Seismicity at Newdigate, Surrey, during 2018-2019:
A candidate mechanism indicating causation by nearby oil production

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Supplementary material

Contents:

1. Reporting of activities in the Brockham and Horse Hill wells

As is evident from the extensive media coverage (e.g., BBC, 2018; Hayhurst, 2018; McLennan, 2019), from the outset, on 1 April 2018, a potential connection between the 'swarm' of earthquakes in the Newdigate area of Surrey and local oilfield activities (in the nearby Brockham and Horse Hill wells) was immediately suspected, but was dismissed by one developer (Hayhurst, 2018a). Concerns about the possibility that activities in these wells were indeed causing these earthquakes were raised through correspondence in The Times newspaper in August 2018 (Gilfillan et al., 2018). A workshop, convened by the Oil & Gas Authority (OGA), followed on 3 October 2018, a summary of its proceedings being reported by OGA (2018), including the statement that '*the workshop participants concluded that, based on the evidence presented, there was no causal link between the seismic events and oil and gas activity although one participant was less certain and felt that this could only be concluded on "the balance of probabilities" and would have liked to see more detailed data on recent oil and gas surface and subsurface activity.*' The workshop presentations included a candidate conceptual model linking the seismicity to site activity, by Haszeldine and Cavanagh (2018), which – its authors admitted – could not be tested at that stage because essential data needed were unavailable. Nonetheless, later in October 2018 the Horse Hill developer issued a communication to local residents, which stated that '*in light of a few misleading and mischievous rumours being circulated, we thought you would appreciate the facts, from the Horse Hill mouth, so to speak. … Following the number of unexplained tremors in Surrey earlier in the year, earthquake-monitoring devices were installed at various nearby locations. A subsequent meeting organised by the OGA with various stakeholders and the British Geological Survey has concluded that there is no link between exploring for hydrocarbons and the tremors. This came as no surprise to us since there was no activity at Horse Hill during the majority of the tremors*' (Horse Hill Developments Ltd., 2018). This was in the context of the developer initiating a planning application to the local authorities for permission to drill five more wells at the site.

By February 2019, additional data regarding the nature and timing of operations at the Horse Hill-1 well had been placed in the public domain. On 5 February Cavanagh et al. (2019) wrote to SCC pointing out the clear correlation between these operations and the Newdigate seismicity and noting other evidence that might reasonably be taken as indicative of a cause and effect connection and was worthy of further investigation. On 12 February, UKOG (2019) wrote a response, which stated that '*in our view Cavanagh et al's document reads more like a protester statement than a serious scientific document*'. UKOG (2019) made many specific criticisms, some of which seem unreasonable. For example, they criticised the application of the Davis and Frohlich (1993) criteria for assessment of whether seismicity is natural or anthropogenic, on the basis that these criteria only apply to seismicity caused by fluid injection, which has not occurred at this site. However, as is well known to subject specialists, these criteria are applicable to anthropogenic seismicity irrespective of its particular mechanism. In any case, Cavanagh et al. (2019) did not refer to Davis and Frohlich (1993), although their previous submission (by Haszeldine and Cavanagh, 2018) did. Haszeldine and Cavanagh (2018) showed that this instance of seismicity satisfies all the criteria for anthropogenic seismicity advocated by

Davis and Frohlich (1993) except one, that a geomechanical mechanism linking the two could not be demonstrated, this being due to a lack of data. Subsequently, Verdon et al. (2019) proposed a new procedure (superseding that by Davis and Frohlich, 1993) for assessing whether seismicity is anthropogenic. Applying these criteria, they reached a strong conclusion that the Newdigate seismicity was a natural occurrence. Several assessments contributed to this conclusion. First, Verdon et al. (2019) claimed that the earthquakes are not correlated in time with well activities, even though Cavanagh et al. (2019) had already shown otherwise. Second, Verdon et al. (2019) claimed that there was no plausible geomechanical mechanism linking the seismicity to well activities. Rather than presenting any geomechanical calculations, they argued this on the basis of the smallness of the fluid volumes involved in the activities at Horse Hill, which they claimed would not affect fluid pressure (and thus, the state of stress) at distances greater than a few hundred metres from the well. They also noted that the seismicity propagated towards the Horse Hill well, whereas if well activities were the cause it would propagate away.

HH-1 April 2018 Re-Completion Operations Sequence

Preparatory Work:

1.
2.
3.
4.

Re-completion operations:

1.
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3.
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14.

Figure S1. Redacted excerpt from a submission by the Horse Hill developer to OGA detailing the well testing activities to be carried out in 2018, as part of the permitting process (https://www.whatdotheyknow.com/request/513050/response/1369572/attach/3/hhrecomp%20marked%20for%20redaction%20Redacted.pdf?cookie_passthrough=1). This redacted document was released on 21 May 2019 as part of a Freedom of Information request, following a protracted email exchange between the requester and the OGA (see https://www.whatdotheyknow.com/request/horse_hill_request_for_informati6ncoming-1239081 for details). In this case, the redaction was pointless, as an unredacted version (https://brockhamoilwell.files.wordpress.com/2019/04/disclosure-201808357-2.pdf) had been placed in the public domain by 10 May 2019 (see https://drillordrop.com/2019/05/10/latest-earth-tremor-prompts-call-for-release-of-data-on-oil-operations/).

In August 2019 Hicks et al. (2019) published a more detailed analysis of the Newdigate seismicity (Figs 01 and 2). They noted that the propagation deduced previously was an artefact of mislocation, thus undermining part of the evidence that influenced Verdon et al. (2019). Despite, once again, not presenting any geomechanical calculations, Hicks et al. (2019) concluded that '*On balance, and based on the available evidence, we find it currently unlikely that nearby industrial activities induced the seismic swarm*'. This work has been widely reported (e.g., BBC, 2019a), albeit noting that the scientific community is divided over these conclusions. In early September 2019, the Horse Hill planning application was approved, the media reporting (e.g., BBC, 2019b) noting the issue of seismicity and that this decision might well be subject to legal challenge.

Technical data from the Brockham and Horse Hill sites that are relevant to the present study will now be summarized. Hicks et al. (2019) had access to proprietary information, but the present study has been reliant on public domain sources. These include public announcements by the developers (required to comply with UK law on transparent disclosure of information that can affect valuation of company shares), online postings by objectors to these projects, and documents provided by regulatory authorities. Some of the latter category of document have only entered the public domain as a result of Freedom of Information (FOI) requests, which are possible under UK law as the OGA is a public body; in the process, many such documents have undergone redaction to eliminate information that might supposedly be commercially sensitive (as in Fig. S1).

Brockham

The first well at Brockham, Brockham 1 (BGS ID TQ14NE95, at TQ 18832 48653), was drilled in 1987. The oil reservoir is in the uppermost ~3 m of the Portland Upper Sandstone, its top at 570 m TVDSS (Angus, 2018), or ~622 m below local ground level. At the October 2018 workshop it was reported (https://www.ogauthority.co.uk/media/5160/7c-angus-maps-for-oga-meeting.pdf) that production up to 2016 in this field had amounted to ~490,000 barrels of fluid. Approximately 62,000 barrels of formation water had been re-injected, making net production ~428,000 barrels or ~68,000 m^3 (Angus, 2018, stated 36,900 m^3, this figure presumably excluding produced water). During this production, the reservoir pressure decreased from ~900 to ~500 psi, a decrease by ~400 psi or ~3 MPa. At this time, and following the subsequent resumption, production was from well Brockham X2Y (BRX2Y; BGS ID TQ14NE141; at TQ 18850 48660), a sidetrack off the original Brockham X2 or BRX2 well (BGS ID TQ14NE136, drilled in 1998), which was left shut in when production ceased in 2016. Water injection to maintain this production has been into well Brockham X3 (BRX3; BGS ID TQ14NE139; drilled in 2007 as a sidetrack from well Brockham-1). Well Brockham X2Y is deviated SW from the wellhead, achieving a ~600 m separation between production and injection (Angus, 2018). Well Brockham X4 (BRX4; BGS ID TQ14NE137; at TQ 18841 48650) was also drilled in 2007. Subsequent events at this site are recorded through press releases by its operator (http://www.angusenergy.co.uk/media/news/; see also https://www.ogauthority.co.uk/media/5159/7b-angus-earthquake-summary-report.pdf), a document outlining the plans for the site, released under a FOI request (Angus, 2018), and online postings by objectors (e.g., https://drillordrop.com/brockham-surrey/). Thus, in November 2016 the developer obtained an environmental permit to drill a sidetrack (called BRX4Z) from well BRX4, to test and potentially produce from the deeper Kimmeridgian and Corallian formations; drilling took place in January 2017. However, no planning permission was obtained; the operator stated at the time that it was covered by existing planning consents, even though this existing permission (https://planning.surreycc.gov.uk/planappdisp.aspx?AppNo=2007/0443) makes no mention of any sidetrack from this well. Pending resolution of this planning dispute, work on testing sidetrack BRX4Z was suspended.

