2018 Newdigate Earthquake Swarm: Induced or Not?

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Are Events Induced: Diagnostic Questions

Temporal Correlation

1. Are these events the first known earthquakes of this character in the region?

2. Is there a clear correlation between injection and seismicity?

Spatial Correlation

3a. Are epicentres near wells (< 5 km)?

3b. Do some earthquakes occur at or near injection depths?

3c. If not, are there known geologic structures that may channel flow to the sites of earthquakes?

Injection Practices

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

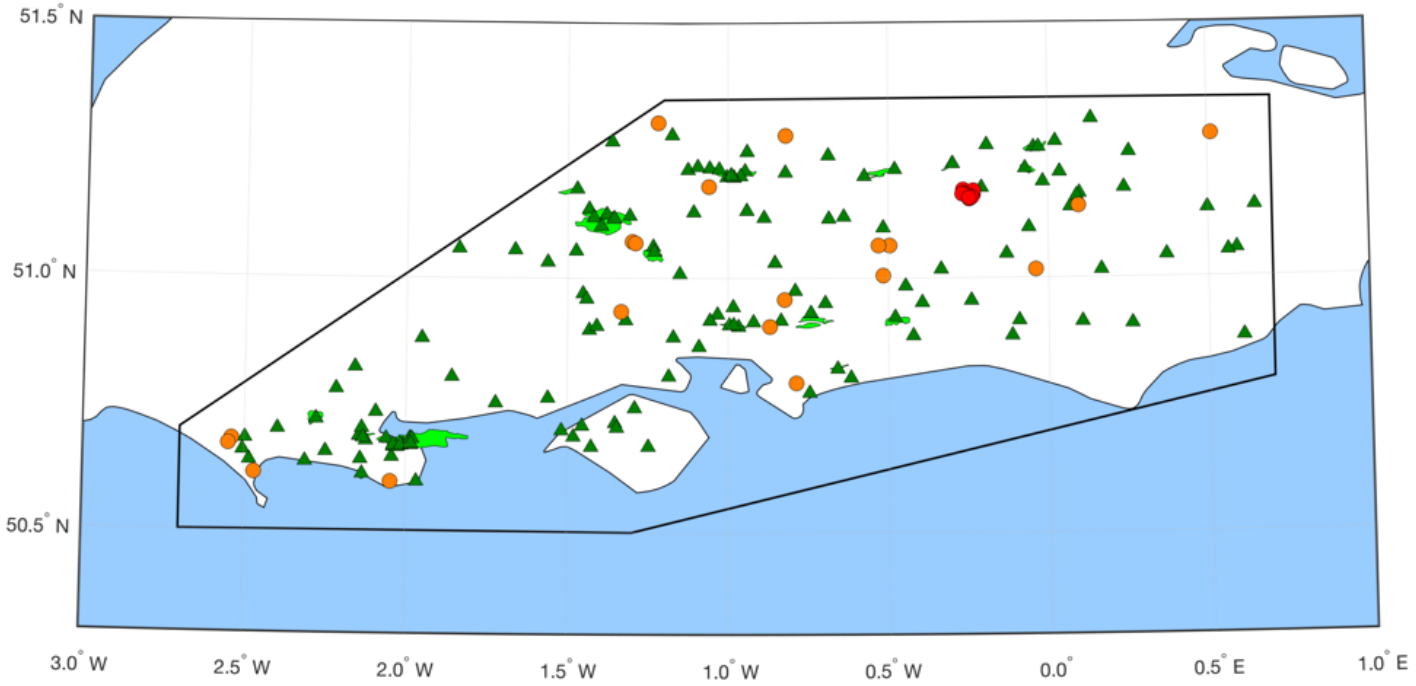
4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

Davis and Frohlich (1993)

Historic Activity in the Weald/Wessex Basins

All earthquakes since 1980, and all oil/gas wells and fields since 1970:

