2010):

- Horizontal drilling, not vertical
- 20 - 50 times greater volume of water used
- Extensive used of viscosity reducers and other chemical additives
- Each horizontal well leg is successively fracked, in 'stages'
- Simultaneous or delayed fracking employing real-time stress changes to control fracture directions.

The differences between this modern *high-volume slickwater fracking* (which is the method that would be used at Fernhurst) and fracking used for non-hydrocarbon resource development (e.g. water wells) is even more pronounced.

Pro-fracking academics such as Styles (2013) and Verdon (2013) have reported that around 200 onshore oil or gas wells in the UK have been fracked. These allegedly include the 'extended reach' horizontal wells drilled out out under Bournemouth Bay from Poole into the Wytch Farm oilfield (Verdon, op. cit.). The quoted figure of 200 is misleading; here is a detailed response obtained from Ms Toni Harvey, senior geoscientist in charge of onshore exploration and development at DECC, obtained in response to email questions from the refracktion.com website about where Professor Styles obtained the figure:

> *"DECC has records of some kind of the drilling of 2159 onshore wells (which we add to*

when a new one is spud, see "basic onshore well data" on https://www.gov.uk/oil-and-gas-onshore-exploration-and-production
We do not however have records of how many of these were fracked, because until recently fracking was regarded as a fairly routine oilfield operation and not subject to specific consent. From enquiries to the operators, we believe that at least 200 did have hydraulic fracturing treatments of some kind, but we would emphasise that these non-shale fracs are not comparable, in the volumes of fluid employed, to Cuadrilla's operations at Preese Hall in 2011 – the non-shale fracs are much smaller."

The message here from this authoritative source is clear – that the non-shale fracking operations are of a different and much smaller order. With the sole exception of the Preese Hall-1 well in Lancashire, drilled by Cuadrilla in 2011, all these wells are vertical.

Concerning the alleged fracking at Wytch Farm; the initial publication on the Wytch Farm oil field, Dorset (Colter and Havard 1981) makes no mention of hydraulic fracturing in the field. Its later development is described by Hogg *et al.* (1999). The extended reach wells attain a maximum horizontal distance of 10 km from the surface drillsite, but they have never been hydraulically fractured. They are designed to inject water low down into the oil-bearing aquifer (a 'bottom waterflood") to help the oil flow. This has no relevance to fracking of any sort.

It is reasonable to conclude that the kind of fracking that will be employed in the Weald (subject to approval of the present and any future planning applications by Celtique) is a new technology (approximately post-2000, or twenty-first century). Furthermore, **it has never been employed in the geological conditions which pertain in the potential oil and shale gas basins of the UK**. Therefore to quote the US experience of the last thirteen years or so as evidence of potentially safe operation in the UK is invalid, as I shall show below.

3.3 Comparison of US fracked basins with UK potential shale gas basins

I have investigated the geological structure of the four principal shale gas basins in the USA; the Marcellus, Barnett, Eagle Ford and Woodford shales. In total there are over half a million horizontally deviated and fracked well in these regions. The states concerned are principally Texas (TX), Oklahoma (OK) and Pennsylvania (PA). It is important to remember the scale of these states in comparison with the UK. Texas is somewhat larger in area than metropolitan France, but with a bit under half the population. Oklahoma is bigger than England and Wales combined, by 20%, but has only one fourteenth of the population of the latter. Pennsylvania is

90% as large as England in area, but with a quarter of the population.

My research has been driven mainly by the desire to investigate the claim made by Fisher and Warpinski (2012), who work for a subsidiary company of Halliburton, that fracking in the four US shale basins mentioned above includes areas of complex geology. In particular, the Halliburton engineers state:

> *"The Woodford's geologic structure can include substantial faulting, highly dipping bedding planes, overturned beds where a vertical wellbore could intersect the same series twice, and all manner of geologic complexity."*

I looked at all four shale basins presented by the Halliburton study, using all available geological maps, cross-sections, and published seismic data. The geological maps of the surface sometimes include detailed United States Geological Survey (USGS) 'quadrant' maps at 1: 24,000 scale. This is twice as large as the 1: 50,000 scale available from the BGS for the UK. There are also digital databases available in the USA of both geological boundary outlines and faults. I confirmed that the latter datasets include surface faults down to lengths of less than 1 km with throws (displacement of one side relative to the other) of a few metres. In effect, no fault data are missing from the digital database.

Except for Texas, my study uses online digital well databases, not just the Halliburton study data, for which the well locations are confidential and only located down to county level. I conclude from this study, which is in preparation for peer-reviewed publication, that the following wells lie within 1 km of a surface fault:

- 3 wells in the Woodford Shale, Coal County, Arkoma Basin, OK
- A further six or so wells in the Woodford Shale, Hughes County, OK near trivially small faults
- 9 wells in the Marcellus Shale, Bradford County, PA.

Any truth in the Halliburton assertion quoted above lies in the occasionally complex geological structure <u>at the level of the fracking</u>, but it is not the case that any faults from the fracked levels extend up to the surface. The only exceptions to this rule are the three examples listed above, comprising about 20 wells out of more than half a million fracked wells.

The Halliburton study, which has been widely quoted in support of the environmental safety of fracking, aims to show that the upward propagation of the fractures created by fracking is limited in extent, and that, in all cases of the c. 10,000 fracked wells used in the study, the highest fracture height lies well below the deepest water well in each county. Therefore, the argument proceeds, fracking *per se* cannot affect near-surface groundwater resources.

But one of the limitations of this study is that the extent of the fracture progress is measured by microseismic activity recorded during each fracking stage. The erroneous assumption here is that no microseismic 'noise' equals non-propagation of the fracture fluid upwards (or downwards). This is discussed in section 4.

The crucial difference, then, between the USA fracked shales and the UK potential shale gas basins is that in the latter, **the faults extend from the shale layer all the way to the surface**. This difference is due to the tectonic (mountain-building, structural) environment of the UK being completely different from all the US shale basins.

There is another fundamental difference between the shale basins or layers of the USA and those of England, and that is their dimension, both vertically and horizontally. In fact, a couple of the UK basins are called *troughs* and not *basins*; this implies that they are narrow and deep, and typically with faulted margins. Figure 15 illustrates this difference with a graph in which both axes are plotted logarithmically. This shows that in general the UK basins are 5 to 50 times thicker than the US basins, but 10 to 100 times smaller in surface area. The Weald basin, extending from Kent to Dorset is 2 to 100 times smaller in area than the US shales basins, but its Kimmeridge Clay shale layer is between 3 and 8 times thicker than any of the US shale layers.

The depths at which fracking has taken place in the US, compared with the depth at which the Kimmeridge Limestone would be fracked if the Celtique development goes ahead, are as follows:

- US shale basins: 1000-4300 m depth; 90% of wells greater than 1600 m depth.
- UK Kimmeridge Limestone: 730 m (Balcombe), 1200 m (Wisborough Green). 1400 m (Fernhurst).
- UK Middle Lias shales: 2400 m (Fernhurst).
- UK Bowland Shale, Lancs.: vertical well tested between approx. 2300 and 2650 m.

So the Kimmeridge Limestone target is unusually shallow compared to the US, only the Middle and Lower Lias shales are at a more suitable depth of burial.

3.4 Earthquake triggering

Because no fracking will be used *in the present application*, there will be no problem of earthquake triggering. However, in the next phase of development, where fracking will have to be used, US and British experience shows that earthquakes may be triggered by:

- The fracking process iself
- Gas production
- Injection of waste water into disused wells.

Note that some of the earthquake triggering correlations are also with activity at conventional oil and gas wells.

3.5 Critique of presentation by Professor Peter Styles to LDNPA

Professor Styles made a presentation to the South Downs National Park Authority on 15 October 2013. He is a prominent proponent of fracking, and has particular expertise in the problem of earthquakes generated by fracking activity. I have no access to what he said, only a pdf copy of his slides. Based on what can be inferred from the slides, there appear to be a number of errors and omissions:

1. He appears to argue that one cannot distinguish between conventional and unconventional exploration (slides 9-10). This is incorrect, as the discussion in sections 2.4 and 3.2 above show.
2. He implies that fracking is not new (slides 14-15) – this is untrue. Fracking of the high-volume slickwater type in horizontally deviated wells has only been around for less than 15 years. Previous types of fracking (which are generally safe) consume only modest quantities of water by comparison with what the public is concerned about.
3. His slide no. 18 illustrating by a cross-section of a fracking well omits any depiction of faults. The geology is grossly oversimplified.
4. Micro-seismic mapping of the progress of fracking is not the whole picture (slide 20). There is evidence of frack fluid progressing up a fault to a new level; this progress is silent, i.e. unaccompanied by the tell-tale signs of microseismic tremors, because a pre-existing fracture has been used.
5. He uncritically quotes a paper by Professor Richard Davies of Durham University (slides

21-23) on the empirical limit of how far fracks can progress upwards, which in turn refers uncritically to a questionable earlier study by Halliburton. This is discussed in the next section.

6. Styles suggests that 'good quality cementing' will protect wells from leaks (slides 23-25). This ignores the fact that all wells will degrade and leak in the long term. His attempt to use the Roman Pantheon as an example of the supposed longevity of concrete is inappropriate.
7. He suggests (I presume) that the Wytch Farm oilfield development in Dorset and below Bournemouth Bay is environmentally safe. I agree with this, but there is no valid comparison with the kind of fracking proposed in the UK shale basins.The 'extended reach' wells drilled out eastwards under the bay are through (or targeting on) the Sherwood Sandstone, the oil reservoir, and have never been fracked (Hogg *et al.* 1999).
8. He points out that the magnitude 2.3 Blackpool earthquake of 2011 is exceptionally large (slide 41), by comparing it with the thousands of far smaller earthquakes generated by fracking in the Barnett Shale of the USA. No explanation is offered (in the slides) as to why this Blackpool earthquake is so exceptional.
9. He quotes the main conclusions of the Royal Society report of 2012 (slides 50-51), but this report failed to discuss the differing geological regime in the UK compared with the US. The failings of this report are discussed in section 4.1 below.
10. Slide 42 states *“Characterisation of any possible active faults in the region using all available geological and geophysical data (BC always has 3-D seismic)"*. This statement, citing a report of which he was a co-author (Green *et al*. 2012) is incomplete, as it should have included all faults, not just 'possible active faults'.

In summary, I find Style's views on the risks of fracking to be complacent, incomplete (because of his partiality), and in places erroneous. The precautionary principle suggests that any region or rock volume cut by faults, whether active or inactive, should not be fracked. This view is developed further in the next section.

4 THE IMPORTANCE OF FAULTS

4.1 Introduction

The Royal Society and the Royal Academy of Engineering issued a combined report into the risks of fracking in the UK (Royal Society and Royal Academy of Engineering 2012). Much of the report concentrated on the risk of induced seismicity. The problem of pre-existing faults was barely discussed at all, even though it was introduced as a subject for concern by a submission to the expert committee by the Geological Society of London.

Instead, the Royal Society report accepted uncritically the Halliburton study (Fisher and Warpinski 2012) discussed above, as did Green *et al*. (2012) in their report commissioned by the Department of Energy and Climate Change (DECC).

This uncritical attitude towards an industry publication is surprising and somewhat naïve, given that:

- Halliburton has not published its database, which remains confidential.
- Wells are only located to county level.
- Individual wells cannot be identified on the four main graphs presented.
- We do not know whether inconvenient results have been omitted.
- We do not know how complete is the database.
- There are essentially no wells in areas of complex geology (faults or tight folds) extending to the surface.

There are some surprising facets to the database; for example Cleveland County (OK) has just one fracked well, but is listed in the graph for the Woodford Shale, whereas several other counties in the Anadarko/Arkoma basin of Oklahoma, with dozens of wells apiece, have been omitted. The answer may simply be that Halliburton did not have contracts for the operators in these counties, but the problem remains that we simply cannot know.

Even if we accept Halliburton's main thesis at face value – that creation of new fractures by fracking has a natural upward limit above the horizontal wellbore of around 500 m, perhaps 1000 m at the most – the story is erroneous at several places:

1. Plotting fractures by microseismic monitoring is incomplete. Pettitt *et al*. (2009) show that a sequence of microseismic events can jump 'silently' up a fault plane to another level, in their example about 100 m higher. Therefore **microseismic activity does not record the passage of fracking fluid up a fault.**
2. Such **leakage up faults could be a slow process**, not necessarily occurring at the time of fracking.
3. The authors argue that, in effect, **if faults were conduits they would have leaked all the gas away by now. This is clearly false**; the whole point of fracking is to release gas which is trapped and therefore unable to migrate.

In conclusion the Halliburton study is severely flawed, even when considered on its own terrain of US geology. It is certainly inapplicable to the UK.

In the UK some publicity was given to the paper by Davies *et al*. (2012) of Durham University, in which natural hydraulic fracture pipes were studied and shown to have a limiting upward extent of about 1100 m. The paper appears to give support to the idea that fracking is safe. But the study is a side issue, because the principal concern regarding fracking safety, not addressed hitherto, is the effects of natural faults, not natural pipes. The latter are a freak phenomenon, geologically speaking, and of no real importance.