On 23 March 2018, production from well BRX2Y resumed from the Portland reservoir, as indicated in Fig. 4. From Hicks et al. (2016), ~4.0 m^3 (~25 barrels) of oil were produced on 23 March followed by ~1.1, ~0.9 and ~1.0 m^3 (~7, ~6 and ~6 barrels) on 25-27 June, the latter accompanied by water injection. Production during subsequent months was intermittent (Fig. 4), including ~2.7 m^3 (~17 barrels) on each of 7 and 8 June, ~2.1 m^3 (~13 barrels) on 11 June, and ~1.6 m^3 (~10 barrels) on 21 June. As detailed in Fig. 4, fluid injection occurred on 26 June, the day before the first earthquake of the second 'cluster', followed by renewed production, but the detailed schedule for these actions has not been placed in the public domain. On 8 August 2018 the developer's retrospective application for planning permission to legitimate sidetrack BRX4Z was approved (https://planning.surreycc.gov.uk/planappdisp.aspx?AppNo=SCC+Ref+2017%2f0215); production from BRX2Y ceased in October 2018 (Fig. 4) as work at the site switched to testing this sidetrack.

Horse Hill

The Horse Hill 1 well (HH1; BGS ID TQ24SE93; at TQ 25255 43600) was drilled in 2014. It was logged to its original total depth (Table 1), before being plugged below the Kimmeridgian. Flow testing in 2016 attracted media attention as the 'Gatwick Gusher'. A press release (http://otp.investis.com/clients/uk/solo_oil/rns/regulatory-story.aspx?cid=983&newsid=1054418; see also https://www.lse.co.uk/rns/UKOG/horse-hill-1-flow-test-yjc35j83vlmcg7a.html) reported that for this testing this well had been perforated over a 35 m interval in the Portland reservoir, ~615 m below ground level, from which oil production at 323 bopd was maintained over an 8.5 hour period. Xodus (2018) noted that to achieve this production rate required acid stimulation of the reservoir, which created a permeability of ~2 mD (mean) to ~20 mD (maximum). Testing in the Kimmeridgian involved two 30 m perforated intervals, centred at depths of 840 and 900 m, in the Kimmeridge Limestone 4 (KL4) and Kimmeridge Limestone 3 (KL3) units. Production rates during testing in 2016 were of 901 bopd from KL4 and 464 bopd from KL3, during short (4-7.5 hour) flow periods. According to UKOG (2019), following this testing, the well was left in a 'suspended' state, with three pressure-tight bridge plugs set, one above each of the intervals that had been tested (see also Horse Hill Developments Ltd., 2018b).

When the seismicity began on 1 April 2018, a potential connection with the HH1 well was immediately suspected. As has been reported (https://drillordrop.com/2018/04/04/oil-company-says-were-not-to-blame-for-surrey-earthquake-but-local-concerns-remain/), the developer issued this statement '*We strongly refute the far-fetched, unscientific and malicious connection made between Horse Hill and the earthquake in Surrey on April 1st. … There is no drilling, testing or underground works taking place at Horse Hill or at any of our sites at present. All such work at Horse Hill ceased over two years ago.*' OGA (2018) later summarized the activity involving this well thus: '*Subsurface operational activity at the Horse Hill 1 site included a flow test in 2016 of 1940 bbls of oil from the Portland and Kimmeridge zones combined, but then activity ceased until 3 July 2018 when the extended well test of the Portland began, long after the first seismic event on 1 April 2018.*' … '*There is no annular pressure evidence of impaired wellbore integrity in the Horse Hill 1 well because of the seismic events, nor evidence of migration of gas outside the wellbore between different zones. The strata are normally pressured and at formation pressures all gas is solution gas and there is no free gas.*' … '*Flow testing at Horse Hill 1 well created pressure drawdown but the radius of influence is small (~200-1000m).*' A summary of the operations at the well, provided by its operator for the October 2018 workshop (https://www.ogauthority.co.uk/media/5168/6-horse-hill-development-limited-operational-summary-of-activity-at-horse-hill-1-wellsite.pdf), indicated that no activity took place between March 2016, when the well was perforated and the aforementioned flow testing was carried out, and June 2018. However, some of the entries in this record are truncated, so the full information cannot be read. This document anyway proved incomplete, requiring OGA (2018) to add as a footnote that prior '*to the recent commencement of the Horse Hill 1 testing in 2018, there had been no sub-surface work at the Horse Hill site since 18 March 2016. Surface activity included the excavation of a nearby new cellar starting on 21 March 2018 using a JCB for a future well and the site was visited by tankers to remove rainwater collected above the impermeable layer. Well integrity tests were conducted by checking annular pressures on 5-6 April 2018. No pressure was detected in either annuli and pressure tests were satisfactory. A workover crane arrived on site on 25 June 2018 in preparation for flow testing and the well was re-entered on 3 July 2018 and the retrievable bridge plug was removed from the well to test the Portland Sandstone. No injection was done, but liquids were drawn out of the well using a downhole pump. On 17 August 2018, a 113 ft interval in the well was perforated using a Geodynamics tool with 6 shots per foot and charges of 39 gm. The modelled stressed rock penetration is 18 inches from this activity.*'

UKOG (2019) added: '*A cursory glance … at publicly available information from the Health and Safety Executive would have revealed that the hydrocarbon bearing horizons in the well were completely isolated from the surface by three pressure tight plugs, as would be the case for any well suspended for future operations. The shallowest plug above the Portland was subsequently removed during operations in July 2018, the deeper plugs above Kimmeridge Limestone 3 and 4 were removed some months later. Therefore, there was no communication to the surface within the well until testing operations commenced.*'

Documents reporting on activities affecting the HH1 well in 2018 include the developer's application to recomplete the well (https://www.whatdotheyknow.com/request/513050/response/1427741/attach/3/Re%20Completion%20Application%20WONS%2010944%200%20RC%201%20Version%201%20LR%2024%204%20Redacted.pdf) and associated supporting material (https://www.whatdotheyknow.com/request/513050/response/1369572/attach/2/ewtapp%20marked%20for%20redaction%20Redacted.pdf?cookie_passthrough=1; https://www.whatdotheyknow.com/request/513050/response/1369572/attach/3/hhrecomp%20marked%20for%20redaction%20Redacted.pdf?cookie_passthrough=1). However, although these documents report some details, such as the design of the test string to be used in the Portland reservoir, overall they have been heavily redacted, as in Fig. S1.