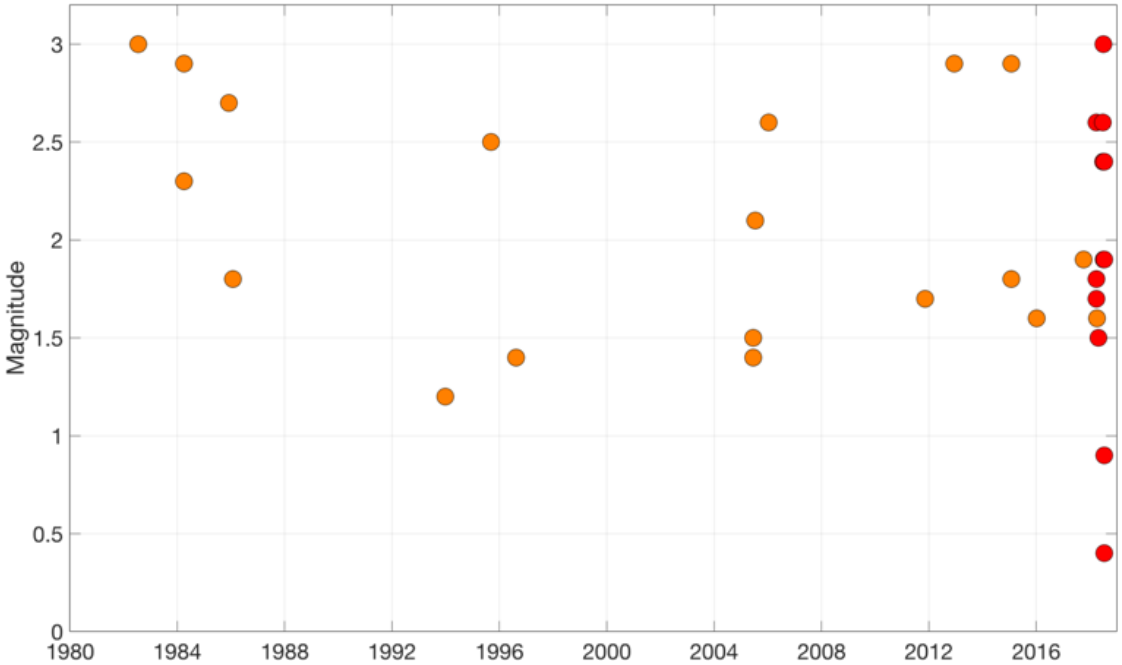
- Fields and wells marked in green
- Earthquakes marked by orange (pre-2018 events) and red (2018 Newdigate swarm events) circles
- Note that earthquake depths are probably not well constrained for most of the pre-2018 events



Seismicity Rate

Seismicity rates and magnitudes through time (from BGS catalogue):

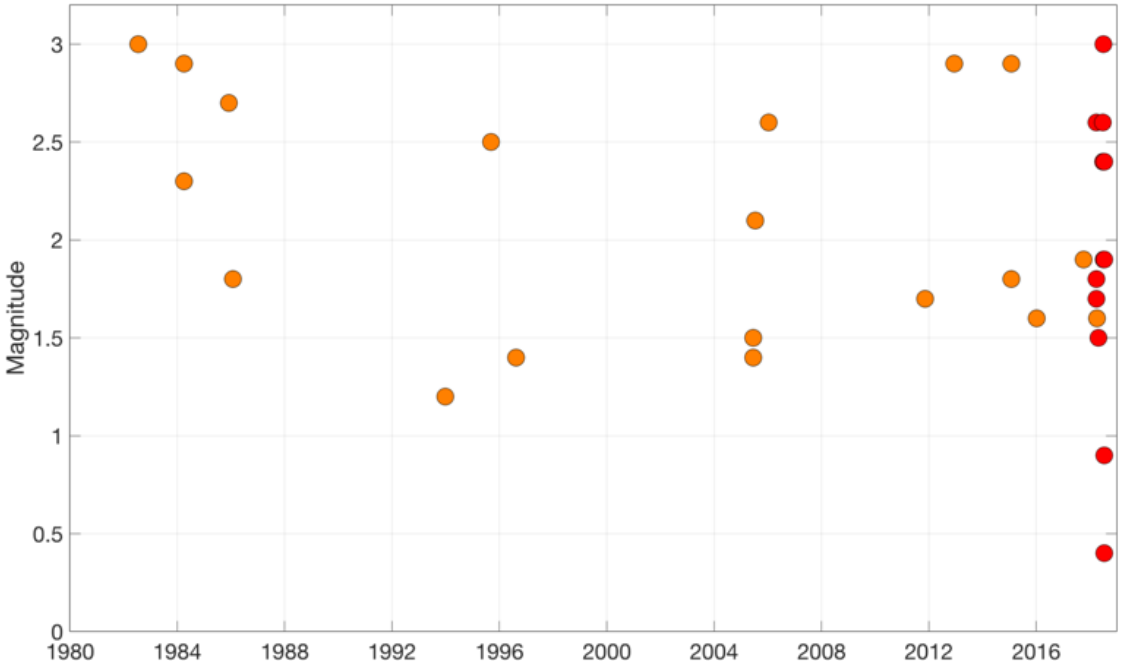
- Magnitudes are < 3. Magnitudes of 2018 events are not different to past events
- Before 2018, c. 20 events recorded in 40 years: average of one event per 2 years, but in fact there is temporal clustering (as usual for earthquakes)
- Estimated magnitude of completeness (above which all events are detected) for the Weald: BGS website suggests somewhere between 2 – 2.5, so caution should be used when making inferences about the numbers of events below this level