4.2 Identification of faults

Faults are mapped at outcrop by field geologists. Identification at depth requires geophysical methods, of which imaging by the seismic reflection method is by far the best. Two-dimensional seismic profiles can image faults having a vertical displacement of one side relative to the other (if the fault cuts near horizontal layers) of 30 m or greater. So the 'resolution'- the finest detail that can be seen - is at least 30 m in length. Strictly speaking, it is this offset of layers one side with respect to the other across a fault which is usually seen, and not the fault itself. With the 3D seismic technique the resolution is brought down to the order of 4-5 m (i.e. improved).

Faults are often missed even when a vertical well is drilled. This is because the drilling process grinds up the rock, which is identified only by the cuttings coming back up with the returning drilling fluid. So it is not surprising that a fault, which is characterised in detail by ground-up, crushed and fractured rock, often cannot be seen. This is what probably happened with Balcombe-2; The vertical section of that well will have cut through the Paddockhurst Park Fault without being recognised, and Cuadrilla was (luckily) then able to drill horizontally to the along the limestone layer without encountering the fault.

Even if a well is cored, which involves the taking of a solid intact cylinder of rock from the inner zone of the drilling, faults can be difficult to recognise with certainty. In oil exploration coring is only done over a few limited intervals of a vertical well, because of the extra costs.

4.3 Permeability, hydraulic conductivity and vertical flow in faults

Permeability is a general term applied to fluids (liquids and gases); it is a measure of how easily the fluid can flow through the medium. Hydraulic conductivity is a more restricted term referring to specifically to water flow, and more frequently used by civil engineers; however it measures the same thing as permeability, but using different units. I frequently find that civil engineers speak of permeability when the parameter they speak of is really hydraulic conductivity. The units used are the key to spotting the difference.

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

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

My brief and necessarily incomplete review of this large field of research and development (R&D) leads me to the following impressions and tentative conclusions:

1. There are field measurements of faults at outcrop and at shallow depth; it is realised that small-scale structures associated with faults dominate the bulk hydrogeological properties These are characteristically fractures sub-parallel to the master fault plane,

which are collectively termed the 'damage zone'. Such zones can be several metres to tens of metres in horizontal width, and are often the locus of fluid flow up or downwards, rather than across the master fault plane. This is illustrated in diagrammatic form in Figure 16.

2. In an unconsolidated mixed sand/clay stratigraphy, the conductivity in the damage zone can be enhanced by several orders of magnitude, but clay smearing along the core fault plane reduces the bulk conductivity.
3. Iron oxide re-precipitation in the core fault, due to the enhanced flow in the damage zone, is another mechanism which can reduce the core conductivity.
4. The relative hydraulic conductivity of a fault cutting indurated low-conductivity clays is neutral; i.e. the conductivity of the fault zone remains within the same order of magnitude as the unfaulted clay. An example is the set of measurements across the Down Ampney fault, made by the BGS, in which Oxford Clay is juxtaposed against Oxford Clay or Forest Marble Clay (Sen and Abbott 1991).
5. However, the same dataset shows that the conductivity of the fault zone as a whole is enhanced by one or two orders of magnitude, because the succession includes limestones and sandstones as well as the aforementioned clays.
6. Smectite in shear zones can be dehydrated to anhydrous illite minerals as a shear fabric develops; this in turn can account for overpressure build-up. This mechanism accounts for high hydraulic conductivity observed in accretionary wedges, but contradicts laboratory experimental studies suggesting that sheared clays in fault zones represent aquitards.
7. Laboratory measurements of permeability or hydraulic conductivity usually give results that are an order of magnitude lower than *in situ* measurements. Tellam and Lloyd (1981) studied the hydraulic conductivity of British mudrocks. The laboratory measurements gave values 2 to 3 orders of magnitude lower than the *in situ* values.

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

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

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

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

From Lunn *et al.*'s observation (which was already widely known across the hydrocarbon exploration industry) that "*faults can be barriers to flow, conduits, or combinations of the two*", one can construct a cartoon of how normal faults cutting sediments will affect flow direction (Figure 16). I have indicated in this cartoon the general flow parallel to sedimentary bedding, in this case down-dip. But when the flow encounters a fault zone it will be redirected upwards; this fact is irrespective of whether the fault is acting as a barrier or as a conduit to fluid flow.

4.4 Summary of the fault problem

Faults are near-planar surfaces cutting through rock layers. In Sussex the fault planes are nearly vertical, cutting through rock beds which are not far from horizontal in attitude. Their key characteristics include:

- Faults are complex and unpredictable in their hydrogeological behaviour
- Faults have to be regarded as leaky (conduit for fluids) unless proven otherwise
- Earthquakes occur on pre-existing faults
- Pre-existing crustal stress and fracking-induced stress is concentrated along faults
- Fracking activities can induce earthquakes
- USA fracking history provides no guide for the UK geological environment
- Leaks of released methane up faults, once started, may continue for decades.

5 IMPLICATIONS FOR ENVIRONMENTAL CONTAMINATION

5.1 Migration up faults and natural fractures

The US fracking experience tells us that faults at the fracking level are to be avoided if possible, because they reduce the effectiveness of the fracking treatment and can divert stresses away from desired trends. According to Baker Hughes (2013), a major service company like Halliburton, **re-activated faults are usually conduits to fluid flow**. The problem of environmental contamination by fugitive methane and/or fracking fluids reaching the surface never arises in the USA because there are practically no faults in the shale basins studied which extend from the fracking level up to the surface.

Controversy over contamination in the USA due to fracking operations has therefore concentrated on the problem of faulty well casings, leading to fugitive methane emissions. There is no question that in some localities, for example at Dimock (PA), there have been severe problems. In the scientific literature there are well-funded (industry-sponsored) papers purporting to show that methane emissions are natural (pre-dating the advent of drilling and/or negligible). One example of this is a just-published paper purporting to show low methane emissions – but the confidential sites were pre-selected by the industry. The most telling paper to date in my view is by Jackson *et al*. (2013), who analysed 141 drinking water wells in Pennsylvania. Their study shows that elevated (and often dangerous) methane levels correlate with nearness to well sites, at a probability level of well under 1% (i.e. the chances of this correlation being by random chance) *and* they prove by its characteristic signature that the methane comes from the Marcellus Shale, and is not a shallow biogenic product.

In the area studied by Jackson *et al*. there are no faults. Even if the source of the methane leak is due to faulty drilling completion, the interesting fact remains that the fugitive methanee is not found just at the wellbore, but up to several kilometres away. This suggests that the cover rocks above the fracked Marcellus Shale, which here is at depths of 1500 to 2100 m, do not make a perfect seal.

5.2 Are the rock layers above the fracking levels in Sussex an adequate seal?

How much rock is required above a fracked zone to seal it? In the East Irish Sea Basin it is reported that at least 600 m of Mercia Mudstone Group (MMG) is required for it to be an effective hydrocarbon seal there, due to the inversion uplift (Duncan *et al.* 1998). However, the

MMG is an effective seal in the Wessex Basin, where 300 m of MMG caps the oil of the Wytch Farm field, together with another 200 m of Liassic mudstone above. The difference in the latter case is that the Tertiary uplift has never taken the MMG into the brittle tensional strength regime, which is the reason for the higher hydraulic conductivity in the Irish Sea region.

The figures used in the following discussion are approximate, based on Celtique's ES Table 11.1. If the Kimmeridge Limestone is fracked at a depth of 1400 m below ground level, at least the 140 m of Upper Kimmeridge Clay overlying it will be fractured, and therefore cannot act as a seal. Above that there are 720 m of Upper Jurassic and Lower Cretaceous sediments below the Weald Clay, comprising around 50% sandstones and limestones. None of the more pelitic (mudrock) sequences making up the remaining 50% is individually thick enough to make a reliable seal.

If the Middle Lias at 2500 m depth is the target, there are an additional 1060 m or so of cover rocks for protection against upward migration. A large proportion of these layers (Lower Kimmeridge Clay, Oxford Clay and Upper Liassic, making up around 80% of the succession) comprises clay or shale rocks.

One cannot simply add up the total thickness of the mudrocks (the potentially good sealing rocks) in this sequence, to conclude that we have around 360 m of mudrock in total above the Kimmeridge Limestone, or alternatively around 360 + 800 = 1160 m of mudrock above the Middle Lias. The reason is that one layer of rock may be linked to another across a fault, because the fault is leaky to fluids. So even small faults are important here. The faults are, in effect, short-circuiting the individual sealing layers.

The Weald Clay lying above the aforementioned layers is about 450 m thick, and occurs at outcrop (the Earth's surface). It has a measured horizontal hydraulic conductivity range of the same order of magnitude as the Mercia Mudstone Group, which acts as a reasonable seal in the Wessex Basin, but is ineffective in the Irish Sea Basin. However, the Weald Clay is full of sandy and silty laminations, which means that the effective bulk horizontal conductivity is likely to be at least an order of magnitude higher than the measured clay conductivity. Together with the fact that the crustal stress regime in the topmost few hundred metres is tensional, this means that the Weald Clay will also be an ineffective seal or barrier. The Weald Clay is discussed further in section 5.4.

In conclusion, there is no effective seal, or caprock, above the potential fracking zones in

PEDL231, because of the presence of faults. A full 3D seismic survey around the region of the proposed Fernhurst-1 well could, in principle, demonstrate that there are no faults in the area. Such a form of imaging provides detail which is several times more precise than the cheaper and simpler 2D seismic surveys. However, the limited evidence available from the existing data shows that faults are present even in this deep flat central part of the Weald Basin (Figs. 2, 12, 13).

5.3 Evidence of seeps

Selley (1992) has described and tabulated 173 occurences of surface petroleum seepages and impregnations in the UK. Eleven of these occur in East Sussex, the nearest one to PEDL231 being at Cuckfield. Two of these (Hawkhurst and Netherfield) are occurences of natural gas.

In three instances the seepage is clearly related to migration up faults from the presumed Lias source rocks below. An alternative source could also be deeper Coal Measures (Carboniferous), even though the Weald is within the outer part of the Variscan fold belt. The Variscan tectonic event (folding and faulting) post-dates the Carboniferous, but it is now thought that the metamorphism (heating and 'cooking' of the rocks) may not have been as severe as previously believed, so that the Coal Measures may have survived nearly intact as a source for seeps.

Selley (2012) discusses in more detail the migration of gas up pre-existing faults elsewhere in the UK, in relation to shale gas basins. At the international level, hydrocarbon seepage is now proven as an exploration tool, and the upward migration of gas can even be directly imaged using high-quality (usually 3D) seismic reflection data combined with clever computer visualisation methods. Aminzadeh *et al.* (2013) provide an up-to-date review of developments. The most important lesson to be learned from their wide-ranging review is that faults are crucially important in providing migration pathways. The next most important lesson is that cap rocks are rarely 100% effective. Petroleum systems with continuous leakage upwards, balanced by continuous replenishment from a source below, are common. The new imaging methods show that gas migration can be diffuse, and is not necessarily confined just to identified faults. The Earth is far from perfect at keeping hydrocarbons underground.

5.4 Groundwater

The Environmental Statement (ES), Chapter 11, discusses the aquifers that will be penetrated by the vertical well. But in view of the fact that the aim of the development will be to frack within the Kimmeridge Clay Formation and/or the Middle and Lower Lias clays over a wide area of the 400 sq km licence, we are justified in looking more generally at the risk to groundwater resources.

The sandstones and limestone units within the Weald Clay are classed as Secondary A Aquifers. A map of the minor beds within this formation is shown in Figure 17 from the BGS Horsham map memoir (Gallois and Worssam 1993). Celtique's Table 11.3 describes the aquifers within the Weald Clay as *"Sandstone inferred to have moderate primary and secondary porosity and permeability with resource value constrained by limited lateral extent"*. Fernhurst-1 lies at the top of the Weald Clay succession. Several of these horizons, such as 3a, 3c, 5c, 6, 7a and 7c, have a regional extent of at least 20 km in both north-south and east-west directions, as shown in Figure 17 and the accompanying cross-section in the memoir. They are therefore much more extensive than is misleadingly implied by the word 'lenses' employed by Celtique (ES, chapter 11, p.11).

The underlying Tunbridge Wells Sands are divided into two, Upper and Lower, separated by the Grinstead Clay. According to the well prognosis provided by Celtique (ES, Fig. 11.5) the top is at around 450 m below ground level, and totals about 195 m in thickness including the thin clay member. The sands are classified as Secondary A aquifers.

Celtique's ES ignores the fact that there are a number of natural 'issues' (water emerging from depth) and/or springs within a few kilometres of the well (Fig. 18). This strongly suggests that there is a natural groundwater discharge system in the area of the well. Four of these in Figure 18 are highlighted and shown in more detail in Figure 19. It is evident that an active groundwater system is rising up from depth and feeding Furnace Pond and the river system running off from the pond to the south-east.

