Were the Newdigate Earthquakes, Southern England, of 2018-2019 triggered by oil extraction?

Matthew Fox[1*] and Phil Meredith[1]

[1]Department of Earth Sciences, University College London, Gower St., London, WC1E 6BT, UK

**Corresponding Author: m.fox@ucl.ac.uk*

Non-peer reviewed preprint submitted to EarthArXiv

Submitted to Geological Magazine

Abstract

The ability to attribute earthquakes to specific causes is challenging. The 2018-2019 earthquake swarm in Newdigate, Surrey, Southern England, coincides with local oil extraction at Horse Hill. Nevertheless, it remains debated whether these earthquakes were triggered by oil extraction or whether they were coincidental. Due to the onset of seismic activity before major oil extraction and the lack of a clear correlation between seismic activity and extraction volume, it has been suggested that the earthquakes may be coincidental. However, we show that time delays between fluid pressure changes and concomitant seismic activity are common in nature. Further, we develop a simple time series model to test whether different units respond differently to oil extraction. We find that extraction from the Portland sandstones at Horse Hill produces earthquakes with a delay of a few days. In contrast, extraction from the Kimmeridge shales produces fewer earthquakes, but with a delay of tens of days. We also show that the occurrence of earthquakes before extraction might be related to surface works. This simple model reproduces the overall trend in seismicity. We are unable to rule out coincidental seismic activity, but our analysis suggests that these earthquakes are triggered by Horse Hill activity.

Keywords: earthquake triggering; Newdigate earthquakes; Horse Hill; induced seismicity.

Were the Newdigate Earthquakes, Southern England, of 2018-2019 triggered by oil extraction?

Matthew Fox[1*] and Phil Meredith[1]

[1]*Department of Earth Sciences, University College London, Gower St., London, WC1E 6BT, UK*

**Corresponding Author: m.fox@ucl.ac.uk*

Non-peer reviewed preprint submitted to EarthArXiv

Submitted to Geological Magazine

Abstract

The ability to attribute earthquakes to specific causes is challenging. The 2018-2019 earthquake swarm in Newdigate, Surrey, Southern England, coincides with local oil extraction at Horse Hill. Nevertheless, it remains debated whether these earthquakes were triggered by oil extraction or whether they were coincidental. Due to the onset of seismic activity before major oil extraction and the lack of a clear correlation between seismic activity and extraction volume, it has been suggested that the earthquakes may be coincidental. However, we show that time delays between fluid pressure changes and concomitant seismic activity are common in nature. Further, we develop a simple time series model to test whether different units respond differently to oil extraction. We find that extraction from the Portland sandstones at Horse Hill produces earthquakes with a delay of a few days. In contrast, extraction from the Kimmeridge shales produces fewer earthquakes, but with a delay of tens of days. We also show that the occurrence of earthquakes before extraction might be related to surface works. This simple model reproduces the overall trend in seismicity. We are unable to rule out coincidental seismic activity, but our analysis suggests that these earthquakes are triggered by Horse Hill activity.

Keywords: earthquake triggering; Newdigate earthquakes; Horse Hill; induced seismicity.

1. Introduction

It is clear that fluid extraction from or injection into Earth's crust (including oil exploration and production) can trigger earthquakes (Segall, 1989; Davies et al., 2013; Goebel and Brodsky, 2018; González et al., 2012; Karamzadeh et al., 2021; Lei et al., 2017). However, discriminating between earthquakes that occur naturally and those that are triggered by anthropogenic activity is challenging (Ellsworth, 2013; Grasso and Wittlinger, 1990). A key issue is that earthquakes can occur in apparently aseismic regions, without an obvious trigger, and this means that the temporal relationship between earthquake occurrence and anthropogenic activity can always be argued as coincidental. Indeed, the occurrence of unlikely seismic events is expected to occur at a specific frequency. The occurrence of *extremely* unlikely events is expected to occur at a far reduced frequency, but is expected to occur nevertheless. For this reason, it is essential to carefully evaluate all possibilities before attributing the occurrence of seismic swarms to any specific trigger (Grigoli et al., 2017).