Cavanagh et al. (2019) reported that prior '*to flow testing in April and July, Horse Hill appears to have encountered a natural source of overpressure in the … Kimmeridge, as observed in the 'gas lift' reported for the well. We infer that management of this pressure (probably by bleeding the well annulus prior to testing) likely altered the … stress balance, which then impacted on the Newdigate fault, causing the earthquakes.*' … '*Freedom of Information requests and social media posting from the fenceline of Horse Hill clearly indicate that well preparations for flow testing immediately precede the Newdigate earthquakes. We infer that the Horse Hill well and site engineering logs (not released at this time for scrutiny) may provide additional information on well intervention pressure changes as the trigger for the 2018 Newdigate cluster.*' In response to this claim, UKOG (2019a) wrote that '*the annulus pressure bleed-off cited by Cavanagh et al. relates to the annulus above the pressure tight plug set above the Portland, i.e. in the shallow part of the well inside unperforated steel casing that is isolated from the oil-bearing sections below. This is standard safety practice for all wells to ensure there is no build up of any biogenic gas from bacterial action in the near surface section. The annular bleed off, amounting to a few tens of psi, therefore, has no physical connection with anything in the deeper isolated oil bearing section below.*'

The above-mentioned report by UKOG (2019a) that there was some pressure change in the well is at odds with the report by OGA (2018) that '*no pressure was detected*'. There has been no subsequent disclosure of pressure data, despite an FOI request. There has also been no disclosure regarding the integrity of the bridge plug that isolated the Portland reservoir from the surface, ahead of its removal on 4 July 2018 (as reported by https://www.ogauthority.co.uk/media/5168/6-horse-hill-development-limited-operational-summary-of-activity-at-horse-hill-1-wellsite.pdf). Regarding the Cavanagh et al (2019) account, as part of the present study no FOI request or social media posting has been identified that establishes any intervention in the well before 1 April 2018. As noted above, the first reported intervention in the well was the measurement of pressure starting on 5 April 2018 (OGA, 2018). According to the published log of site activities (https://www.ogauthority.co.uk/media/5168/6-horse-hill-development-limited-operational-summary-of-activity-at-horse-hill-1-wellsite.pdf), the first intervention in the well ahead of the July 2018 flow testing in the Portland reservoir occurred on 1 July 2018, when it is reported that flow was circulated around the well (presumably its upper part, above the Portland bridge plug).

It has been suggested (Hayhurst, 2019) that the Horse Hill-1 well became pressurized while suspended between 2016 and 2018 and this pressure was released when activity at the well site resumed in the spring of 2018, potentially having an effect on the seismicity at this time. The state of this well during this suspension has been reported by Horse Hill Developments Ltd. (2018b); as they have indicated, the interval of the well open to the Portland reservoir was at this time isolated from the shallow part of the well by a removable bridge plug. This would mean that for any pressure change in the shallow part of the well (potentially caused by activity at the well pad) to affect the Portland reservoir would require this bridge plug to have failed. As already noted, this bridge plug was removed on 4 July 2018; the Portland reservoir at this site was thereafter hydraulically connected with the surface in this well.

During the phase of production in well HH1 from the Portland reservoir, the developer reported rates of 140-160 bopd, plus gas production rates of an additional ~50 bpd before the gas separator, equivalent to ~15000 cubic feet per day or ~425 m^3 per day at standard pressure (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-ewt-updates-portland-and-kimmeridge-oil-discovery-gzgkrfuq4fzq6lq.html). During this testing, the developer reported sustained pumping with stable bottom hole pressures of ~200 psi (~1.4 MPa) below the initial reservoir pressure of ~915 psi (~6.3 MPa), and that bottom hole pressures recovered rapidly back to initial reservoir pressure during periods of shut-in, indicating good connectivity within the oil pool in the Portland reservoir.

On 10 September 2018 the operator announced (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-ewt-updates-portland-and-kimmeridge-oil-discovery-gzgkrfuq4fzq6lq.html) that the flow testing of the Portland reservoir had ended and work was under way to re-complete the well to test the Kimmeridgian reservoirs. It is inferred from this announcement that this phase of flow testing ended around the end of August 2018, the precise date having not been reported. An additional ~4 m of perforated section had been created in the well, resulting in a sustainable production rate estimated as 362 bopd. On 5 October 2018, the operator announced (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-extended-well-test-and-regulatory-update-xgqw1sw82jyk4k1.html) that analysis of the testing established that this well is in hydraulic connection with a Portland reservoir of 7-11 million barrels of oil. This was considered a commercial discovery, although rather less than the range of estimates of 20-44 million barrels deduced from modelling of the original flow testing in 2016 (Xodus, 2018). This was followed by an announcement on 10 October (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-ewt-update-horse-hill-1--xa4zpctdu1tpii9.html) that an initial 50 hour flow test from the KL3 reservoir had been completed. Flow rates of up to 771 bopd were attained, significantly higher than in 2016. A subsequent announcement (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-kimmeridge-oil-production-continues-at-hh-1--5g16kgournvimc5.html) reported that production from the KL4 reservoir began in late November, the sustainable production rate being 300 barrels of oil per day, and that simultaneous pressure measurements established that the KL3 and KL4 reservoirs are hydraulically connected. As a result, it was decided to produce from both sources together, which began on 4 December.

Early on 18 February 2019, the developer announced (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-portland-oil-production-resumes-at-horse-hill-1zdan7c12i5yeog.html) that production had ceased from the Kimmeridgian reservoir and had resumed from the Portland reservoir. The developer appeared to have not announced the exact date, but it is reported as 11 February 2019 in Fig. 4(d), from Hicks et al. (2019). The announcement of resumed Portland production included the statement '*For prudent reservoir management purposes, the average test production rate from the 114 ft vertical perforated Portland section has been maintained below the previously reported 362 bopd calculated optimised sustainable rate.*' An online comment on this (https://drillordrop.com/2019/02/18/oil-production-updates-for-horse-hill-and-lidsey/), included '*Hmmm…..Prudent reservoir management purposes? No worries about changing the pressure enough to cause further earthquakes then?*' The reservoir pressure draw-down at this time was described as 'modest' (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-production-test-update-eyt2n45v64zsvqx.html), although with no quantitative information. Production from the Portland reservoir ceased for 60 hours in mid April (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-oil-production-test-update--diew7rpxvbd4576.html), before resuming at a steady 220 bopd through into May, when it was announced (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-production-test-update-eyt2n45v64zsvqx.html) that it would cease in June and resume in the Kimmeridgian reservoir, in order to permit safe drilling of new Horse Hill-2 (HH2) well through the Portlandian succession (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-production-test-update-8mg2yi5vjywnu71.html). Production from the Portland ceased in late June, when the volume produced reached 29568 barrels (equivalent to ~4700 m^3), and resumed in the Kimmeridgian on 6 July (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-50000-barrels-of-oil-production--xd4jh1jjpiw92j9.html; https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-production-test-update-8mg2yi5vjywnu71.html).

On 30 September the start of drilling of well HH2 was announced (https://www.lse.co.uk/rns/UKOG/hh-2-2z-drilling-commences-spud-at-horse-hill-aw1qz6dh9uts74p.html) This vertical pilot well was drilled to ~900 m depth and logged, concentrating on the Portlandian section, to optimize the design of a side track in the Portland reservoir to be known as Horse Hill 2Z (HH2Z), before being plugged back to the kick-off point for this lateral. Well HH2Z has been designed with a total length of ~5,800 ft (~1800 m) from the surface, with a ~1000 m horizontal section in the most productive zone of the Portland reservoir. The aim of this long production interval is to achieve much higher production rates than are feasible from the Portland reservoir using HH1. By 8 October, drilling of well HH2 had reached a depth of 615 m, near the top Portlandian, with preparations under way to recover core (https://www.lse.co.uk/rns/UKOG/drilling-update-horse-hill-lx7s8ddu8e14cc8.html). The lateral, well HH2Z, was duly completed in November 2019 (https://www.lse.co.uk/rns/UKOG/hh-2z-completed-horse-hill-7qxv12c1g58vjb2.html). Flow testing took place in December 2019, ending by 18 December, when a maximum rate of fluid production of 1087 bpd was achieved (https://www.lse.co.uk/rns/UKOG/hh-1-and-hh-2z-extended-well-test-update-xjk6frv4uqebsr1.html), indeed much higher than the maximum rate from well HH1. Production at this site then switched back to the Kimmeridgian reservoir in well HH1.