Figure 20 shows a perspective view looking NW up the river to Furnace Pond, with the geological map draped over vertically exaggerated topography. The circled water issues of the previous diagram are marked by vertical red poles (the second-nearest one is partially hidden). The greenish-yellow colour labelled 'Sst' is sandstone bed no. 7ef within the uppermost Weald Clay (see Fig. 17). The remainder of the geological outcrop is Weald Clay, in places overlain by a Quaternary-age unconsolidated deposit called 'Head', as at the wellsite itself. The four issues are between 0.8 m lower and 9.5 m higher than the elevation of the wellsite. The two most westerly issues are situated on the sandstone bed, but the two issues south of Furnace Pond lie on Weald Clay. Thus in the vicinity of the wellsite there is an **active groundwater system** passing upwards through the Weald Clay, which is designated a Secondary A aquifer. The hydraulic potential, or head of water, is at least as as high as the wellsite location.

We do not know whether this discharge emanates from the permeable horizons within the Weald Clay, or from the deeper Tunbridge Wells Sands. However, it would appear that both of the following statements by Celtique on groundwater flow (ES, chapter 11, p. 12) are erroneous:

> *"groundwater in the superficial deposits and in the Secondary Aquifer sandstones in the Weald Clay … is locally recharged and unconfined at outcrop with subsequent down-dip flow into a confined zone"*
>
> *"groundwater in the deeper Secondary Aquifers, starting with the Upper Tunbridge Wells Sand … will be recharged on the outcrop area, which is some 20 km to the north east and beyond; … will flow according to the regional dip of the strata; and … has no practical connection with groundwater beneath the site or through which the proposed hydrocarbon exploratory borehole will penetrate."*

The evidence cited above shows that Celtique has taken a complacent view of current groundwater resources. The risk to the groundwater is probably low from the drilling of the vertical well Fernhurst-1 itself, but if and when a much wider area is developed for shale gas (or oil) by fracking, then these resources will be put at serious risk. The proven upward groundwater flow through the Weald Clay in the well locality would, if contaminated by fugitive methane or other fluid contamination from below, feed into the Rother and Arun river system from the springs and issues identified (Fig. 18).

6 DISCUSSION AND CONCLUSIONS

6.1 Implications of the faulted geology for environmental contamination

Celtique's clear intention is to investigate and then frack:

- the Kimmeridge Clay shale for oil or gas, using the Kimmeridge Limestone as a guide layer, and/or
- the deeper Middle and Lower Lias shales for oil.

The present application is just the first stage of this process. Fracking technology is not only unconventional; it has never been tested to any degree in a highly faulted shale basin such as the Weald. Faults are complex features, and difficult to understand. In the USA faults at the frack level are avoided because they reduce the efficiency of the fracking process. In addition, no faults within any fracking province of the USA extend all the way to the surface.

In NW Germany, a thorough study of fracking risks has been carried out by neutral academic experts (but funded by ExxonMobil), which includes the question of fracking through faulted zones (Borchardt *et al*. 2012). I have not completed translating this report, which is in German and runs to some 140 pages; however, there is an English-language summary (Ewen *et al*. 2012), one of the main conclusions of which is that fracking in fault zones should be banned. It states:

> *"The following hydrofracking fluid transport barriers are crucial:*
> - *The presence of massive sealing clay strata and other strata.*
> - *The barriers resulting from the fact that salt fractures close up naturally.*
> - *The absence of faults or fault zones, i.e. underground areas that are more porous owing to fractures in geological materials."*

Note that the Celtique drill site area lacks the first requirement (massive sealing strata, discussed in section 5.2), and in addition has many faults (section 4 above). Although surface-mapped faults are practically absent throughout PEDL231 (Fig. 1), there is good evidence that they exist at depth below 300-400 m, and may even penetrate into the Weald Clay, the topmost layer which is being relied upon to be the final barrier (Fig. 12). There are no salt layers in Sussex, so the beneficial effect of salt as a barrier to migration does not apply here. The presence of oil and gas seepages in East Sussex (section 5.3) is evidence that faults in the Weald Basin cannot be assumed to be barriers to migration.

6.2 Baseline surveys

The Royal Society and others have called for baseline surveys to be conducted before any fracking operation. This means establishing what the environmental state is before any work is undertaken that might alter this state. The surveys that it would be appropriate for Celtique to undertake before the drilling envisaged in the present application include monitoring of groundwater and possible natural leakages of methane. Seismicity should also be monitored.

There is no 3D seismic reflection survey over the licence area. Such a survey could image faults down to a resolution of a few metres, and would go some way to mitigating the very incomplete knowledge of faulting in this area. In my view this would need to be a semi-high resolution survey targeted at the uppermost two kilometres or so.

Monitoring of groundwater and potential natural leakages of methane should be carried out before any drilling is undertaken. Seismicity should also be monitored.

6.3 Conclusions

West Sussex County Council must consider the present application in the context of what logically must follow on if the phase of testing proves encouraging. **That means fracking, and no other outcome is possible.**

Celtique has divided up its exploration programme into small chunks as a way of manipulating the Council into permitting fracking. The present application, stage 1, has been couched in terms of being a simple straightforward oil exploration well test – but it is not. If it were, I would have no objection to it. But if the present test boring, including horizontal drilling, is permitted, then Celtique's next application will be presented as a simple extension to what has already been done, but with some 'stimulation' added (this being the new word adopted by by the shale gas industry, to avoid mention of hydraulic fracturing, or fracking). The Council must not permit itself into being bounced by this tactic into an agreement to frack.

Celtique has been evasive about its intentions. As a result, among other things, the Alternative Sites Assessment cannot be judged as having any validity. For example, is it not possible that suitable sites might be found outwith the National Park? Based on the incomplete evidence supplied by the Applicant, we just do not know.

It is appropriate for the SDNPA to take into account Celtique's plans elsewhere in the Weald; that includes both its conventional oil exploration plans in licence areas PEDL231 and PEDL234, together with its proposed wellsite at Wisborough Green in PEDL234. For example, as I have pointed out above, if Wisborough Green-1 is targeting the same Kimmeridge Limestone in which oil has been discovered by Cuadrilla in Balcombe-2, then there is no rational reason for allowing a repeat of the limestone investigations within the National Park.

If the SDNPA permits the present application to go ahead, subsequent applications may be more difficult to refuse. It would be wiser to take the possibly difficult decision immediately, rather than delay a decision until after a further application has been submitted.

The Weald's geology is intrinsically unsuitable for fracking. No similar geology been fracked before. The USA experience is completely irrelevant. Fracking poses a direct threat to groundwater resources, and there is the possibility that fugitive methane may even reach the surface.

The Council should bear in mind when determing this application:

- What benefits to the community arise (if any) from the present application?
- Will any of these benefits (if they exist) outweigh the clear inconvenience to the community?
- Can Celtique prove that fracking in Sussex will be environmentally safe?
- Conversely, can Celtique provide a legally-biding promise that fracking will not be used?
- Why should parts of West Sussex be put at potentially grave environmental risk, when the main beneficiaries will be the applicant and the Exchequer?
- Would the financial benefits of any putative Community Benefit Scheme based on a share of royalties outweigh the costs of possible accidents, leakage and other deleterious effects on the environment?
- What do the constituents wish?
- Why have countries such as France and Bulgaria banned fracking outright, while Germany and several US states have moratoria until the environmental and health impacts have been assessed?

On the technical and environmental safety grounds discussed above, **the current planning application should be refused.**

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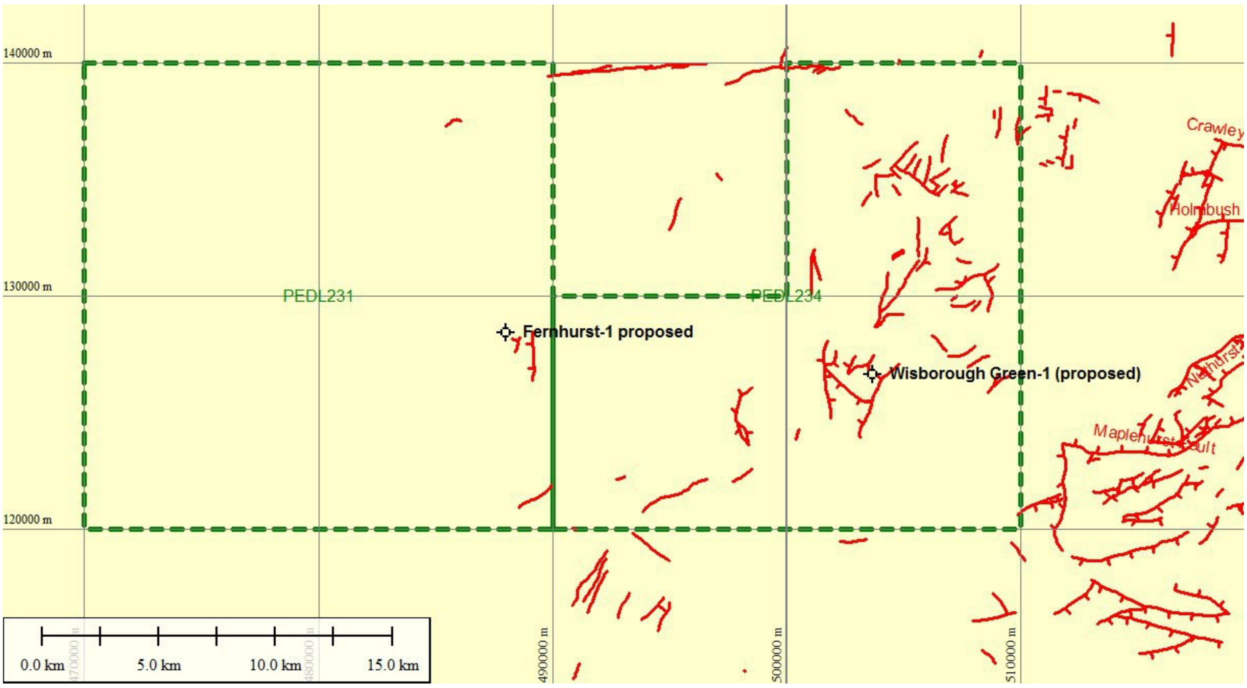


Fig. 1. The PEDL231 licence area showing proposed Fernhurst-1 wellsite, PEDL234 with Wisborough Green-1 wellsite, and surface-mapped faults (red).

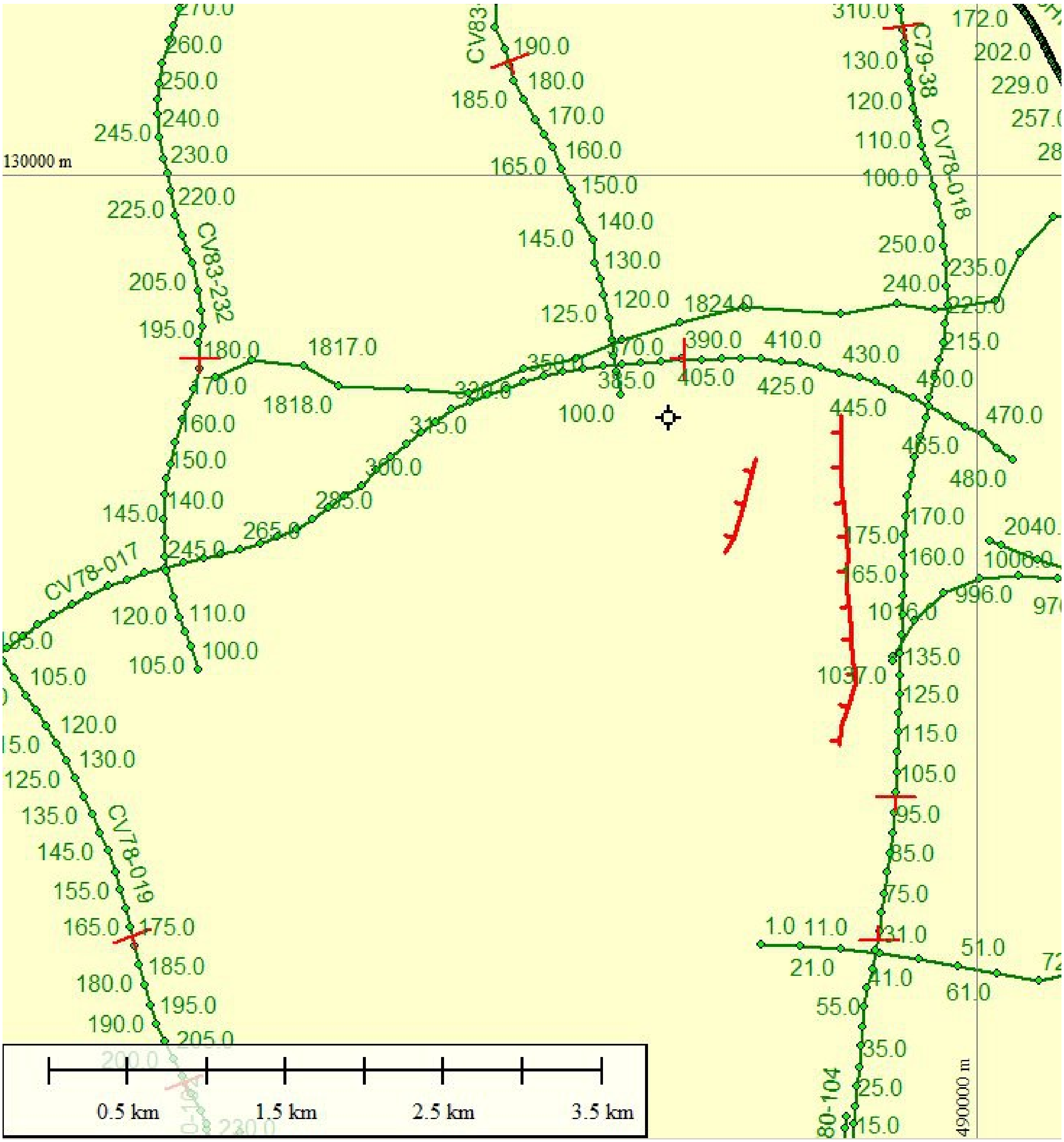


Fig. 2. Faulting in the vicinity of the proposed Fernhurst-1 wellsite (black circle over cross). The pecked red lines are surface-mapped faults. The green lines with numbered shot-points are available seismic reflection lines. There is a large seismic data gap south and SW of the well. The short red lines show where faults at depth can be recognised from the seismic images. No attempt has been made to correlate these with one another, although it is probable that their general trend is east-west.