The Newdigate, Surrey, seismic swarm is characterized by a series of low to moderate magnitude earthquakes, that began in April 2018 and persisted into early 2019. Residents of Newdigate reported cracks appearing in the walls, ceilings, and foundations of their homes, damage to chimneys, misaligned windows and doors, and broken pictures and ornaments that fell due to shaking. There are also reports of a small landslide in the vicinity of Newdigate, likely triggered by seismic activity (BGS, 2019). The swarm's occurrence in a region with historically low seismicity levels has led to various hypotheses about its origins, including natural tectonic processes and anthropogenic triggers (OAG, 2018). Notably, this period aligns with significant oil extraction and production activities in the nearby Horse Hill and Brockham oil fields, prompting investigations into whether these operations may have influenced the seismic activity (Hicks et al., 2019; Verdon, 2019; Cavanagh et al., 2019; Westaway 2022).

Hicks et al., (2019) provided a detailed analysis of the swarm of earthquakes close to the Horse Hill site. Over 168 earthquakes were located between April 2018 and June 2019 ranging in magnitude between -1.34 and 3.18. For reference, between 1995 and April 2018, there had been three earthquakes in Billingshurst in May 2005 and there have been 28 between June 2019 to July 2024 (Supplementary Material). During the swarm, there was no gradual migration of the focus of the earthquakes as might be expected if they were produced by fluids fracturing and infiltrating into rocks (Keranen et al., 2014). Instead, earthquakes clustered around a previously mapped fault, and focal mechanisms indicate strike slip motion on this fault. The association of the earthquakes with the fault, the lack of the migration in seismicity and the apparent weak correlation between the earthquake frequency and oil extraction led Hicks et al. (2019) to argue that these events were probably not induced by anthropogenic activity. This supported the earlier analysis carried out by Verdon et al. (2019).

By contrast, Westaway (2022) presented a geomechanical model highlighting how oil extraction can lead to changes in the local stress field, which can trigger slip on the identified strike slip fault. In this model, pressure changes caused by oil extraction can be transmitted through permeable units, and across permeable faults and through ‘calcite beef’ (Howitt, 1964; Hesselbo and Jenkyns, 1995). He also highlighted several complexities associated with previous analyses of the data and local geology. The key complexity for our current analysis, however, is related to extraction of oil from different geological units.

2. Problems with simple correlations between oil extraction and seismicity

There is no clear relationship between the frequency of earthquakes and the timing of oil extraction from Horse Hill. This led Hicks et al. (2019) to argue that the earthquakes were not induced by oil extraction. Two key factors highlight the lack of an obvious correlation. First, it appears that the seismicity began before the onset of oil extraction at Horse Hill. If this is the case, it means that oil extraction could not have caused the seismicity. Second, the period of maximum oil extraction (October 2018- January 2019) coincides with a period of very low seismic activity (Figure 1). A simple correlation model would require increased seismicity during increased oil extraction. However, we show here that there are also simple explanations for these two apparent anomalies.

2.1 The onset of seismic activity

Prior to the onset of activity at Horse Hill, there was a period of surface works at the same locality. However, these also included sub-surface work such as annular pressure checks on 5th-6th April 2018, and other well activities. The exact details are uncertain and further details can be found in Westaway (2022). Here, we therefore consider it appropriate to accept that earthquakes occurring prior to the onset of oil extraction at Horse Hill could be related either to these prior surface works at Horse Hill or to oil extraction at Brockham which was ongoing at the same time.

2.2 Aseismicity during maximum oil extraction

Oil extraction at Horse Hill was not confined to a single geological unit, but switched between the Portland and Kimmeridge units. These units are remarkably different. Initially, the Portland unit, that is rich in strong, permeable sandstone, was targeted. On 10th September 2018 production switched to the weak, shale rich, impermeable Kimmeridge units. Then on 11th February 2019, production returned to the Portland unit. Details of this analysis can be found in Westaway (2022) and the reports to investors detailing these operations can be found there. The period of reduced seismicity corresponds to the time of oil extraction from the Kimmeridge units (Figure 3). Importantly, this formation-level comparison was not accounted for in Hicks et al. (2019) as the formation-level operation data were not made available by operators either directly, or via the regulator (with a sufficient temporal resolution).