The production figures reported by Hicks et al (2019) in Fig. 4 are not consistent with the above-mentioned values reported by the developer. For example, during the initial Portland testing phase for well HH1 in July-August 2018, Hicks et al (2019) reported the maximum production rate as 19.4 m^3 per day or 122 bopd (Fig. 4(d)), whereas the developer reported rates of 140-160 bopd, plus the aforementioned gas production (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-ewt-updates-portland-and-kimmeridge-oil-discovery-gzgkrfuq4fzq6lq.html). During the February-June 2019 phase, Hicks et al (2019) reported the maximum production rate as 33.0 m^3 per day or 207 bopd (Fig. 4(d)), whereas the developer reported a steady rate above 220 bopd (https://www.lse.co.uk/rns/UKOG/uk-oil-and-gas-plc-horse-hill-1-50000-barrels-of-oil-production--xd4jh1jjpiw92j9.html). No attempt is made here to resolve discrepancies such as these.

2. Geolocation issues

The study area has been illustrated using the map (Fig. 01), and seismic cross-section (Fig. 2) from Hicks et al. (2019). However, the original versions of both these figures have required significant amendment regarding accuracy issues. These aspects will now be discussed. The issues covered include the scaling and the depictions of faults and seismic lines for Fig. 01, and the vertical and horizontal geolocation of Fig. 2.

First, the original version of the map, presented by Hicks et al. (2019), had a scale bar that was too small and thus gave a misleading impression of the distance between the Horse Hill-1 and Brockham wells and the seismicity. The original scale bar is shown 'greyed out' in Fig. 01. This map also shows seismic lines. The source of information for positions of seismic lines, including line TWLD-90-15 that is illustrated in Fig. 2, was not reported by Hicks et al. (2019); it is evident that they are from the UK Onshore Geophysical Library (OGL; https://ukogl.org.uk/) location map, which is itself indexed to the BNG, so the information provided therein must have been transformed to geographical co-ordinates by Hicks et al. (2019). Moreover, the OGL index map is highly schematic and so cannot be used for accurate location, although careful comparison of it with definitive maps can indicate the routes followed by seismic lines along roads and rural tracks and, thus, indirectly provide accurate location.

Faults

Hicks et al. (2019) explained (in Note S6 of their online supplement) that (rather than using the existing literature) they located faults in the study area through their own analysis of 2-D seismic reflection profiles, including making their own interpretations of how to interpolate faults between these profiles. Where points of comparison are available, Fig. 01 can be seen to lack accuracy. For example, definitive geological maps (available online via BGS Digimap) and the structural map available as Fig. 22 of Gallois and Worssam (1993) indicate that there is no significant fault at the position indicated in Fig. 01 for the 'Faygate Fault'. The Holmbush Fault crosses seismic line TWLD-90-15 at BNG reference TQ 21766 33846, south of the village of Faygate and also south of the intersection with the east-west seismic line depicted in Fig. 01 south of this village, which follows the main road (the A264) between Crawley and Horsham. The depiction of this fault by BGS Digimap is consistent with that by Gallois and Worssam (1993): at outcrop it has modest upthrow to the south (as a result of reverse slip during the Cenozoic basin inversion) and separates the Early Cretaceous (Valangian) Tunbridge Wells Sand Formation (https://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=TWS) to the south from the younger (Hauterivian-Barremian) Weald Clay Formation (https://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=WC) to the north. This geological boundary corresponds to the transition in the landscape from the 'Low Weald' in the Weald Clay, which is mostly agricultural land, to the 'High Weald' in the Tunbridge Wells Sand, which is forest and heathland, and is unequivocal. Initial attempts to correctly geo-locate the information presented by Hicks et al. (2019) assumed that their 'Faygate Fault' is in fact the Holmbush Fault but was depicted by them in Fig. 01 several hundred metres too far north.

A further difficulty concerning Fig. 01 is that according to both Digimap and Gallois and Worssam (1993) seismic line TWLD-90-15 crosses another significant fault, the Crawley Fault, at BNG reference TQ 21657 36444, just south of the village of Lamb's Green. However, no fault is depicted in this vicinity in Fig. 01.

Another significant issue affecting Fig. 01 concerns the faulting in the vicinity of the Brockham well; here, too, Hicks et al. (2019) have proposed a reinterpretation of the structure rather than familiarizing themselves with the established interpretation, from documentation provided for the petroleum licensing process (e.g., Europa, 2004). Thus, in Fig. 01, the Brockham oil reservoir is depicted as separated from the source area of the Newdigate earthquakes by two faults, the Brockham and Holmwood faults, both with downthrow to the south (Fig. 01). In contrast, the definitive interpretation (Europa, 2004), envisages the structure rather differently. In their view, as the Holmwood Fault approaches the Brockham Fault from the east, it bends to WNW strike, joining the Brockham Fault circa TQ 17520 47483. Furthermore, although the Holmwood Fault has substantial downthrow to the south in older deposits, at the stratigraphic level of the top Portland Sandstone the downthrow is reversed, due to the effect of Cenozoic reverse-slip reactivation, but its throw is small, circa 10 ms in terms of TWT. A subsidiary normal fault splays WSW from the Holmwood Fault circa TQ 18991 46988, but has a similar small offset at the level of the top Portland Sandstone and dies out circa TQ 16163 46416. The Brockham Fault bends around the southern end of the Brockham oil reservoir, located within the Upper Portland Sandstone, before resuming westward strike, with a subsidiary normal fault splaying WSW from it circa TQ 15961 47458. Thus, between TQ 17520 47483 and TQ 15961 47458, a distance of ~1.5 km, the top Portland Sandstone is offset by ~40 ms in terms of TWT.

Seismic section – horizontal scale

Regarding the horizontal scale of Fig. 2, the clearest indication of an apparent lack of accurate geolocation by Hicks et al. (2019) is again provided by the position of their 'Faygate Fault'. With the horizontal scale used by Hicks et al. (2019), this fault projects to the surface at a point ~11 km from the northern end of the profile, whereas when Fig. 01 is correctly scaled and the fault positioned in the correct place it is ~13 km from this northern end. The southern end of the profile is also much closer to this fault as depicted in Fig. 01 than in Fig. 2.

Having noted these difficulties, an initial attempt was made to rectify them by correctly geo-locating Fig. 2. Figure 2 shows seismic line TWLD-90-15; from OGA records, this was shot in 1990 using Vibroseis, with 12.5 m shot spacings, its overall length of 24.55 km spanning shot points 112 to 2078. However, the seismic section depicted is clearly shorter than the total length of the seismic line and thus does not necessarily reach either of its ends. Nonetheless, checking against the OGA index map and its schematic locations to actual locations on real roads indicates that the northern end of Fig. 2 does in fact coincide with the northern end of the seismic line, at shot point 2078, located using the OGA index map at BNG reference TQ 20322 46930 (at Gad Brook Bridge, Bunce Common). However, to position and scale Fig. 2 correctly, using this constraint, another point of reference is needed. After trying multiple options, a provisional geo-location of Fig. 2 was achieved as follows. A clear feature of Fig. 2 is the section of it that has been muted, in a location ~600 m north of the surface trace of the Faygate Fault. This part of the seismic line was shot along a minor road that heads northward through the village of Faygate, crossing over the Crawley-Horsham railway on a bridge (at BNG reference TQ 21777 34426). When shooting seismic lines in the UK, it is standard to skip Vibroseis shot points that would otherwise endanger sensitive infrastructure, such as railway bridges and their approach embankments; it is inferred that this was done in this particular instance. Using the OGL index map (which shows shot points with numbers that are multiples of 100) and definitive local maps, from Digimap, the shot point that was muted was tentatively identified as number 1034, making this point 13050 m from the northern end of the seismic line. Provisional horizontal scales could thus be added to Fig. 2, a first one assuming that the seismic line runs due north-south. A second scale is also added, showing the shot point numbers, which can be used to locate other points on the profile, by interpolating between the known co-ordinates of adjacent shot points with numbers that are multiples of 100. This provisional attempt at geo-location is illustrated in Fig. S2.