Seismicity Rate

Seismicity rates and magnitudes through time (from BGS catalogue):

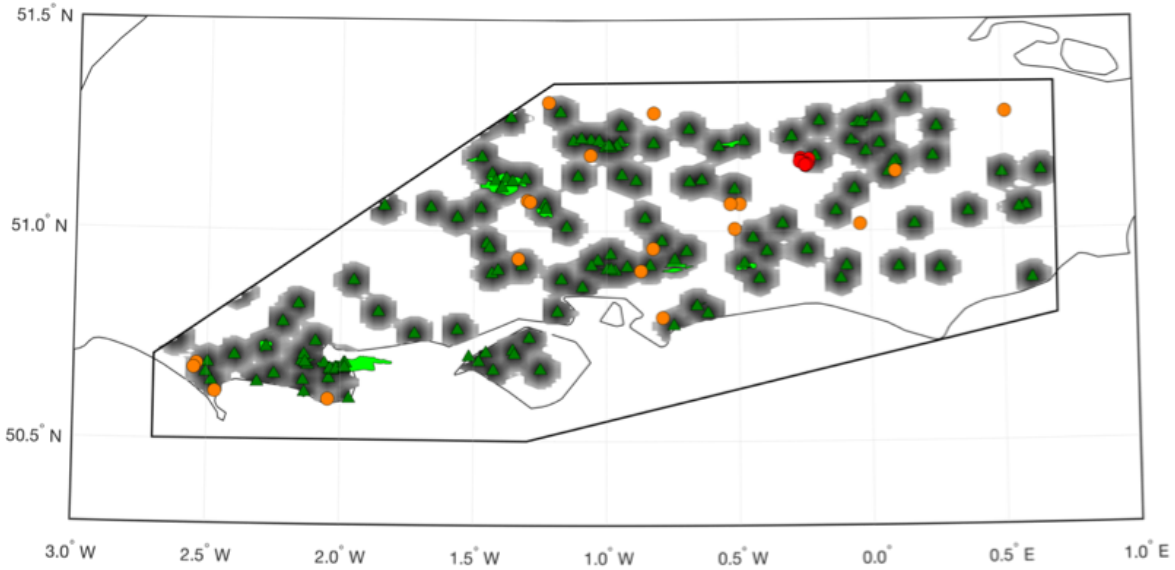
- The Newdigate swarm has more events than previous sequences, such as Weymouth (1984) which had 3 events, Billingshurst (2005) which had 3 events, or Winchester (2015) which had 2 events
- Is this simply a function of detection capability? My gut feeling is “maybe a little bit, but not entirely”. BGS would have a better idea of changing detection thresholds. Either way, with small numbers of events any inference is difficult to prove statistically



How far from an oilfield?

All earthquakes since 1980, and all oil/gas wells and fields since 1970:

- Same map as Slide 3, but shaded areas represent 5 km from a well or an oilfield that has been active since 1970
- Roughly 50% of the land area within the study box is within 5 km of a well or field (this is an area that has seen extensive drilling and oil production activity)!
- Co-location between seismicity and oil wells is inevitable in this region, regardless of whether seismicity is induced or not



1. Are these events the first known earthquakes of this character in the region?

Maybe.

These are the first events at this exact locality. However, the region in general experiences a quake roughly every 2 years. Instrumental records are relatively short (c. 40 yrs), and historical records may not be particularly useful for events of this size ($M < 3$)

The magnitudes of the Newdigate swarm are in line with past seismicity in the region.