2.3 Additional complexity due to time lags

More generally, time lags between extraction and earthquakes complicate the correlation. Such time lags are not uncommon and have been well documented in the literature. For example, it is now known that even small stress or pressure changes can cause fractures to nucleate and propagate through the mechanism of stress corrosion (Atkinson, 1984; Atkinson & Meredith, 1987). In this instance, rock-fluid chemical reactions allow fractures to grow slowly (at rates that are orders of magnitude below critical velocity) at stresses that are well below the short-term strength of the rock. However, the growth rate of such sub-critical fractures accelerates as they lengthen until becoming critical. This can lead to a natural time delay (lag) in triggering seismic activity (Das & Scholz, 1981). Furthermore, we know that earthquakes can induce changes in fluid pressure that trigger other earthquakes at considerable distances (multiple kilometres) and after significant time delays, and vice versa (e.g., Brodsky et al., 2003; Brodsky & Prejean, 2005; Van der Elst & Brodsky, 2010). The extent of the time lag is generally a function of the distance and the fluid diffusivity of the intervening lithology.

3. A simple model to predict the observed seismicity

The simplest model relates oil extraction to seismicity accounting for variable forcings and variable time lags. This model simplifies the geomechanical model proposed by Westaway (2022) in that the lag is defined in days and the scaling simply relates the volume of oil extracted (barrels) to seismicity. The time lag is a function of bedrock permeability, width of permeable units, fluid migration pathways, pressure variations and distance. Because these parameters are all unknown and trade-off against one another, we prefer this simple implementation. Similarly, the scaling is a function of pressure variations, the state of stress of the fault plane, asperities on the fault plane, earthquake detection limits, and many other factors. Our simple model is therefore suitable to explore the correlations between earthquakes and oil extraction. For example, we might expect more seismicity if oil is extracted from the stronger (more brittle) Portland unit and we might expect this to happen more closely in time after the oil is extracted, due to its higher permeability. In this way, the model prediction of the number of earthquakes in a single day is equal to:

$$E_t = S_P P_{t-l_P} + S_K K_{t-l_k} + S_B B_{t-l_P}$$

where E_t is earthquakes in a given day, S_P is the scaling of extraction from the Portland at Horse Hill and P_{t-l_P} is the number of barrels of oil extracted from the Portland at a time in the past given by t-l_p , where l_p is the lag associated with extraction from the Portland. Similarly, S_P is the scaling of K_{t-l_k} barrels from the Kimmeridge at Horse Hill at a specific time in the past given by the lag. For the Brockham site, we have a unique scaling, but the lag time is given by the Portland lag time. The unknown parameters are the scaling relationships and the lag times.

To infer the unknown parameters and predict the data, we use the Markov Chain Monte Carlo algorithm (Metropolis et al., 1953; Hastings, 1970). We run one million models varying the values of the parameters and storing models that are accepted. This ensemble of accepted models is proportional to the posterior probability of the parameter values. We also solve for the unknown pressure changes associated with surface works before the operational tests. This is modelled as $E_t = S_P X_{t-l_P}$, where X is the unknown number of equivalent barrels, l_p is the lag associated with extraction from the Portland and S_P is the scaling of extraction from the Portland. Importantly, we attempt to explain the cumulative number of earthquakes. We use the cumulative number as this is more robust with respect to earthquake swarms: we will never be able to explain each earthquake on each day, but we can attempt to explain apparent increases or decreases in seismicity. We expect that the magnitude is controlled by far field stresses and the oil extraction simply triggers the faulting. For this reason, we do not expect a simple relationship between earthquake magnitude and oil extraction, as might be expected for induced seismicity (McGarr et al., 2014).

4. Results

The very simple model reproduces the key characteristics of the data set, in that we identify two periods of increased seismicity associated with extraction from the Portland units. Most of our model parameters are well-resolved by the model. We are able to resolve the amount of equivalent extraction during the surface preparation work associated with annulus pressure checks, however, this parameter displays multiple peaks. This suggests that this poorly resolved. Our lag times for extraction from the Portland units are very short and suggest connectivity between the well and the fault plane. These lags times are comparable to those predicted by Westaway (2020). In contrast, the lag time for the Kimmeridge units is much longer, but this parameter is less well resolved and might simply reflect the concept that extraction from the Kimmeridge is not producing earthquakes.