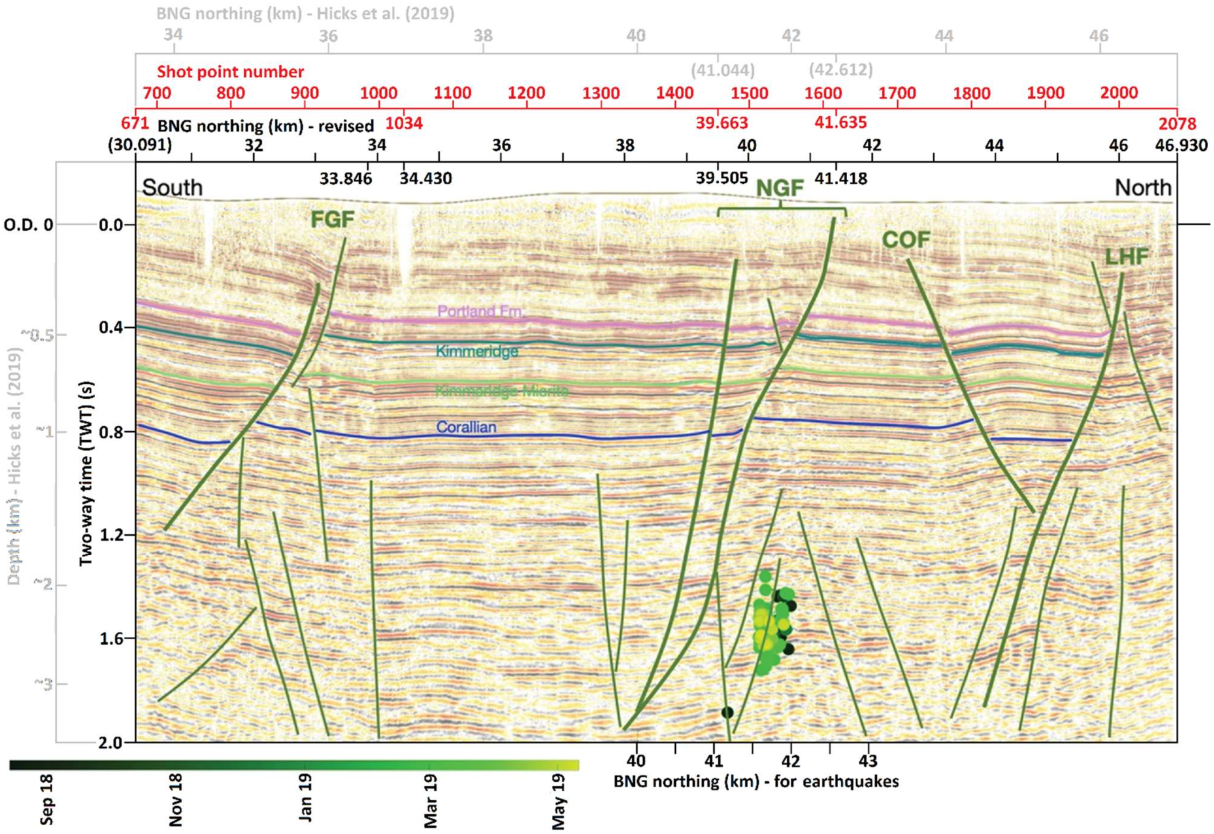

Figure S2. Seismic section along seismic line TWLD-90-15, modified from Fig. 6 of Hicks et al. (2019), annotated to facilitate the attempt, discussed in the supplementary text, to try to reconcile the position of the 'Faygate Fault', depicted here, with the depiction of the same fault in Fig. 01. The original was indexed to the British National Grid (BNG), rather than the geographical co-ordinates used for Fig. 01; the co-ordinates reported by Hicks et al. (2019) have been 'greyed out'. New co-ordinates have been added, based on geo-location of features in the seismic section and by counting the shot points, as described in the text. Further consideration, including inspection of the original seismic section and metadata from UKOGL, established that the 'Faygate Fault' (FGF), depicted here, is the Crawley Fault of previous authors (e.g., Gallois and Worssam, 1993), and this fault was depicted by Hicks et al. (2019) in the wrong place in Fig. 01.

To test this geo-location, the resulting co-ordinates of the Newdigate Fault (the structure associated with the 2018-2019 seismicity, according to Hicks et al., 2019, as already noted) were calculated at the Earth's surface and at a point on its footwall cutoff at a two-way time (TWT) of 1.264 s. Using the shot point co-ordinates gave TQ 22031 41635 and TQ 21884 39663 as the BNG references of these two points, whereas approximating the seismic line as straight, due north-south, gave TQ 22085 41418 and TQ 21917 39505. Conversely, the original interpretation of the seismic section by Hicks et al. (2019) placed these two points circa TQ 21426 42612 and TQ 22162 41044. The two provisional revised geo-locations are consistent to within a margin of ~200 m in this locality and, if correct, would indicate that Hicks et al. (2019) placed this fault ~1 km too far north. Extrapolation on the basis of counting shot points places the southern end of the excerpt of seismic line TWLD-90-15 in Fig. 2 at shot point 671, with co-ordinates TQ 21694 30698. The alternative extrapolation, assuming that the excerpt is oriented north-south, places its southern end at TQ 21194 31091. Because this southerly part of the seismic line includes a number of significant changes in direction, as it follows forest tracks through the High Weald, the extrapolation by counting shot points is likely to be the more accurate of the two.

Given the need to check this apparent mislocation, imagery and metadata for seismic line TWLD-90-15 were obtained from the UKOGL/Beneath Britain archive. The metadata included a list of shot point co-ordinates and excerpts from large-scale maps showing the surveyed location of the seismic line. However, as will become clear, these two forms of metadata are not consistent, with discrepancies of up to ~100 m; the map has been assumed to be definitive. It was thus established that the northern end of the excerpt depicted by Hicks et al. (2019) is indeed of the northern end of the seismic line, ending at shot point 2078. The co-ordinates of shot point 2076 are reported as TQ 20358 46937. However, if this were so, the seismic line would have run ~30 m east of the road in Bunce Green, through a row of houses, rather than along the road. The true northern end of the line appears to be at Gad's Bridge, circa TQ 20326 46935.

The muted section of the seismic line, thought in the tentative geo-location process to be at Faygate, turned out to be at shot point 1224. Shot point 1221 was reported at BNG reference TQ 21785 36777 but this point is ~100 m NW of the road followed by the seismic line through Lamb's Green. The UKOGL location map also shows the seismic line too far to the west, but from it the correct location of shot point 1200 can be estimated as circa TQ 21734 36513. It follows that shot point 1224, where the section is muted, is ~300 m farther NNE, so circa TQ 21915 36771.

The southern end of the Hicks et al. (2019) excerpt of the seismic section turns out to be circa shot point 921. Shot point 930 was reported at BNG reference TQ 22332 33383, from which the position of shot point 935 can be estimated as TQ 22404 33297. This is near, roughly 200 m south of, the position estimated by Hicks et al. (2019), which is circa BNG northing 33500. To this margin of uncertainty, it can be seen that this end of the seismic section is depicted in the correct place in Fig. 01.

The structure named by Hicks et al. (2019) as the 'Faygate Fault' projects to the Earth's surface in the vicinity of shot point 1171. Taking shot point 1200 at TQ 21734 36513, as before, the position of shot point 1171 can be estimated as circa TQ 21546 36256. On this basis it can be seen that the BNG northing co-ordinates provided by Hicks et al. (2019) for the surface projection of their 'Faygate Fault' is circa 36300. Overall, it is therefore concluded that the seismic section in Fig. S2 was in fact accurately geo-located by Hicks et al. (2019). Any mislocation is small, no more than ~200 m, and would be difficult to improve upon given the uncertainty in the reported shot point co-ordinates for this seismic line. However, the realisation that their 'Faygate Fault' projects to the Earth's surface in the same place as the previously recognized Crawley Fault (surface trace on seismic line at TQ 21657 36444; see above) means that these faults are one and the same; the name Crawley Fault should be given precedence. Moreover, the surface trace of the 'Faygate Fault' in Fig. 01 is depicted >2 km south of its position by Hicks et al. (2019) in Fig. S2.