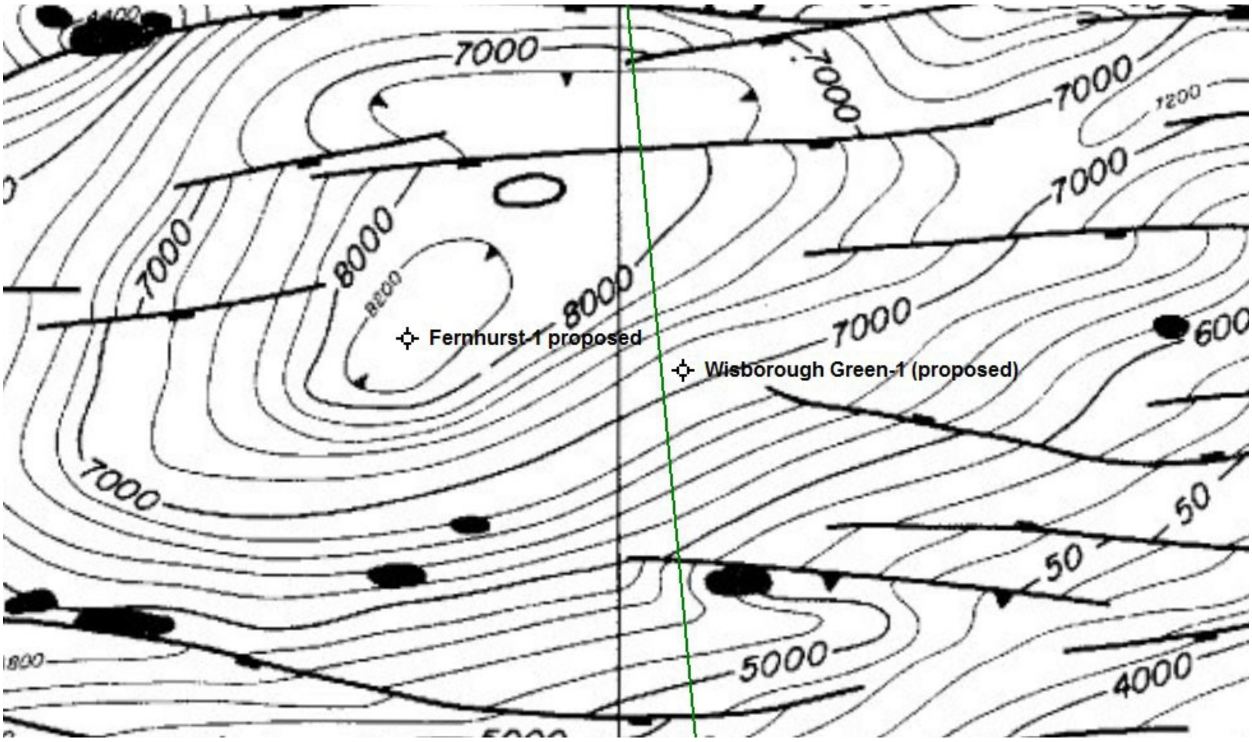


Fig. 3. Faulting at Base Jurassic level (thick lines running E-W). Structure contours (finer lines) are labelled in feet. The green line shows the location of the geological profile shown in the next figure.

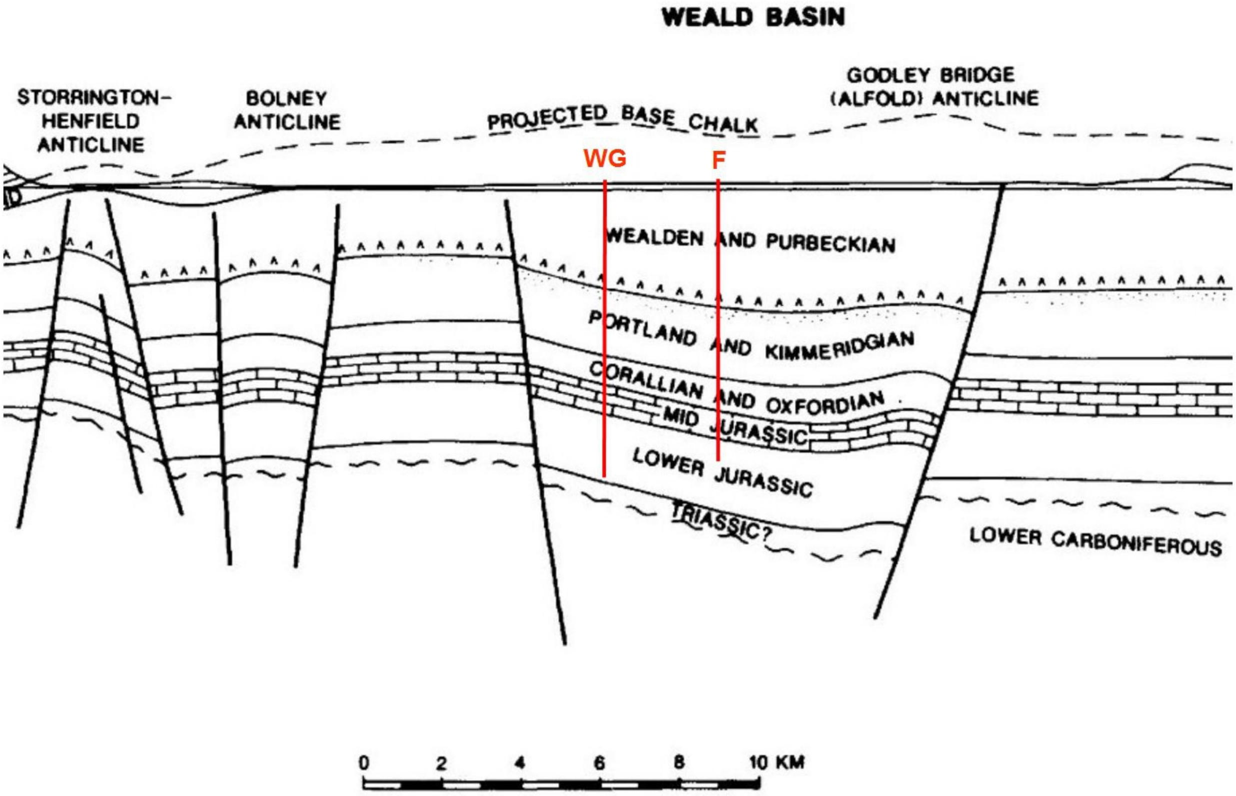
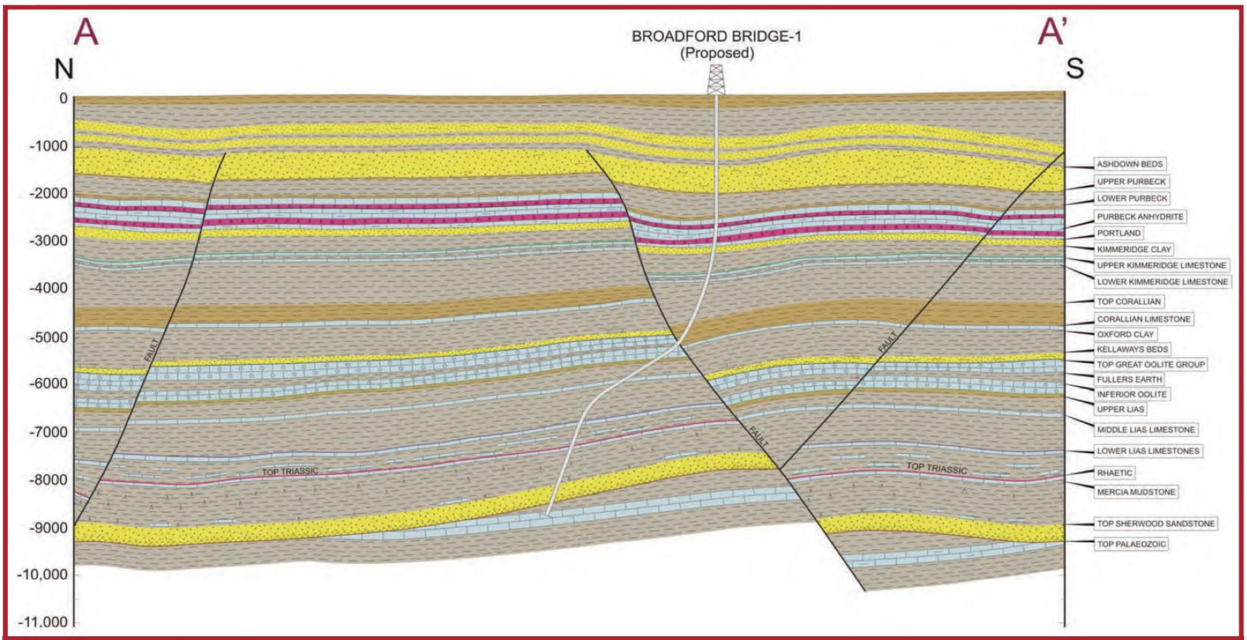


Fig. 4. Central part of regional north-south cross-section across the Weald (Butler & Pullan 1990). South is at the left. WG – Wisborough Green-1 proposed well, projected west by 1 km; F – Fernhurst-1 proposed well, projected east by 14 km.



Geological cross-section over the Willow structure showing the proposed well path

Fig. 5. Geological cross-section through the Willow conventional oil prospect, south-eastern PEDL234, illustrating large E-W trending faults which extend upwards to about 300 m below the surface.