The model fails to explain the sharp increase in cumulative earthquakes at the time production at Horse Hill returned to the Portland unit. This highlights that there is not a simple relationship between pressure changes in the well and earthquake frequency. Of course this is to be expected as pressures are expected to build and release in non-linear and complex ways. We also do not account for the aftershocks, that dissipate strain following a large earthquake. Instead, these aftershocks are assumed to be triggered by the same process of oil extraction. We also do not resolve the flattening-off of the earthquake frequency towards the end of the model. This might be related to our inability to accurately resolve the sharp increase during the return of extraction from the Portland units as increased seismicity in the past might reduce seismicity later on. Future work should account for these complexities.

5. Summary

A simple model that accounts for the differences between the two lithologies encountered at Horse Hill reproduces many of the features of the transient earthquake swarm. It is possible that this could be a coincidence, but the fit of the model to the data supports the conclusion that the Newdigate earthquakes are a direct result of oil extraction at Horse Hill. The key component of the model is the differentiation of the data on extraction into two very different lithologies. It is clear that different lithologies respond differently to variations in fluid pressure and stress due to permeability and rheological variations.

Identifying the source of seismicity remains a major challenge and the Newdigate swarm of earthquakes provides a unique dataset to address this challenge. Crucially, this case study highlights the role seismic monitoring plays in oil exploration.

Acknowledgements

We would like to thank Steve Hicks, Gerald Roberts and Eric Newlands for comments on earlier versions of the manuscript and support through out this research. M. Fox is supported by NERC (NE/X009408/1).

Data Availability

Data used in this analysis are available in Hicks et al., (2019). The dates used to determine extraction from different units can be found here. (https://www.lse.co.uk/rns/ewt-updates-portland-kimmeridge-oil-discovery-x282xeqhbcutm8m.html, https://www.lse.co.uk/rns/UKOG/portland-oil-production-resumes-at-horse-hill-e1jf7s92q1dsoex.html).

References

Atkinson, B.K., 1984. Subcritical crack growth in geological materials. Journal of Geophysical Research: Solid Earth, 89(B6), pp.4077-4114.

Atkinson B.K. & Meredith P.G. (1987) The theory of subcritical crack growth with applications to minerals and rocks, in Fracture Mechanics of Rock, Academic Press, London, pp. 111-166.

BGS. (2019). Earthquakes near Newdigate, Surrey, British Geological Survey: < http://earthquakes.bgs.ac.uk/research/SurreyEarthquakes.html; (accessed June 25, 2019).

Brodsky, E.E., Roeloffs, E., Woodcock, D., Gall, I. and Manga, M., 2003. A mechanism for sustained groundwater pressure changes induced by distant earthquakes. Journal of Geophysical Research: Solid Earth, 108(B8).

Brodsky, E.E. and Prejean, S.G., 2005. New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. Journal of Geophysical Research: Solid Earth, 110(B4).

Cavanagh, A., Gilfillan, S., Haszeldine, S., 2019. Further potential for earthquakes from oil exploration in the Weald. https://www.keithtaylormep.org.uk/sites/default/files/download/2019-02/Newdigate%20Short%20Summary%20Edinburgh%20Uni%20Feb%202019.pdf

Das, S. and Scholz, C.H., 1981. Theory of time-dependent rupture in the Earth. Journal of Geophysical Research: Solid Earth, 86(B7), pp.6039-6051.

Davies, R., Foulger, G., Bindley, A. and Styles, P., 2013. Induced seismicity and hydraulic fracturing for the recovery of hydrocarbons. Marine and petroleum geology, 45, pp.171-185.

Ellsworth, W.L., 2013. Injection-induced earthquakes. Science, 341(6142), p.1225942.

Goebel, T.H. and Brodsky, E.E., 2018. The spatial footprint of injection wells in a global compilation of induced earthquake sequences. Science, 361(6405), pp.899-904.