The Holmbush Fault can be recognized on the OKOGL version of the record section for seismic line TWLD-90-15 at shot point 971, although the small throw on this fault in the shallow subsurface makes it near the limit of seismic resolution. The co-ordinates of shot point 971 are listed as TQ 21966 33725; this point is on the route taken by the seismic line, but ~200 m ESE of the outcrop of the fault as recognized by Digimap and by Gallois and Worssam (1993). The position of this fault is labelled on Fig. S2 and Fig. 2, the image presented by Hicks et al. (2019) being less clear than that from UKOGL.

The excerpt of seismic line TWLD-90-15, provided in Fig. R to illustrate the structure of the Newdigate Fault, spans between shot point 1400 and the northern end of the seismic line at shot point 2078. Its southern end point now requires geo-location. According to the metadata for the seismic line, shot point 1405 was located at TQ 21796 39007, but these co-ordinates are >200 m east of the route followed. Taking this and the depiction of the seismic line on the UKOGL map into account, the co-ordinates of shot point 1400 can be estimated as TQ 21585 39125.

Seismic section – vertical scale

The existing tie between the Horse Hill-1 well and a seismic section (reported by Pullan and Butler, 2018) can form the basis of validating the vertical scale deduced by Hicks et al. (2019) in Fig. 2(a). This well is deviated NNW by 604 m, as shown in Fig. 01. From OGA documentation, it deviates to a maximum inclination of 45°, gradually returning to a vertical orientation near the well bottom. The detailed structure in the vicinity of this well is illustrated in a seismic section provided as Fig. 22 of Pullan and Butler (2018). Table 1 indicates that the base of the Jurassic succession is encountered in this well at a depth (TVDSS) of 2204 m that corresponds to a two-way time of 1.286 s; given the near-vertical orientation of the bottom part of the well, this point is ~604 m NNW of the wellhead. Pullan and Butler (2018) reported that at the western end of their seismic section, ~2 km west of the wellhead, the two-way time to the base Jurassic is ~1.2 s, which they converted to a depth of ~6900 ft or ~2100 m. Their seismic line intersects that in Fig. 2 at TQ 21062 43513, near shot point 1785; around this point Pullan and Butler (2018) indicated that the base Jurassic is again at ~2100 m depth.

Experience of other seismic sections in the Weald Basin, such as those depicted by Andrews (2014) and Pullan and Butler (2018), indicates that the Lias Group sediments, in the lower part of the Jurassic succession, typically do not produce strong seismic reflections. The underlying strong reflectors thus represent the Penarth Group of Late Triassic age (https://www.bgs.ac.uk/Lexicon/lexicon.cfm?pub=PNG; formerly known as the Rhaetic beds; Table 1). On this basis, the base of the Jurassic succession can be tentatively interpreted as indicated in Fig. 2(b). The seismic reflector thus interpreted appears (Figs 2, 3) offset across the Newdigate Fault by 0.107 s two-way time, between 1.264 s at its footwall cutoff (circa TQ 22163 41030, shot point 1567) and 1.371 s at its hanging-wall cutoff (circa TQ 22135 40970, shot point 1562). Using the interval velocity for the Lower Lias (Table 1; nowadays formally designated as the Scunthorpe Mudstone Formation; https://www.bgs.ac.uk/lexicon/lexicon.cfm?pub=SMD) the height of this footwall escarpment is estimated as ~230 m; its ~60 m estimated width thus indicates a dip of ~75°, a reasonable value for a low-displacement normal fault (cf. Walsh and Watterson, 1988).

Comparison with the Horse Hill 1 well log (Table 1) suggests that the footwall cutoff of the Newdigate Fault is at a depth of ~2160 m, placing the hanging-wall cutoff at ~2390 m. The position of the Newdigate Fault where it offsets the base of the Jurassic succession, thus interpreted, is in roughly the same place as that estimated by Butler and Pullan (1990), although these authors estimated only a small displacement (Fig. 6). It is also in roughly the same place as where Pullan and Butler (2018) reported a ~300 m north-south increase in the depth of the base Jurassic, from ~7000 ft (~2130 m) to ~8000 ft (~2440 m), although these authors depicted this as occurring over a distance of ~2 km, rather than as a fault offset. The depth-conversion used by Hicks et al. (2019) (illustrated in Fig. 2) places these interpreted footwall and hanging-wall cutoffs at depths of ~1800 and ~2000 m, rather shallower than the depths deduced from the present analysis. It is thus evident that Hicks et al. (2019) used the velocity model in Table 2 for depth conversion of their seismic section, and this procedure has made the structure too shallow relative to what would be obtained for the velocity model in Table 1.

Earthquake locations

Hicks et al. (2019) reported epicentral positions using geographical co-ordinates; in Table 3 these have been converted to BNG references. In their original version of Fig. 2, Hicks et al. (2019) plotted hypocentral co-ordinates as BNG northings, not as latitudes. Again using the online co-ordinate converter, it has been confirmed for a representative subset of these events that their hypocentres were correctly positioned as BNG northings relative to the seismic section, as geo-located by Hicks et al. (2019), in Fig. 2.

The vertical mislocation of the earthquake 'cloud' in Fig. 2 is now considered. The base Jurassic (Lias Group / Penarth Group) unconformity beneath a representative point (at TQ 21983 41750) is at 1.322 s TWT; depth conversion relative to the footwall cutoff of the Newdigate Fault (assuming that the additional TWT is in Lower Lias rocks; cf. Table 1) places this point 2.28 km below O.D. (Fig. 2(b)). Interpolating the Hicks et al. (2019) depth conversion from Fig. 2(b)) for the same point gives a depth of ~1.85 km, ~400 m less. At greater depths, the Hicks et al. (2019) velocity model (Table 2) incorporates P-wave velocities of 4.7, 5.0 and 5.5 km s^{-1} that are reasonable for the rocks encountered, such as the Penarth Group and Carboniferous Limestone, so no significant additional systematic error in depth conversion will result. In the absence of repeating the location process for all the Newdigate earthquakes, using a more accurate velocity model, the present best estimate is to apply a uniform adjustment, throughout the earthquake 'cloud', by ~400 m. The focal depths of the majority of the earthquakes listed in Table 3 thus adjust from ~1.9-2.2 km to ~2.3-2.6 km. An equivalent adjustment should be made to the vertical scale of the seismic section in Fig.2 which, as already noted, was depth-converted by Hicks et al. (2019) using their velocity model for earthquake location that now appears too slow. As a result, if the seismic section is depth-converted using the faster set of velocities in Table 1, and the set of hypocentral depths are amended as noted above, then their relative vertical positions remain unchanged. Nonetheless, as a result of this depth adjustment, the earthquake 'cloud' can be reliably placed beneath the Jurassic succession, not within this succession as Hicks et al. (2019) thought.

A further issue is that the Hicks et al. (2019) velocity model does not take into account the evident fault offsets and tilts of layer boundaries, which will affect the paths of seismic waves between the earthquake sources and the seismograph stations. Each of these factors was shown to be significant for obtaining reliable locations for the induced earthquakes at Preese Hall in 2011 (Westaway, 2016, 2017). Extensive numerical tests have been carried out on this aspect, from which it has been concluded that the low-angle dips (~1-2°) of the beds in the present study area and the ~200 m throw on the Newdigate Fault (Fig. 2) affect hypocentral co-ordinates by no more than ~100 m. In this particular case, these aspects are therefore of lesser importance than the adjustment to correct for the incorrect velocity model for earthquake location, so will not be considered further.