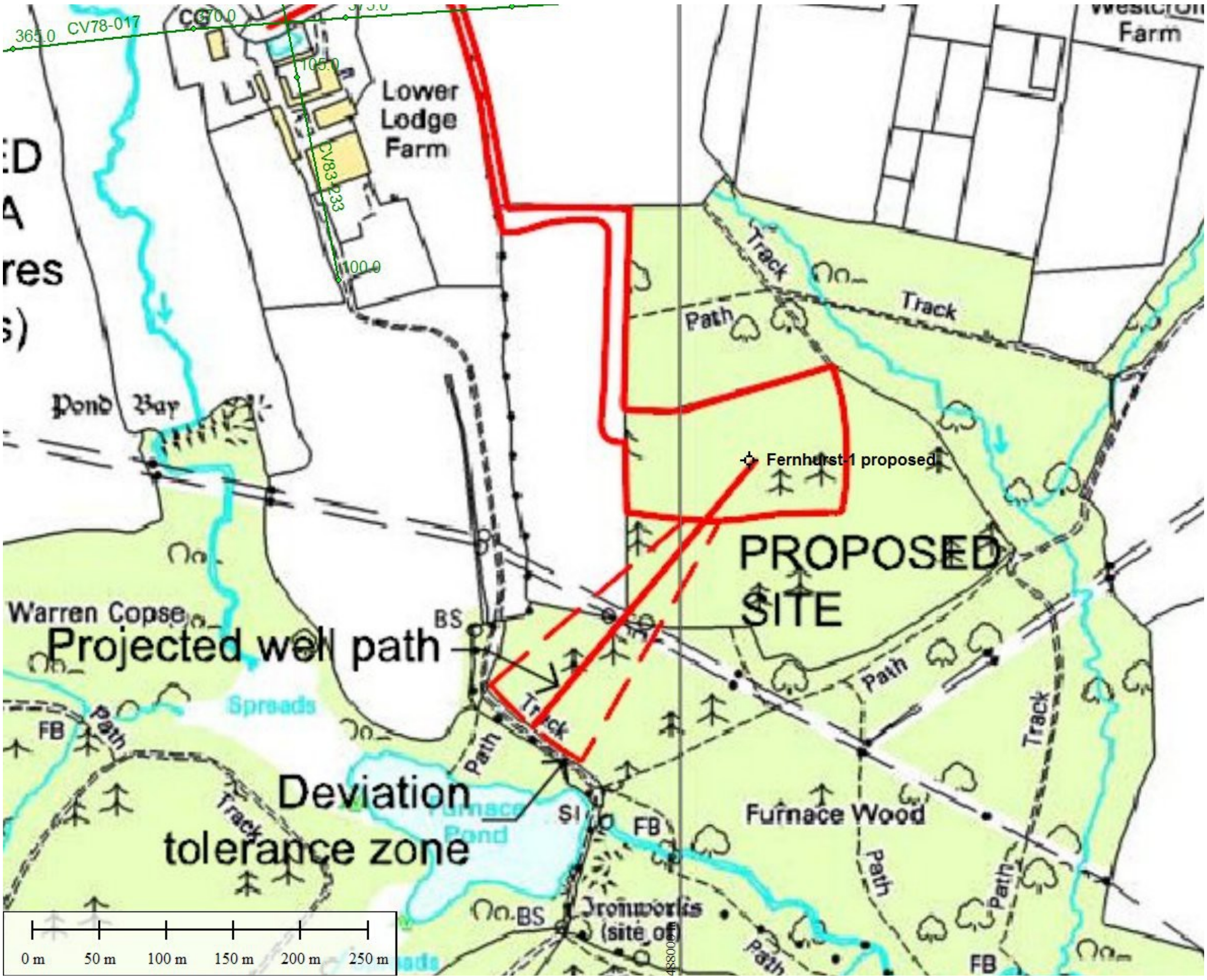


Fig. 6. Fernhurst-1 proposed deviated well plan according to Celtique, shown as a solid red line extending 260 m SW of the wellsite. The dashed line arc indicates the tolerance (error) zone of the deviation.

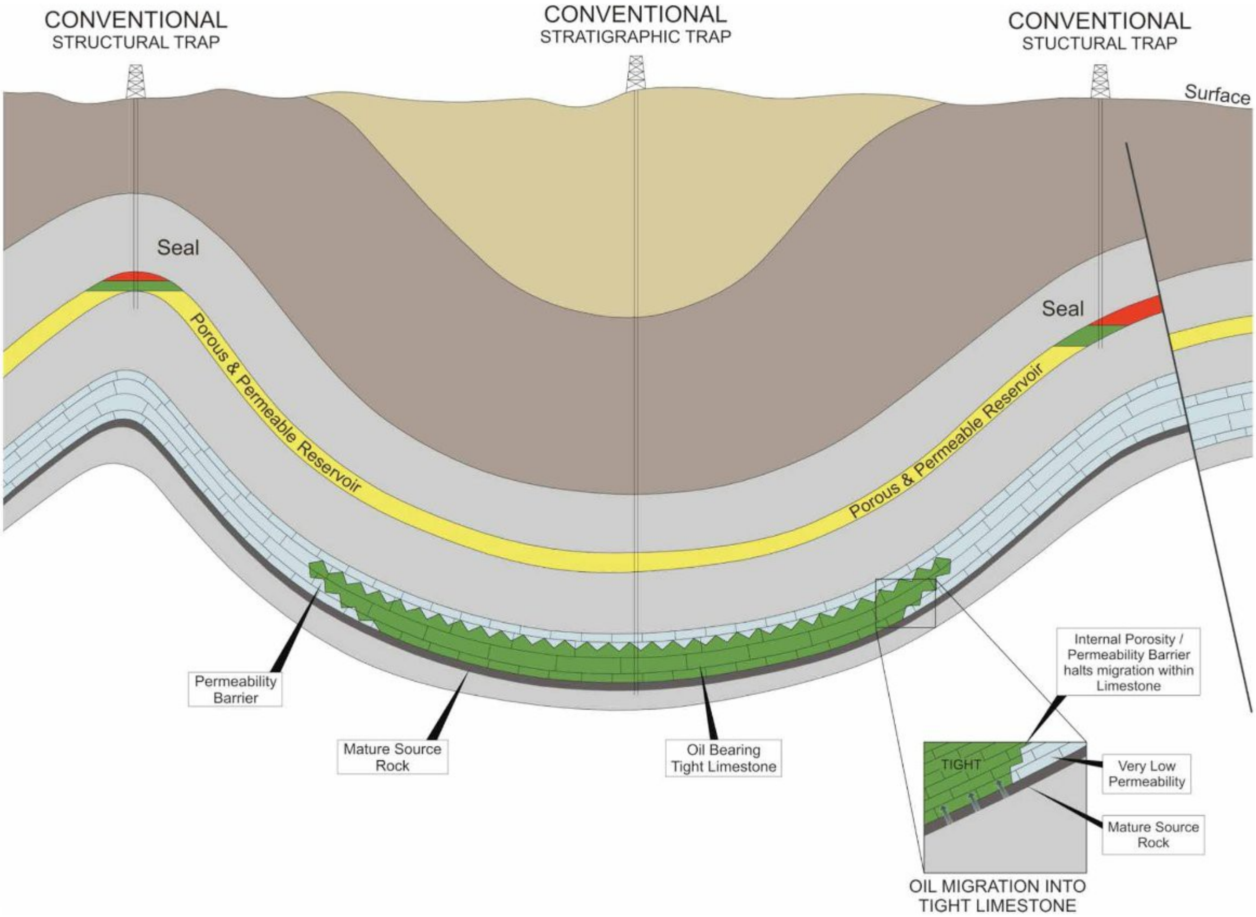


Fig. 7. Celtique schematic cross-section showing that the oil-bearing 'tight' (very low permeability) limestone (one of the possible targets in the present application, shown in light blue) is an *unconventional* resource. It is in contrast to the two examples shown at either side of *conventional* structural traps (green – oil; red – gas). The central oil bearing zone (green) within the limestone is not a conventional trap, as misleadingly labelled at the top of the figure.

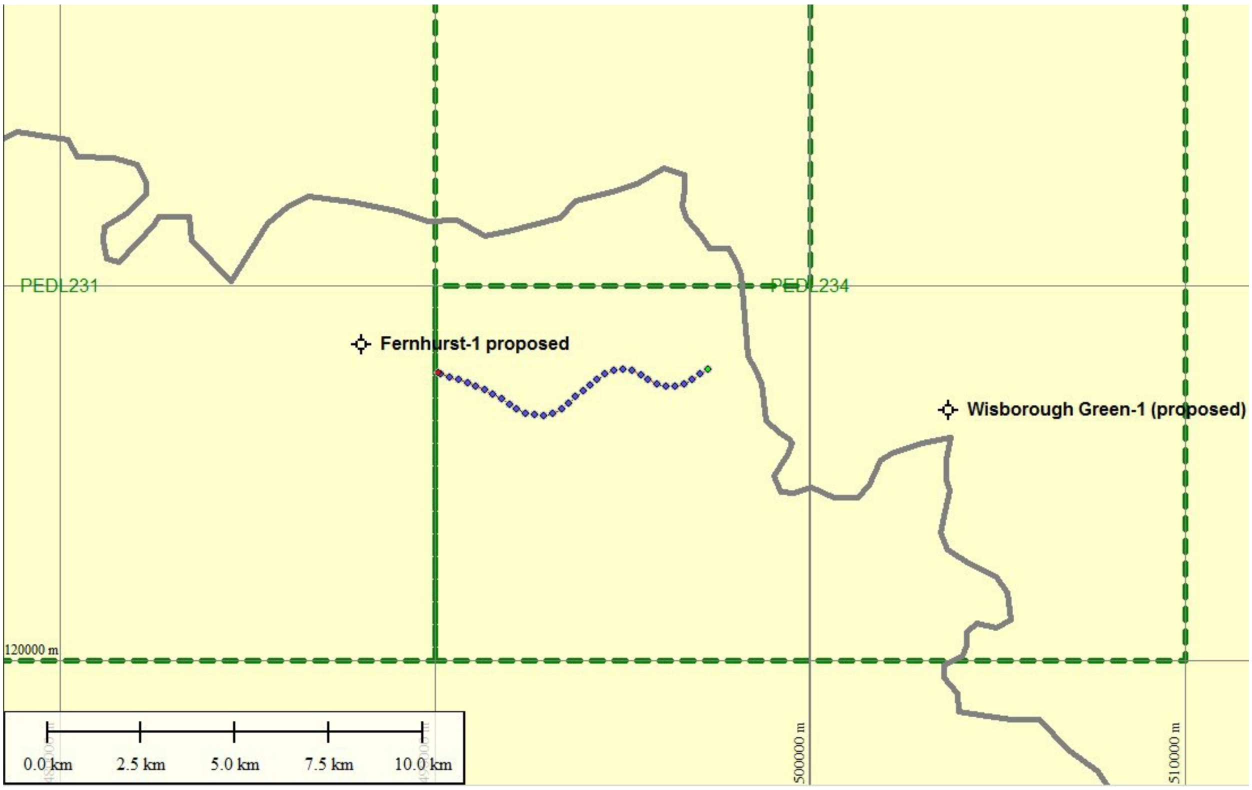


Fig. 8. Location map of seismic line TER-91-06 used by Celtique (blue dots) to illustrate both the Wisborough Green and the Fernhurst prospects. The grey line is the South Downs National Park boundary.

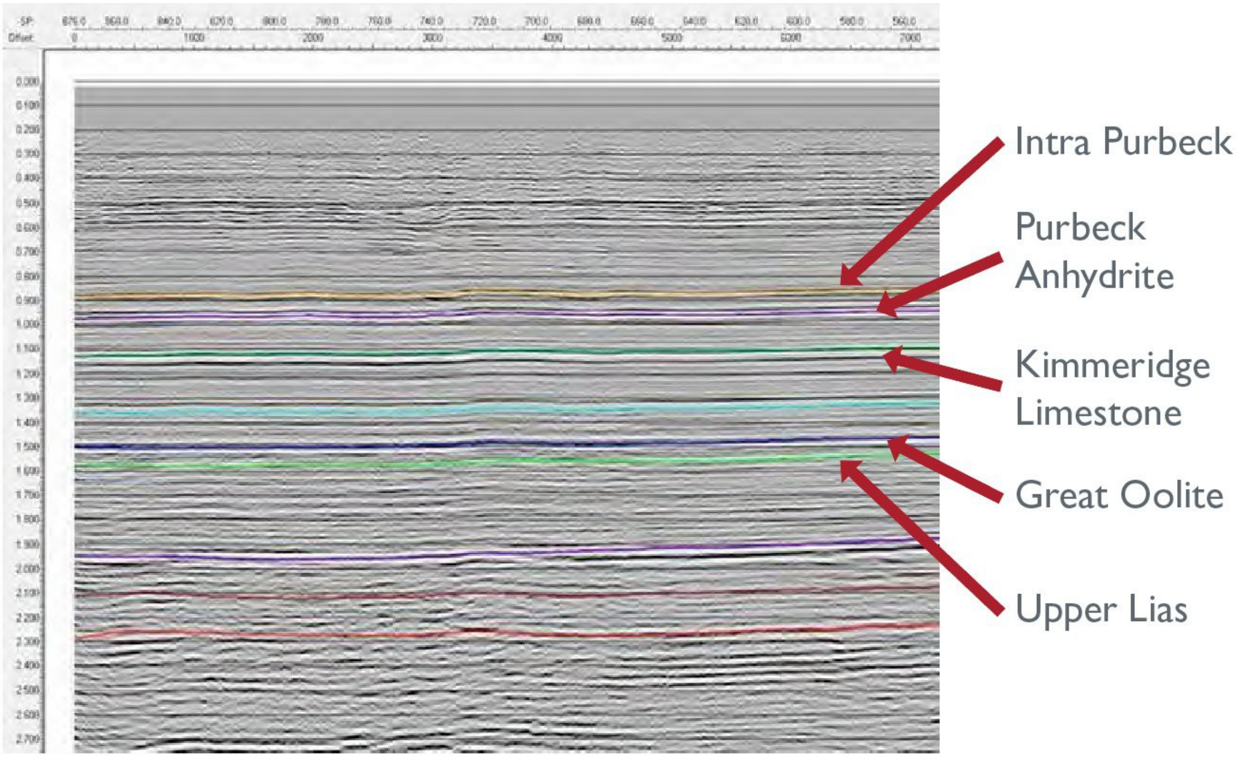


Fig. 9. Seismic line sample used by Celtique. This appears to be a reprocessed version of line TER-91-06, located in the previous figure.