González, P.J., Tiampo, K.F., Palano, M., Cannavó, F. and Fernández, J., 2012. The 2011 Lorca earthquake slip distribution controlled by groundwater crustal unloading. Nature Geoscience, 5(11), pp.821-825.

Grasso, J.R. and Wittlinger, G., 1990. Ten years of seismic monitoring over a gas field. Bulletin of the Seismological Society of America, 80(2), pp.450-473.

Grigoli, F., Cesca, S., Priolo, E., Rinaldi, A.P., Clinton, J.F., Stabile, T.A., Dost, B., Fernandez, M.G., Wiemer, S. and Dahm, T., 2017. Current challenges in monitoring, discrimination, and management of induced seismicity related to underground industrial activities: A European perspective. Reviews of Geophysics, 55(2), pp.310-340.

Hastings, W.K., 1970. Monte Carlo sampling methods using Markov chains and their applications.

Hesselbo, S.P., Jenkyns, H.C.A., 1995. A comparison of the Hettangian to Bajocian successions of Dorset and Yorkshire. In Taylor, P.D. (Ed.), Field geology of the British Jurassic. Geological Society, London, pp. 105-150.

Hicks, S.P., Verdon, J., Baptie, B., Luckett, R., Mildon, Z.K. and Gernon, T., 2019. A shallow earthquake swarm close to hydrocarbon activities: Discriminating between natural and induced causes for the 2018–2019 Surrey, United Kingdom, earthquake sequence. Seismological Research Letters, 90(6), pp.2095-2110.

Howitt, F., 1964. Stratigraphy and structure of the Purbeck inliers of Sussex (England). Quarterly Journal of the Geological Society, 120(1-4), pp.77-113.

Karamzadeh, N., Lindner, M., Edwards, B., Gaucher, E. and Rietbrock, A., 2021. Induced seismicity due to hydraulic fracturing near Blackpool, UK: source modeling and event detection. Journal of Seismology, 25, pp.1385-1406.

Keranen, K.M., Weingarten, M., Abers, G.A., Bekins, B.A. and Ge, S. (2014). Sharp increase in central Oklahoma seismicity since 2008 induced by massive wastewater injection. Science, 345(6195), pp.448-451. doi:10.1126/science.1255802.

Lei, X., Huang, D., Su, J., Jiang, G., Wang, X., Wang, H., Guo, X. and Fu, H., 2017. Fault reactivation and earthquakes with magnitudes of up to Mw4. 7 induced by shale-gas hydraulic fracturing in Sichuan Basin, China. Scientific reports, 7(1), p.7971.

Metropolis, N., Rosenbluth, A.W., Rosenbluth, M.N., Teller, A.H. and Teller, E., 1953. Equation of state calculations by fast computing machines. The journal of chemical physics, 21(6), pp.1087-1092.

McGarr, A., 2014. Maximum magnitude earthquakes induced by fluid injection. Journal of Geophysical Research: solid earth, 119(2), pp.1008-1019.

OGA, 2018. OGA Newdigate Seismicity Workshop –3 October 2018. Summary and conclusion. UK Oil & Gas Authority, Aberdeen. https://www.ogauthority.co.uk/media/5174/2018_11_23-newdigate- workshop-summary-finalv3.pdf

Segall, P., 1989. Earthquakes triggered by fluid extraction. Geology, 17(10), pp.942-946.

Van Der Elst, N.J. and Brodsky, E.E., 2010. Connecting near-field and far-field earthquake triggering to dynamic strain. Journal of Geophysical Research: Solid Earth, 115(B7).

Verdon, J.P., Baptie, B.J. and Bommer, J.J., 2019. An improved framework for discriminating seismicity induced by industrial activities from natural earthquakes. Seismological Research Letters, 90(4), pp.1592-1611.

Westaway, R., 2022. Seismicity at Newdigate, Surrey, during 2018-2019: A candidate mechanism indicating causation by nearby oil production. Authorea Preprints.