3. State of stress

Kingdon et al. (2016) and Fellgett et al. (2017) provided syntheses of data pertaining to the stress field across much of Britain. However, these authors wrote little about the Weald Basin; Fellgett et al. (2017) noted that many hydrocarbon wells in this area have yielded stress data but it had not yet been analysed by BGS, other than to note that the vertical stress gradient in the top 1.4 km is ~22-25 kPa m^{-1} (i.e., lithostatic). The World Stress Map (Heidbach et al., 2016) provides no data from the Weald Basin but interpolates a stress field for it using data from surrounding regions. The submission regarding the stress field to the OGA (2018) workshop (https://www.ogauthority.co.uk/media/5152/2-bgs-andy-chadwick-uk_stress.pdf) noted the input from Fellgett et al. (2017) and emphasized the significant uncertainty regarding the magnitude and orientation of the stress field in the Weald Basin.

The view is well established that, to first order, the stress field in Britain is dominated by effects of adjoining plate boundaries, 'ridge push' from the Mid-Atlantic Ridge and the effect of the convergent plate boundary in the Mediterranean region, and this results in a roughly NW-SE maximum principal stress, σ_H (e.g., Klein and Barr, 1986; Gölke and Coblentz, 1996). The minimum principal stress σ_h is thus roughly NE-SW, the intermediate principal stress being vertical, σ_V. However, it is also well understood that local effects cause significant variations in the stress field; the predicted orientation determined by plate tectonics cannot be assumed for the purposes of site-specific geomechanical calculations (e.g., Pine and Batchelor, 1984). The analyses by Kingdon et al. (2016) and Fellgett et al. (2017) indeed indicate significant local variations in the stress field. These are to be expected from the growing knowledge of active crustal deformation of Britain, which includes lateral variations in uplift rates and strong evidence of Quaternary slip on faults, such as the Portsdown Fault to the south and southwest of the Weald Basin (e.g., Westaway et al., 2006; Harding et al., 2012). Such effects will cause complex local changes to the state of stress, making it significantly 'rougher' rather than the smooth variations expected from simple considerations of plate tectonics (Westaway, 2006). As was discussed by Westaway (2016, 2017), an important realization to have emerged relatively recently in Britain is that the differential stress in the crust is high, consistent with the observed seismicity and crustal deformation, which makes it possible for small changes in the local state of stress to bring 'critically stressed' faults to the condition for slip and to thus cause earthquakes. The Westaway (2017) analysis of the induced seismicity at Preese Hall in 2011 developed a model stress field for this locality; this consisted of σ_H oriented at azimuth N7°E-S7°W and σ_h oriented at S83°E-N83°W, the model principal stresses at 2400 m depth being σ_h=39.2 MPa, σ_V=54.3 MPa, and σ_H=63.3 MPa. This north-south maximum principal stress in the Blackpool area of northwest England, derived initially at the Preese Hall well, was confirmed by Cuadrilla (2019) using data from the Preston New Road 1 well.

Table S1: Stress field data for the Weald Basin

Name	BGS ID	BNG reference	Code	σ_H	G	Surf. (m O.D.)	Depth (TVD SS) (m) KC	CC	OC	ULC	MLC
Palmer's Wood 1	TQ35SE94	TQ 36450 52620	PAL1	NE-SW	V	140	517	789	860	1073	1180
Godley Bridge 1	SU93NE21	SU 95232 36640	GB1	N65°E-S65°W	V	71	1028	1527	1578	2017	2149
Iden Green 1	TQ83SW1	TQ 81325 31568	IDE	N40°W-S40°E	D	48	328	563	634	828	884
Wallcrouch 1	TQ62NE3	TQ 66050 29800	WLC	NW-SE	V	116	310	713	783	1079	1164
Stanmer 1	TQ31SW13	TQ 32631 11423	STA	N30°W-S30°E	V	198	488	695	748	989	998

Data listed are for the five wells in the Weald Basin (in the 110 km × 60 km rectangle with corners at SU 900 000 and TR 000 600) that have yielded caliper data indicating the orientation of the maximum horizontal stress, σ_H, according to Chadwick et al., 1996). Orientations of σ_H have been measured from Fig. 5.3 of Chadwick et al. (1996). The wells have been identified by matching their locations to Fig. 11 of Andrews (2014) to obtain the abbreviations of their names listed in the Code column, then using the table in Appendix E of Andrews (2014) to get the well names and depth information, then finally using the online BGS borehole viewer (http://mapapps.bgs.ac.uk/geologyofbritain/home.html) to obtain the BGS IDs and BNG references of the wells. Column G, for 'geometry', indicates whether each well is vertical or deviated. Surface levels (Surf.) and depths of stratigraphic boundaries are converted into metres, from Appendix E of Andrews (2014). The boundaries listed are: KC, top Kimmeridge Clay; CC, top Corallian Clay; OC, top Oxford Clay; ULC, top Upper Lias Clay; and MLC, top Mid Lias Clay.

At the OGA (2018) workshop a map was presented (https://www.ogauthority.co.uk/media/5152/2-bgs-andy-chadwick-uk_stress.pdf) to indicate the orientation of the stress field in the Weald Basin, with no source given. This map is from Evans and Brereton (1990); despite its age it continues to provide the most recent published information available. To facilitate the present analysis, this dataset has been curated (Table S1), identifying the boreholes that yielded the σ_H orientations, also providing summary stratigraphic details at these sites. As can be seen, three of the five measurements show the roughly NW-SE orientation that is expected, the other two show a roughly perpendicular orientation. Kingdon et al. (2016) have noted issues with the Evans and Brereton (1990) study, including input data of relatively poor quality by modern standards and an unclear analysis workflow. In their view, instances like this of highly discrepant data in the Evans and Brereton (1990) dataset resulted from the combination of erroneous data and poor analysis. This deduction is supported by the present analysis, implying that the data indicating a roughly NW-SE orientation of σ_H in the Weald Basin are valid.

4. The *Davis and Frohlich* criteria for anthropogenic seismicity

The Davis and Frohlich (1993) criteria will now be applied to the Newdigate earthquake sequence.

The first criterion is '*Are these events the first known earthquakes of this character in the region?*' The Newdigate earthquakes occurred in what is usually one of the most aseismic parts of Britain (e.g., Hicks et al., 2019), and are unprecedented for their epicentral area, inviting the answer '*yes*' to this question. However, Baptie and Luckett (2018) noted the preceding Billingshurst earthquake swarm (Baptie, 2006; Table S2) as a potential basis for concluding that the Newdigate earthquake swarm was not in fact unprecedented. Nonetheless, other wells were producing in the Weald Basin in 2005, notably those at Storrington (TQ 068 149), which were drilled from the 1980s onwards and continue to produce from the Middle Jurassic Oolitic Limestone (e.g., McLimans and Videtich, 1989). The closest of the earthquake epicentres listed in Table S2 is >10 km from the Storrington well pad, more than the 5 km separation recognized by Davis and Frohlich (1993) as significant for identification of induced seismicity (see below). However, the sparseness of the BGS seismograph network in 2005 makes mislocation of these earthquakes by many kilometres a strong possibility.

Table S2: The 2005 Billingshurst earthquake swarm

Date	Time	Latitude (°N)	Longitude (°W)	BNG reference	Depth (km)	M_L
18 June 2005	07:50:55.7	51.069	0.511	TQ 04425 31017	5.0	1.4
19 June 2005	11:49:34.3	51.064	0.512	TQ 04366 30460	5.0	1.6
16 July 2005	18:29:09.2	51.008	0.392	TQ 12910 24410	5.0	2.2

Data from the International Seismological Centre online catalogue (http://www.isc.ac.uk/iscbulletin/search/catalogue/), with BNG co-ordinates calculated as part of the present study. Focal depth was held fixed at 5 km during the location process for all these events.

The second Davis and Frohlich (1993) criterion is '*Is there a dear correlation between injection and seismicity*'. In the present context, this should be reworded as '*Is there a dear correlation between injection or production and seismicity*'. As already noted, Fig. 4(c) indicates a compelling correlation between production from the Portland reservoir and the Newdigate seismicity, so the answer to this question is clearly '*yes*'.