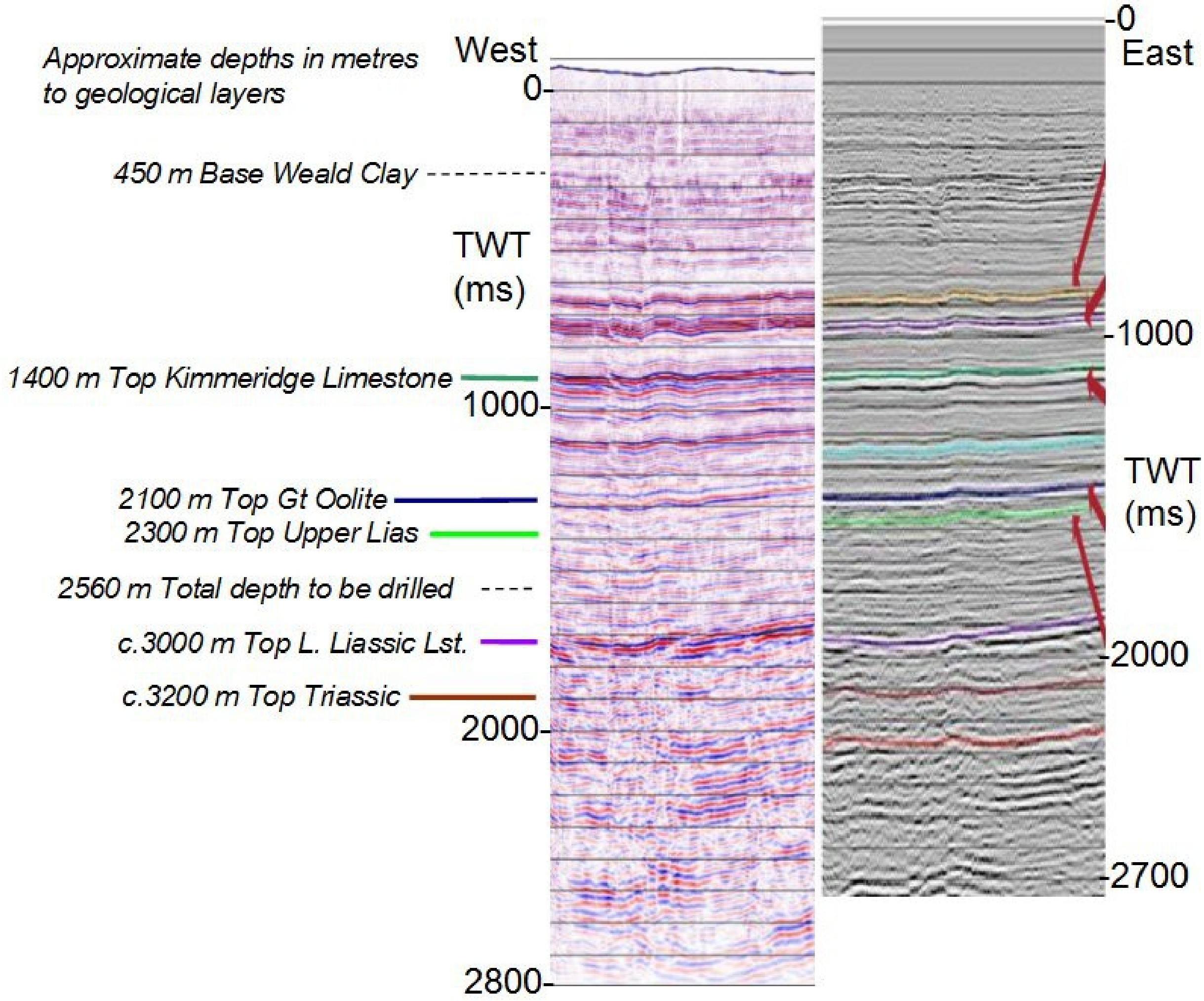


Fig. 10. Comparison of original version of TER-91-06 (left) and the reprocessed version used by Celtique (right). Both versions have been trimmed to approximately the same data area, from shot-points 1400 to 2046 and down to 2700 ms two-way time (TWT), and compressed horizontally. Details of the faults evident only in the original version are shown in the next two diagrams.

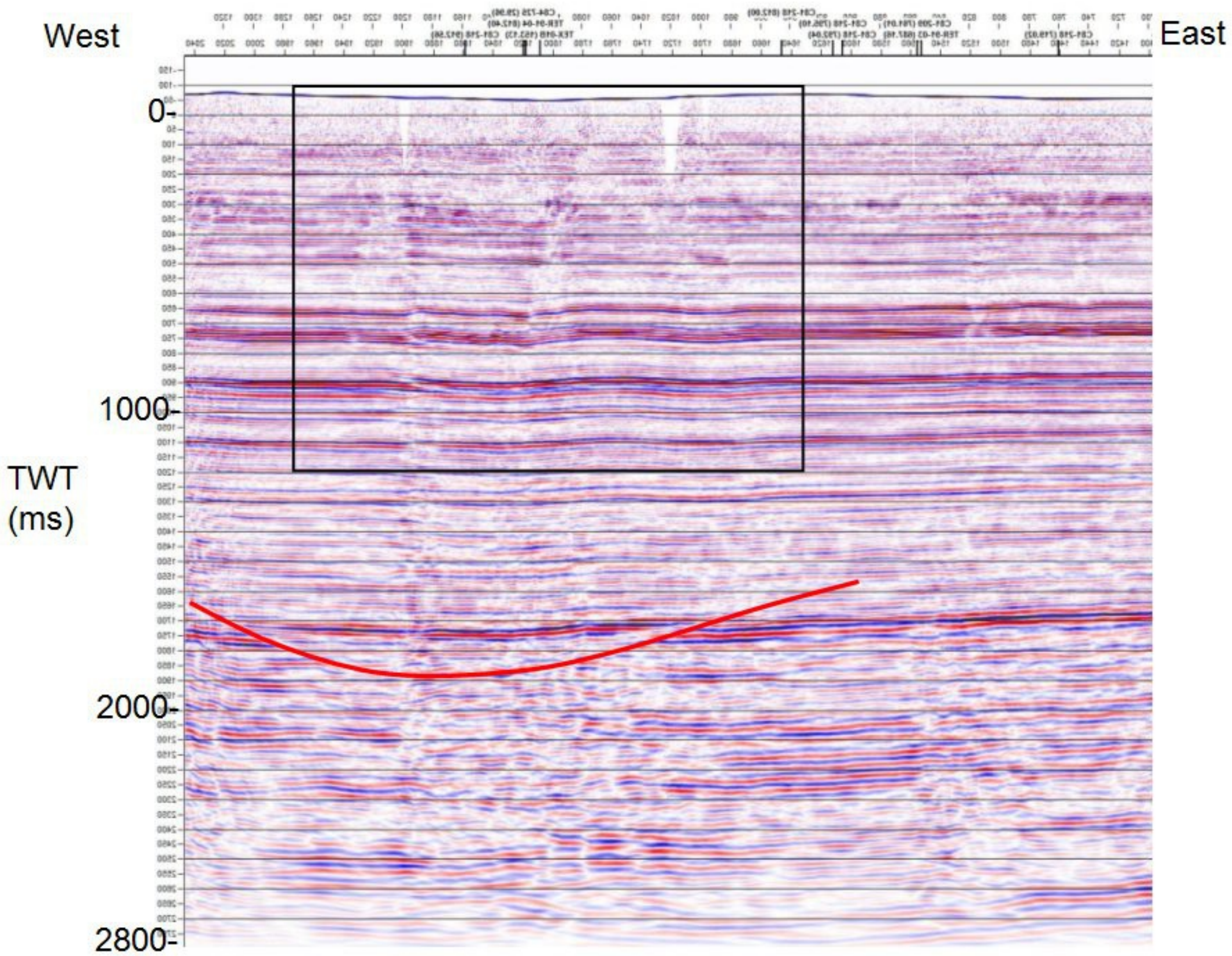


Fig. 11. Original version of TER-91-06. This shows clear evidence of a fault (red curve) cutting very obliquely through the section between 1600 and 1900 ms. The fault is probably planar; it is the seismic line that is curved and hence intersects the fault-plane twice. The central part above the 'smile' is the upthrown side. Detail within the black rectangle is shown in the next figure.

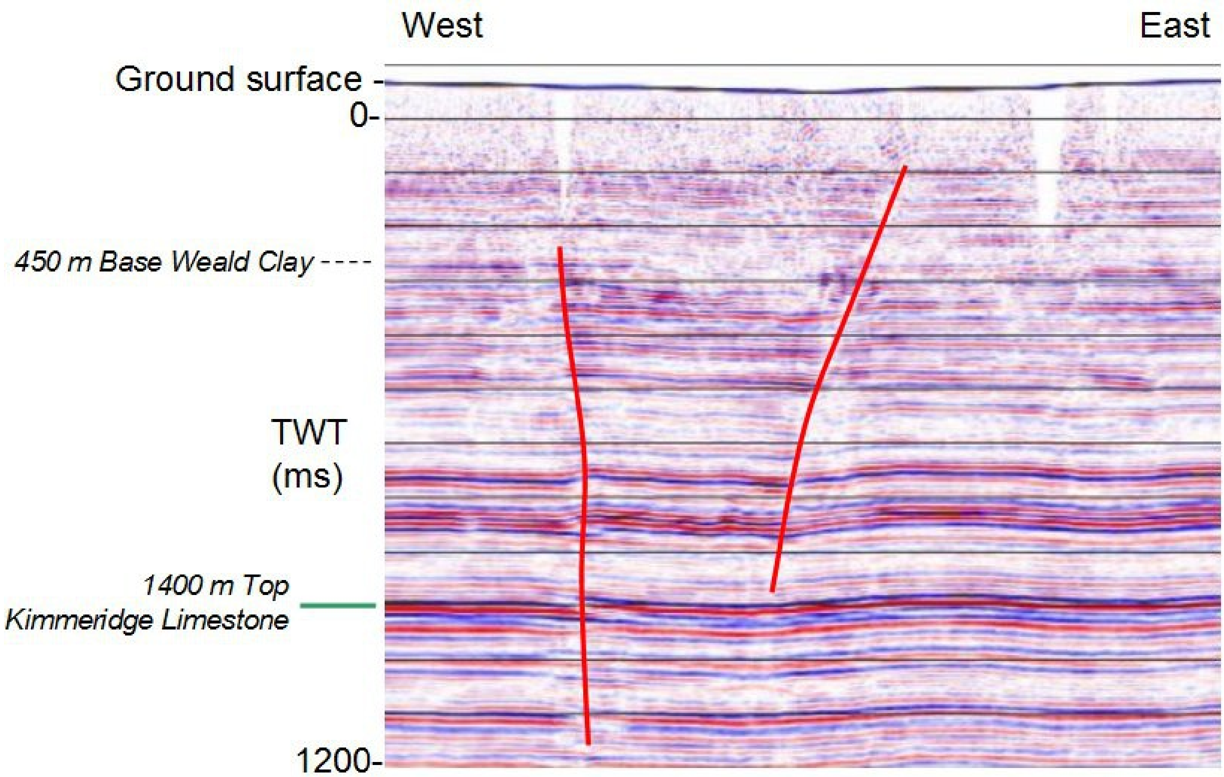


Fig. 12. Detail from preceding figure showing faults at shallow depth, penetrating well into the Weald Clay.

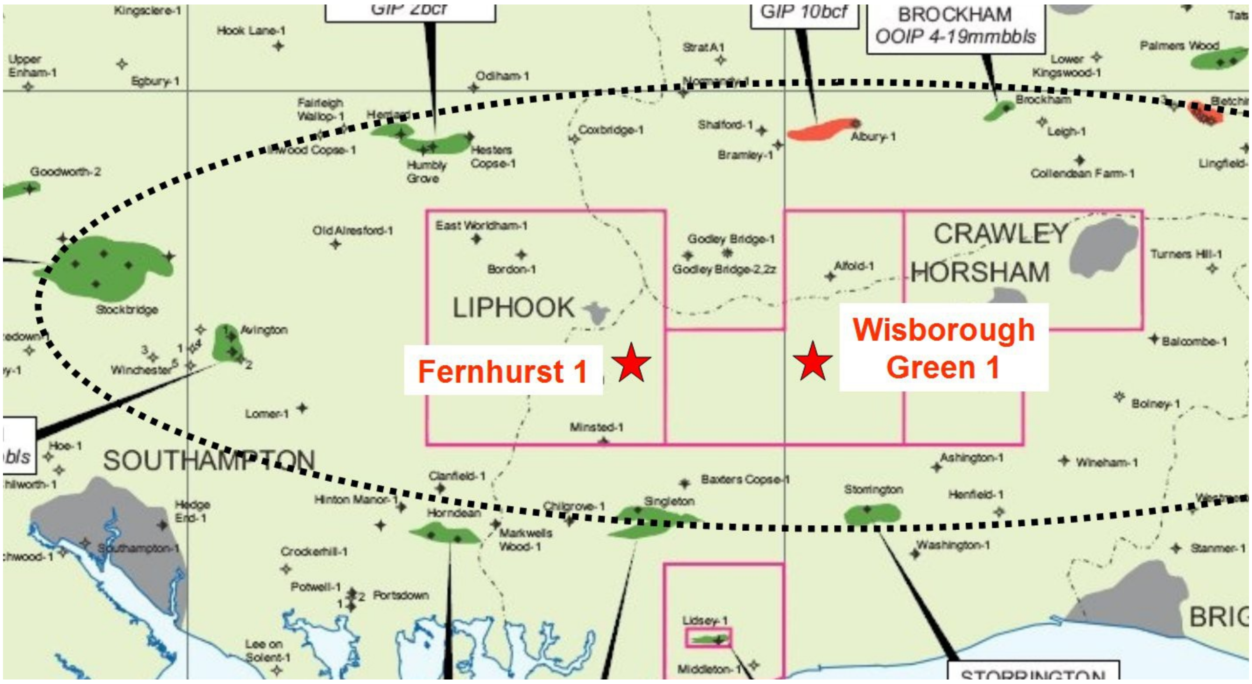


Fig. 13. Celtique map showing how conventional oil and gas already discovered in the Weald occurs in local high spots (green or red) around the edge of the basin (near the dotted elliptical line), whereas Celtique's proposed wells lie in the centre of the basin.