Xodus, 2018. 2018 Competent Person's Report to UK Oil & Gas Investments PLC. Xodus Group, London, 112 pp. https://www.ukogplc.com/ul/UKOG%202018%20CPR%20060618.pdf

Figure 1. Map of the area showing the earthquake swarm, located by Hicks et al., (2019) and the seismometer stations used to locate these events. The stations are shown as triangles. The acronyms are not useful here but this is simply to highlight that the coverage is excellent. The grey shaded area is the reservoir area taken from Xodus (2018) and combines the Horse Hill and Collendean Farm Blocks. The black lines are mapped faults from Hicks et al., (2019) and these are mainly normal faults, although focal mechanisms indicate strike-slip faulting during the swarm. The blue lines are rivers that drain into the Mole River and on into the Thames. Between days 200 and ~350 there was no extraction from the Portland Sandstones. Brockham well is a further 10 km NNW of BRDL.

Figure 2. A) Extraction of oil in the vicinity of Newdigate. The red bars show extraction from the well at Brockham. The blue bars show extraction from Horse Hill. Here we do not divide the extraction from Horse Hill into contributions from the Portland and Kimmeridge units. B) Earthquake magnitudes during the earthquake swarm. Four main clusters can be identified: at the start of April or days 40-60; in July close to day 125; close to day 350; then there is another magnitude 2.5 event at day 440.

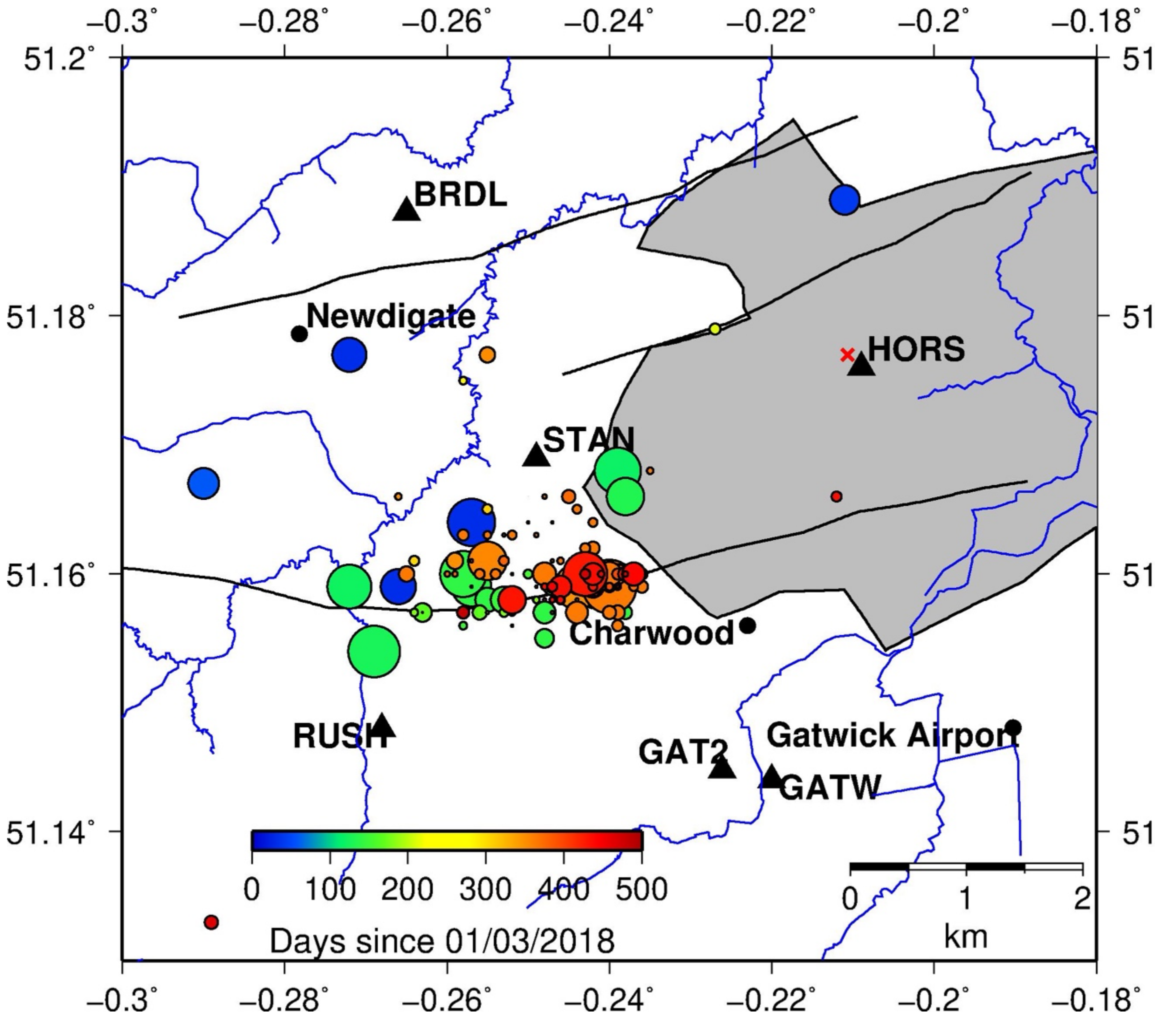
Figure 3. A) Extraction of oil in the vicinity of Newdigate. As in Figure 1, the red bars show extraction from the well at Brockham. The blue bars show extraction from the Portland units at Horse Hill and the green bars show extraction from Kimmeridge units. B) Cumulative earthquake distribution shown in red with model predictions shown in grey. The model predictions are shown for 100,000 models taken every 10 iterations during the sampling process. The opacity shows the relative frequency of model predictions.