The third criterion is '*Are epicenters near wells (within 5 km)?*'. As Fig. 01 shows, the Newdigate earthquake epicentres cluster ~4 km from the Horse Hill-1 well, so this question can be likewise answered 'yes'. However, it should be clear that this 5 km threshold should be seen as a general indication rather than a hard-and-fast rule, earthquakes that are accepted as anthropogenic having occurred much farther from any causative well (up to ~40 km according to Goebel et al., 2017, based on the Hornbach et al., 2016, case study). The centre of the Newdigate earthquake epicentre cluster is ~8 km from the Brockham site; the 5 km distance threshold proposed by Davis and Frohlich (1993) is moot.

The fourth criterion is '*Do some earthquakes occur at or near injection depths? If not, are there known geologic structures that may channel flow to sites of earthquakes?*' In the present context, the first of these questions should be reworded as '*Do some earthquakes occur at or near depths of injection or production?*' As already noted, the earthquakes cluster around 2400 m depth whereas the production is from a reservoir at ~600 m. The earthquakes are thus much deeper than the reservoir. However, the conceptual model (Fig. 5) and supporting explanatory text indicate structures that might well direct flow between the seismogenic fault and the well bottom. This question can be therefore answered 'yes'. Like the previous question, this question is made moot by the conceptual model.

The fifth criterion is '*Are changes in fluid pressure at well bottoms sufficient to encourage seismicity? Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?*' The absence in the public domain of quantitative data on pressure changes in the Portland reservoir means that the first of these questions cannot be answered at this stage. The expectation, from the conceptual model, is that a small reduction in groundwater pressure within the strands of the Newdigate fault zone (smaller than a plausible estimate for the reduction in reservoir pressure) will cause significant changes to the state of stress that will bring the fault to the Coulomb condition for slip. However, no proof is possible as this would require detailed data on the size and shape of asperities on this fault and accurate data on the local state of stress, both of which are currently unavailable. Nonetheless, the conceptual model predicts changes to the state of stress that facilitate slip (Fig. 8).

The conclusion drawn from this summary is that the conceptual model in Fig. 5 provides a plausible explanation for the Newdigate earthquake swarm. Nonetheless, uncertainty remains, but much of it could be eliminated by release of appropriate data. As noted above, the principal data required to validate or refute this hypothesis are site engineering logs including pressure logs.

5. Regulatory issues

Following the Preese Hall seismicity in 2011, the UK Government imposed extremely tight regulation on seismicity caused by fracking, requiring any developer to suspend operations following the any earthquake of magnitude $M_L \geq 0.5$. This form of regulation has been criticised by many people, notably by Westaway and Younger (2014), for two main reasons. First, earthquakes of magnitude 0.5 at depths of, say, 2-3 km are too small to be felt. Moreover, given the sparseness of the network of permanent seismograph stations in Britain, which does not guarantee event detection below magnitude ~2 (e.g., Baptie and Luckett, 2008), such small events are unlikely to even be detected but for the regulatory requirement for the operator to install a temporary local seismograph network. Second, it does not make sense to regulate anthropogenic seismicity by magnitude but, instead, by felt effects, expressed either as seismic intensity (as already noted) or as peak ground velocity (PGV). As Westaway and Younger (2014) indeed noted, other forms of industrial nuisance vibration, such as quarry blasting, have been uncontroversially regulated in the UK for many years on the basis of PGV, the specification being to keep PGV measured at any residential property below 6 mm s^{-1} during the working day, with lower thresholds at other times. Wald et al. (1999) and Worden et al. (2012) noted that PGV 6 mm s^{-1} corresponds to seismic intensity 3 on the Modified Mercalli (MM) intensity scale used in the USA, which is defined similarly to the European Macroseismic Scheme (EMS-98; Grünthal, 1998) used in Europe. However, the UK regulation (effective between 2012 and 2019) governing seismicity caused by fracking did not apply to earthquakes caused by other activities such as geothermal energy projects or 'conventional' extraction of hydrocarbons.

According to BGS (https://earthquakes.bgs.ac.uk/research/SurreyEarthquakes.html), seven of the Newdigate earthquakes in 2018 and four in 2019 have been strong enough to be felt. For the largest, on 27 February 2019, >1600 people reported felt effects to BGS; these were interpreted as indicating a peak EMS intensity of 5. The resulting distribution of seismic intensity from this event (illustrated by https://earthquakes.bgs.ac.uk/research/SurreyEarthquakes.html) is quite unusual, with intensity 5 persisting to distances of ~10 km from the epicentre, but no higher intensity observed nearer the epicentre. The distinction between intensities 5 and 6 is significant; intensity 5 means that an earthquake is strongly felt and buildings shake, but there is no damage so the earthquake represents a nuisance. On the other hand, intensity 6 denotes (slight) damage to buildings, for example, plaster cracking and pieces of it falling off walls, so it indicates a hazard rather than a nuisance. A possible explanation for the observed distribution in seismic intensity, after Westaway and Younger (2014), recognizes that the vertically upward direction from a strike-slip earthquake source, such as those beneath Newdigate (Fig. 01), is along a node of the radiation pattern for both P- and S-waves, so – but for effects of geological structure, such as scattering of the seismic waves – the amplitude of the ground shaking in this direction would be zero. Stronger seismic radiation occurs obliquely to the vertical, but the greater amplitudes radiated are offset by the greater geometrical spreading and anelastic attenuation caused by the longer ray paths to the Earth's surface. But for this quirk of seismology, the residents of Newdigate might well have experienced damage to their property. The seismicity at Newdigate is thus of significance, far more so than M_L ~0.5 events caused by fracking. Following the granting in September 2019 of permission to develop more oil wells from the Horse Hill well pad, much higher production rates can be expected, which will cause greater pressure reductions in the reservoir. The proposed geomechanical model (Fig. 5) thus raises the possibility of more seismicity in future, although it does not specify whether this will involve more frequent events or larger events, with M_L significantly greater than 3.

To explore this issue further, the dataset for the sequence of earthquakes in the Groningen area of The Netherlands is utilized. These earthquakes have occurred as a result of reduction in the pressure in a gas reservoir in Triassic sandstone at a depth of ~3 km (e.g., Spetzler and Dost, 2017; Willacy et al., 2019). Much work has gone into the prediction of PGV from these earthquakes as a function of magnitude and epicentral distance to determine potential impacts (e.g., Bommer et al., 2017a,b,c; Pruiksma and Rózsás, 2017). The largest event, the Huizinge earthquake (M_L 3.6) of 16 August 2012, produced the largest single-component record of PGV, 34.6 mm s^{-1}, at a seismograph station at an epicentral distance of 2 km (Bommer et al., 2017c). Many records of earthquakes with M_L ~3 indicate PGV ~10 mm s^{-1} near the epicentre (Pruiksma and Rózsás, 2017). Bommer et al. (2017c) developed an empirical equation that, at the epicentre, predicts PGV 2-4 mm s^{-1} for M_L 2, 10-17 mm s^{-1} for M_L 3, and 52-82 mm s^{-1} for M_L 4, the range of vales for each magnitude depending on definition of PGV (e.g., single-component or vector sum of all three components). Omitting any correction for several complicating factors, including the different geological structure at Groningen and its effect on attenuation of seismic waves, the different focal mechanisms of the Groningen earthquakes, and the different definition of M_L in the Netherlands, one may use the ratio of focal depths (~2.4 km for Newdigate and ~3.0 km for Groningen) to crudely estimate PGV for the Newdigate earthquakes. The Bommer et al. (2017c) predictions for M_L 3 can be adjusted by a ratio of 3.0/2.4 or 5/4 and indicate epicentral PGV in the range 13-21 mm s^{-1} at Newdigate. Values in this range greatly exceed the UK regulatory limit for non-earthquake-related ground vibrations of 6 mm a^{-1}. By similar calculation, the predicted values for M_L 4 will adjust to 65-103 mm s^{-1} for Newdigate, exceeding the Wald et al. (1999) threshold of 81 mm s^{-1} for intensity 6 (and the revised 67 mm s^{-1} threshold, from Worden et al., 2012), for which minor damage might be expected. These considerations might help to inform debate about the potential environmental impact of activities at the Horse Hill site.