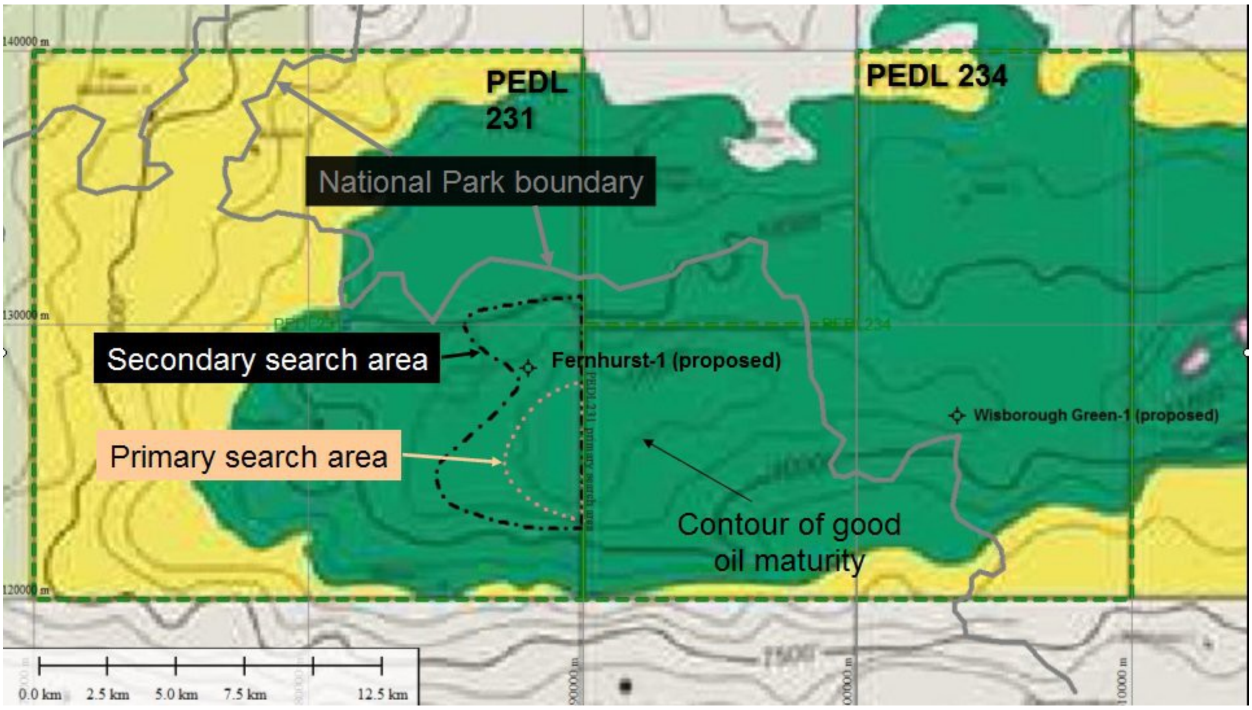


Fig. 14. Celtique website map of Base Middle Lias maturity. Yellow indicates immature hydrocarbon content. The green area is predicted to be oil-mature, with more central contours being more mature. Celtique's primary and secondary site search areas are marked. The primary search area correlates well with one of the contours of high oil maturity.

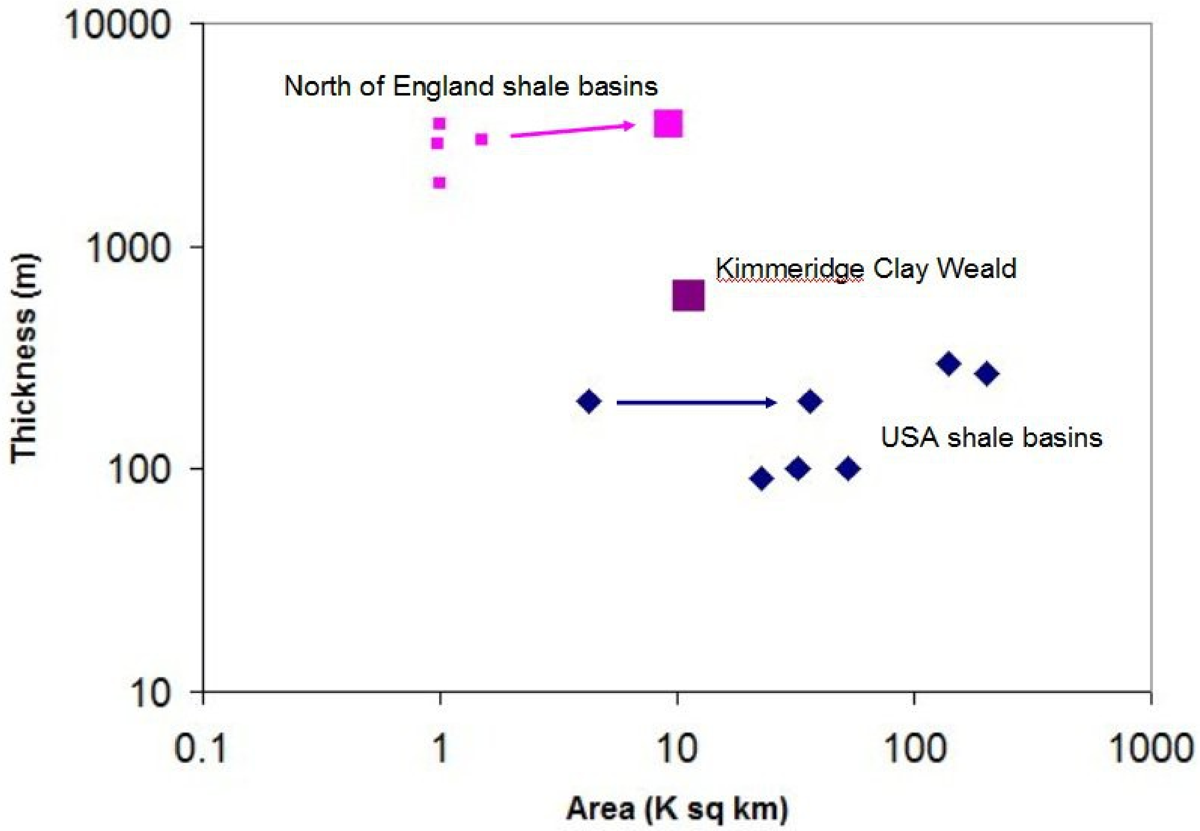


Fig. 15. Log-log graph of the maximum thickness of shale layer *vs.* basin area. Lilac arrow shows four north of England basins combined as one; blue arrow shows that the smallest US basin (Arkoma) is really part of the bigger Anadarko Basin to the right. In general the UK basins are 5 to 50 times thicker than the US basins, but 5 to 100 times smaller in surface area.

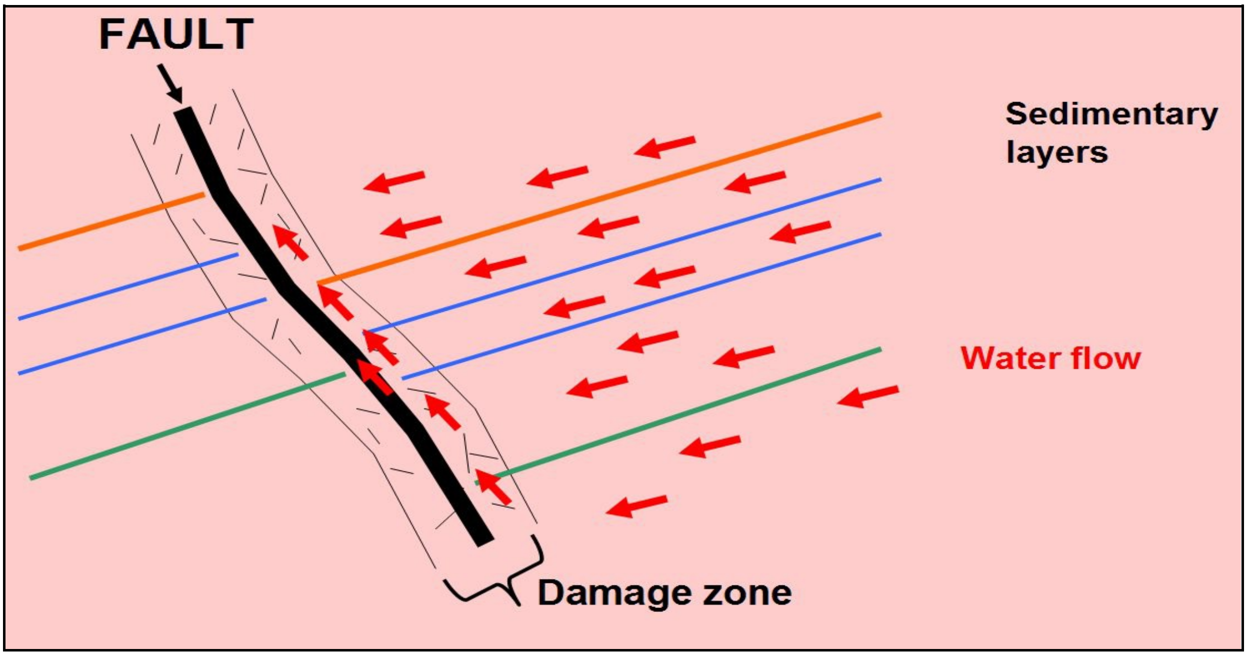


Fig. 16. Cartoon of a fault zone and resulting fluid flow (red arrows). The core zone (black) could be a barrier, or it could be a conduit. The damage zone on either side is always a conduit because it is fractured.

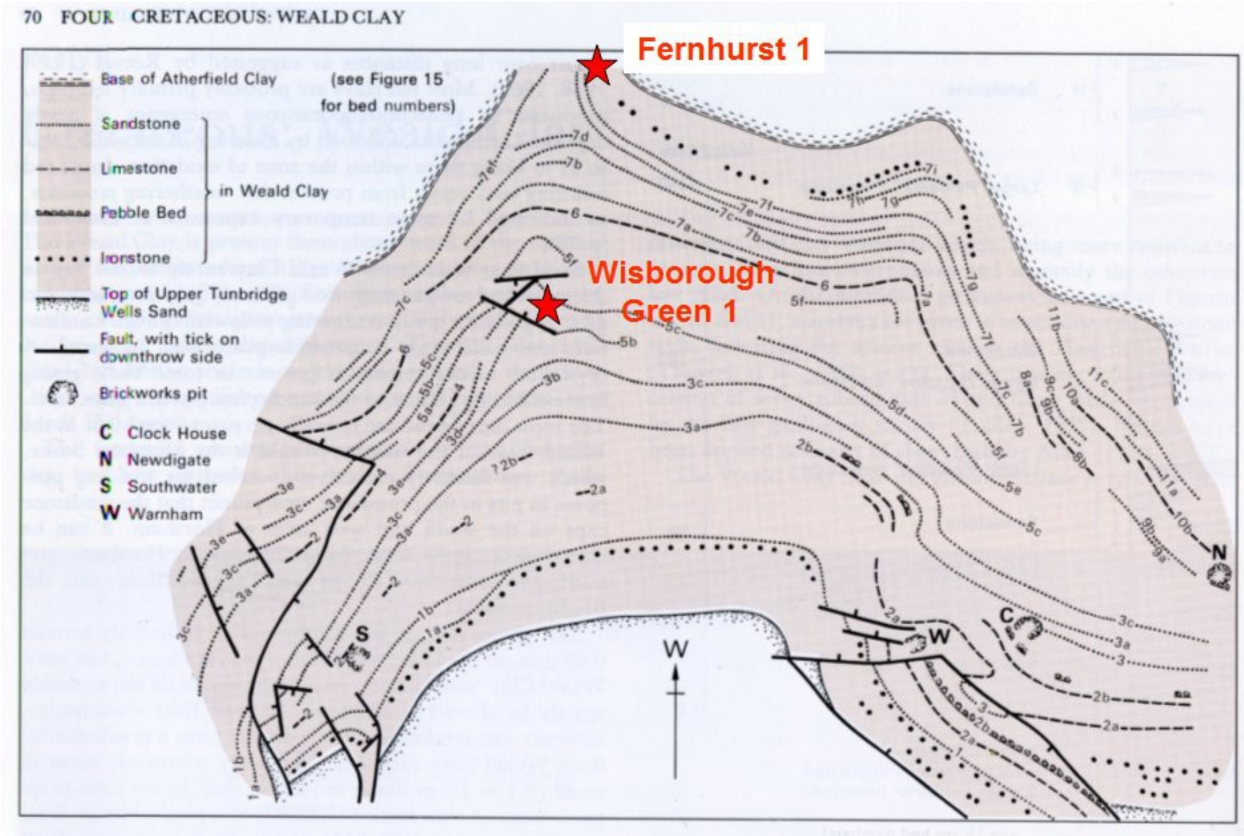


Fig. 17. BGS map of the Weald Clay. West is up, and the map is anamorphic; it has been highly compressed in the E-W direction. Celtique's other proposed well, Wisborough Green-1, is 16 km east of Fernhurst-1. Fernhurst-1 is almost at the top of the Weald Clay succession; Wisborough Green-1 is in the middle of the succession.