Figure 4. A) Time lags for the relationship between oil extraction and earthquake activity. The red histogram shows the relationship for the well at Brockham. The blue histograms shows

values for the Portland units at Horse Hill and the green histogram shows the relationship for extraction from Kimmeridge units. The number of models in the ensemble approximates the posterior probability. B) Scaling between the number of barrels of oil extracted and the number of earthquakes measured. Similar values are predicted for the Portland units for the well at Brockham and Horse Hill. Lower scaling values are predicted for the Kimmeridge units.

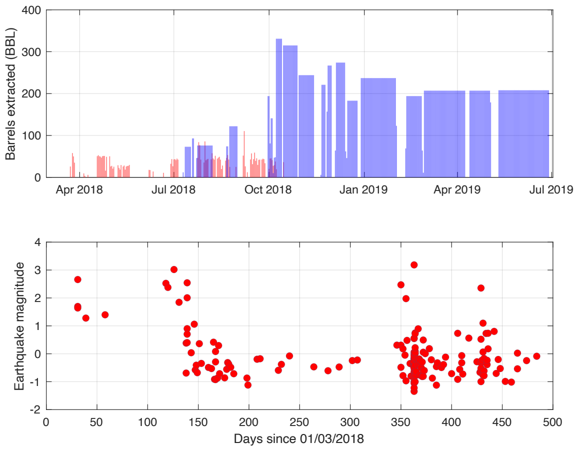
Figure 5. Equivalent number of barrels of oil extracted during the surface works. This is a parameter that is solved for during the inversion. The peak is very unclear and poorly resolved but a small amount of equivalent extraction is inferred. This does not mean that oil was extracted, but it does suggest that some pressure change occurred at the well that might have influenced seismicity.

Figure 1.



−0.3˚
−0.28˚
−0.26˚
−0.24˚
−0.22˚
−0.2˚
−0.18˚
51.2˚
51.18˚
51.16˚
51.14˚
BRDL
Newdigate
HORS
STAN
Charwood
RUSH
GAT2
GATW
Gatwick Airport
0
100
200
300
400
500
Days since 01/03/2018
0
1
2
km

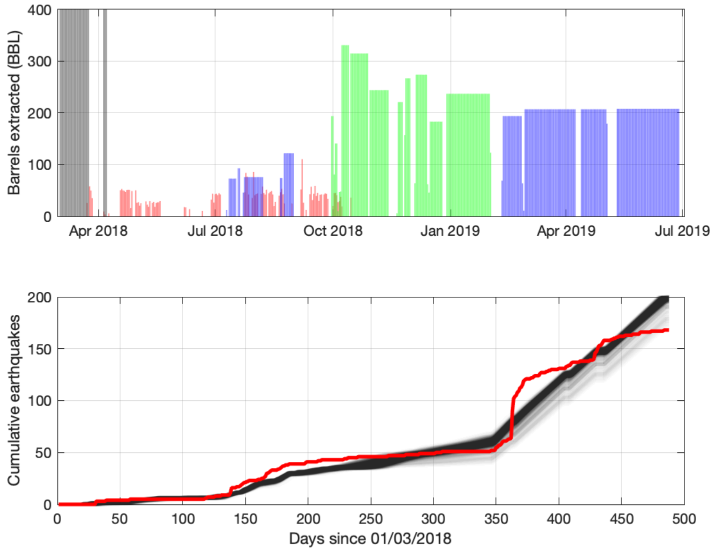
Figure 2



Barrels extracted (BBL)
400
300
200
100
0
Apr 2018
Jul 2018
Oct 2018
Jan 2019
Apr 2019
Jul 2019
Earthquake magnitude
4
3
2
1
0
-1
-2
0
50
100
150
200
250
300
350
400
450
500
Days since 01/03/2018

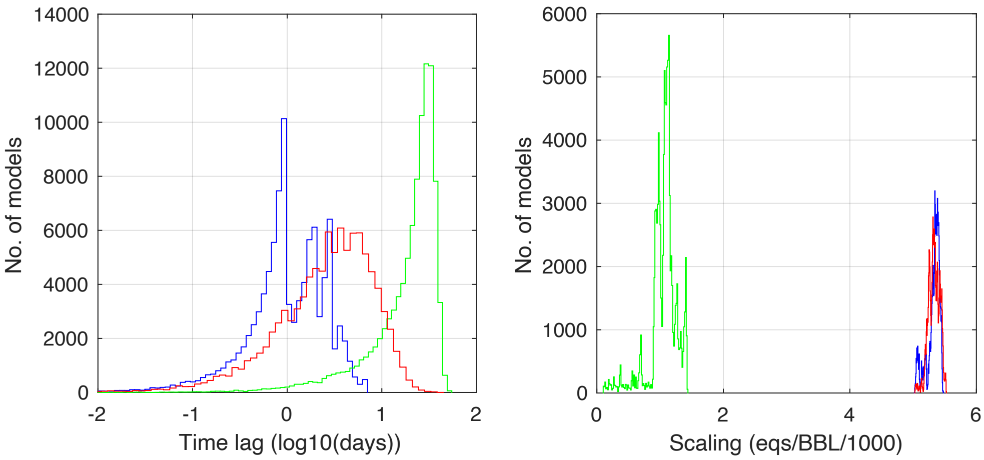
\

Figure 3



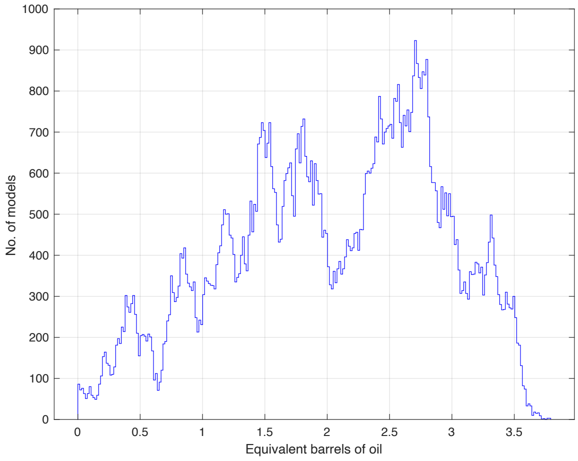
Barrels extracted (BBL)
400
300
200
100
0
Apr 2018
Jul 2018
Oct 2018
Jan 2019
Apr 2019
Jul 2019
Cumulative earthquakes
200
150
100
50
0
0
50
100
150
200
250
300
350
400
450
500
Days since 01/03/2018

Figure 4.



No. of models
Time lag (log10(days))
No. of models
Scaling (eqs/BBL/1000)

Figure 5.


No. of models
Equivalent barrels of oil
0
100
200
300
400
500
600
700
800
900
1000
0
0.5
1
1.5
2
2.5
3
3.5