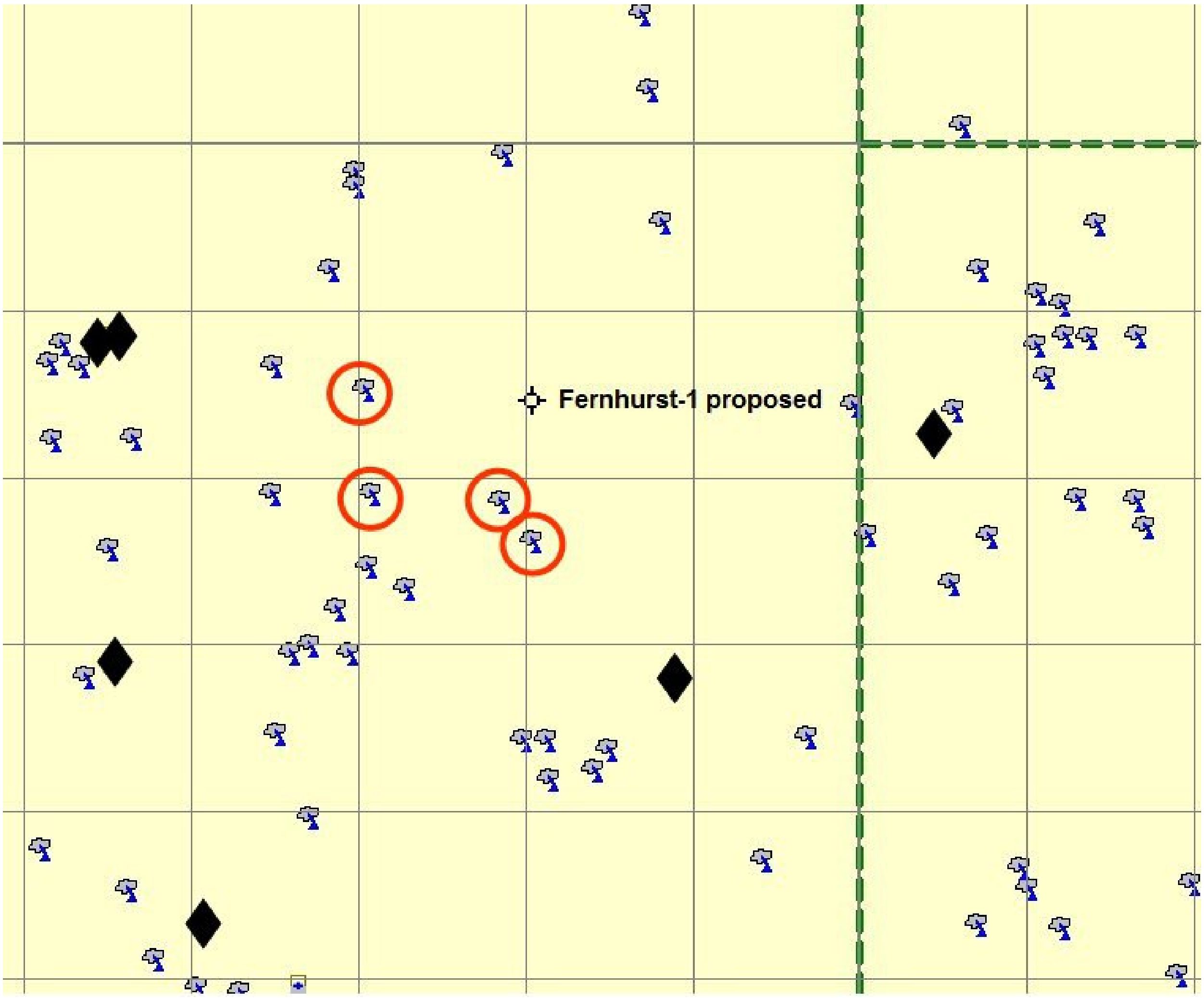


Fig. 18. Issues of water and springs (grey/blue symbol) around the proposed Fernhurst-1 well location, from OS 1:10K maps. The four circled in red are discussed in the text and shown in the next figure. Wells marked on the OS maps are shown by a black diamond. OS grid spacing 1 km.

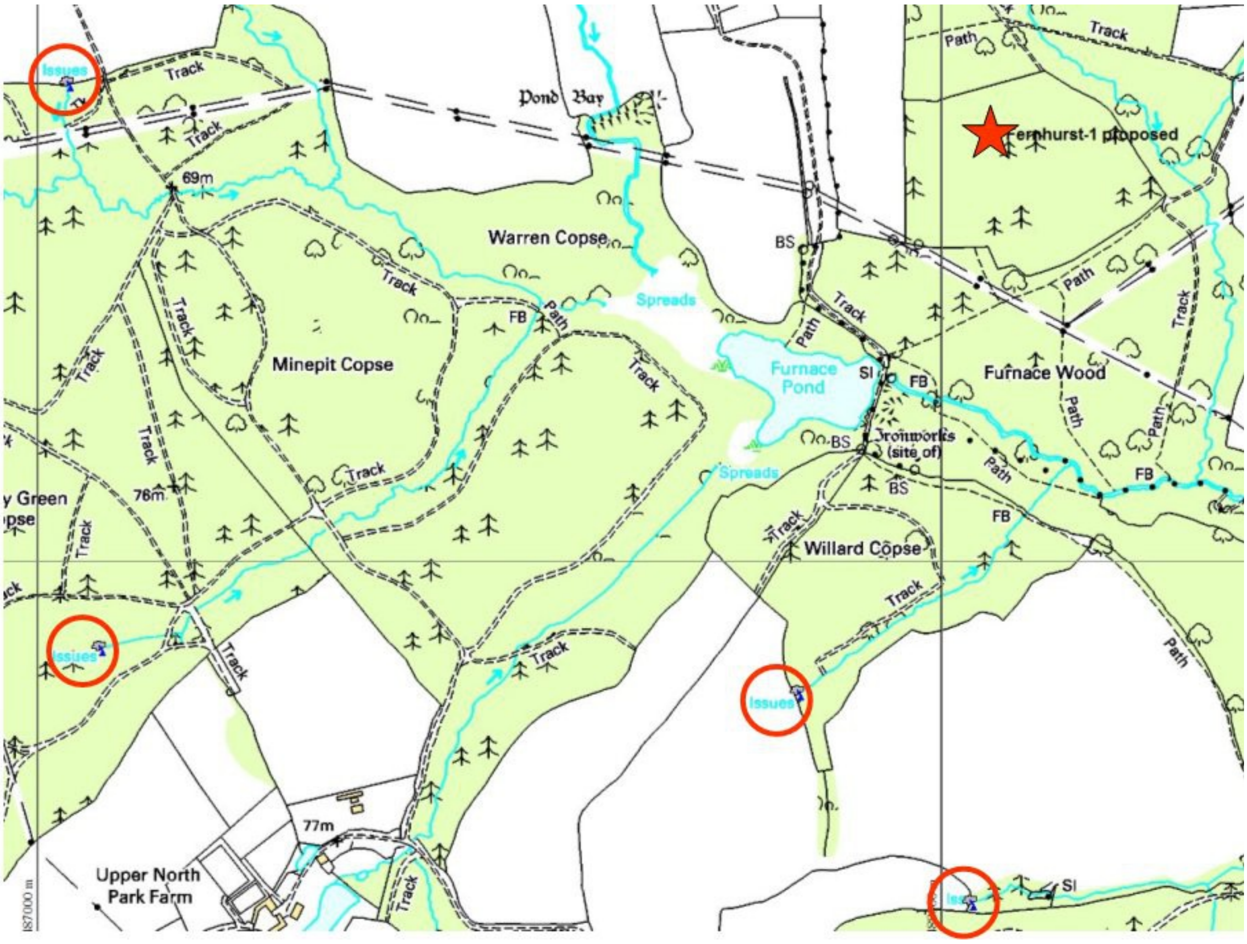


Fig. 19. Detailed map of the four issues (red circles) south and west of Fernhurst-1 (red star). The OS grid is at a 1 km spacing.

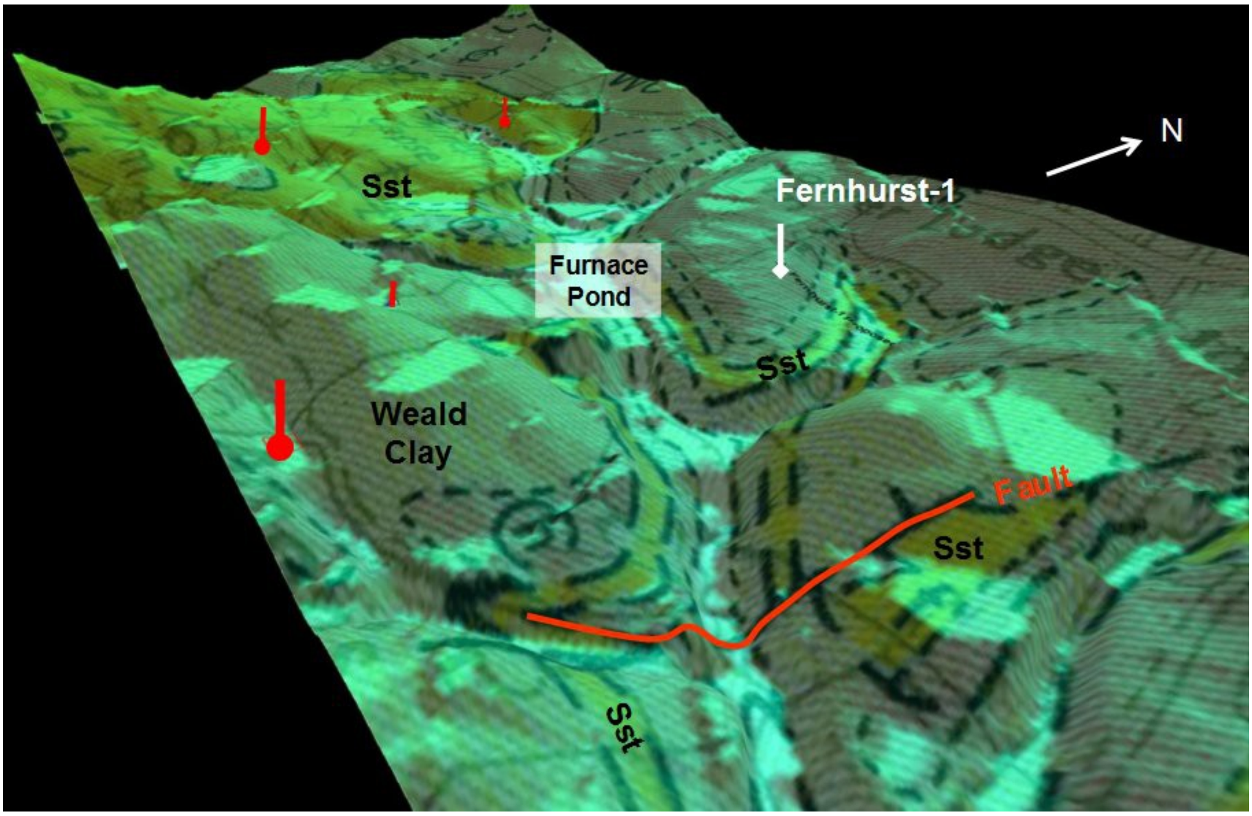


Fig. 20. Perspective view looking NW towards Furnace Pond, with the geological map draped over vertically exaggerated topography. The circled water issues of the previous diagram are marked by vertical red poles (the second-nearest one is partially hidden). The greenish-yellow colour labelled 'Sst' is sandstone bed no. 7ef within the uppermost Weald Clay (see Fig. 17). The remainder of the geological outcrop is Weald Clay, in places underlain by a Quaternary-age unconsolidated deposit called 'Head'.