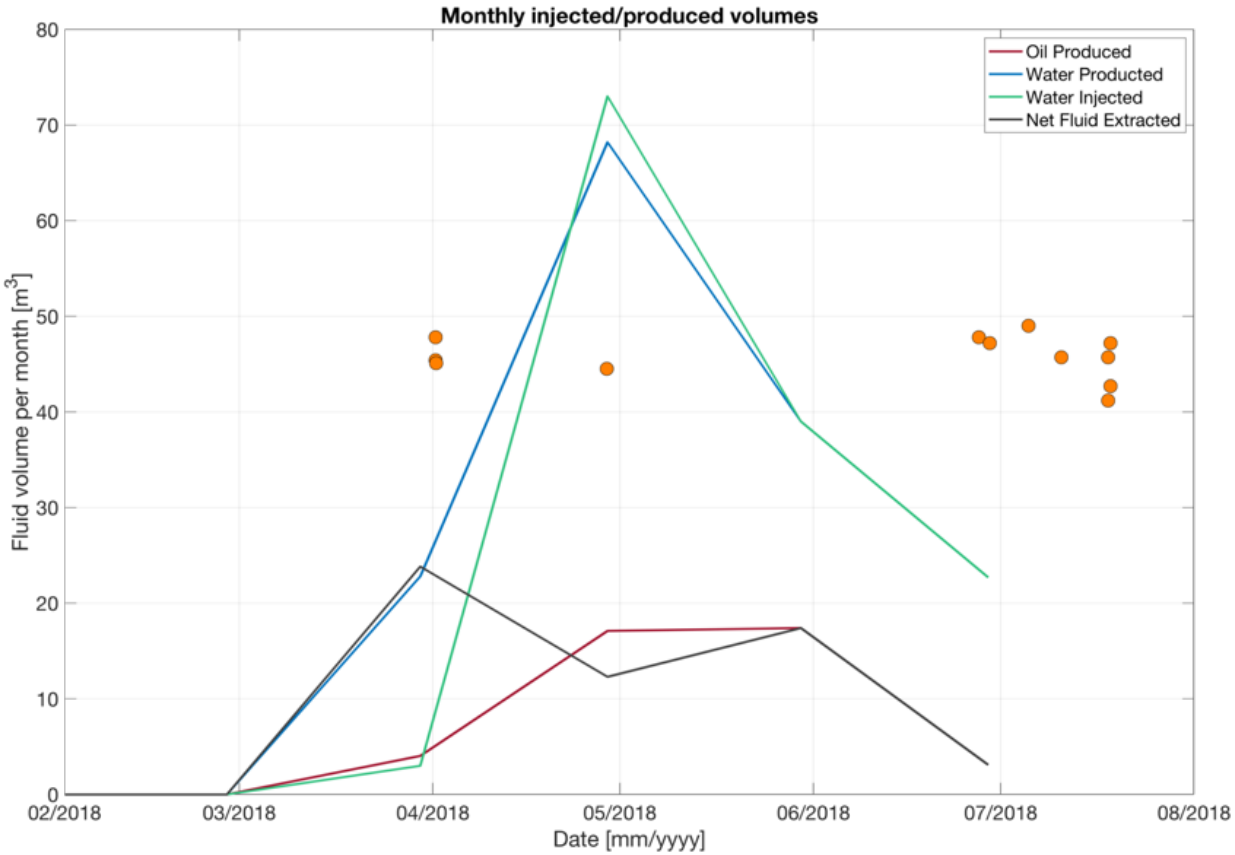
Given that c. 50% of the study area has an oil field or well drilled since 1970 within 5 km, any co-location between events and earthquakes could be coincidental.

The number of events in the Newdigate swarm is larger than past seismic sequences in the region. The extent to which this may be a product of improved monitoring and detection is not clear.

Temporal Correlation (Brockham)

Injection/Production rates at Brockham:

- Data is from OGA website (reported monthly, available up to June 2018)
- Apparent correlation between re-start of activities at Brockham in March 2018 (orange dots show the events)
- Net injection is less than net production



Temporal Correlation (Brockham)

Injection/Production rates at Brockham:

- Viewed over the life of the field, there is no correlation between oilfield activities and seismicity. Both injection and production rates have been far higher in the past, without causing seismicity. Current activities are “a blip” when seen in this context
- Injection rates are less than production rates at almost all times (bar 2 months in 2010). While there may be a local pore pressure increase at the injection well, the net pressure change across the field, which would be felt at a distance of 8 km, will be negative
- Any putative mechanism for fault reactivation must be based on extraction and subsidence triggering, and cannot be based on injection triggering

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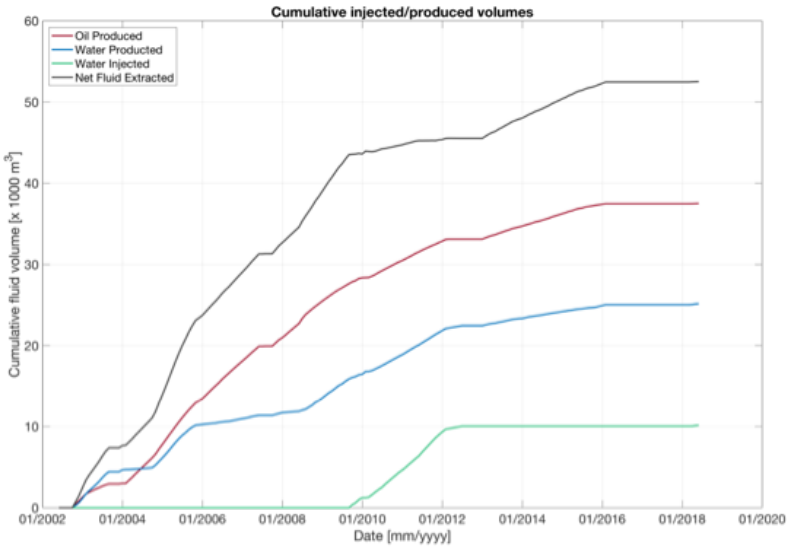
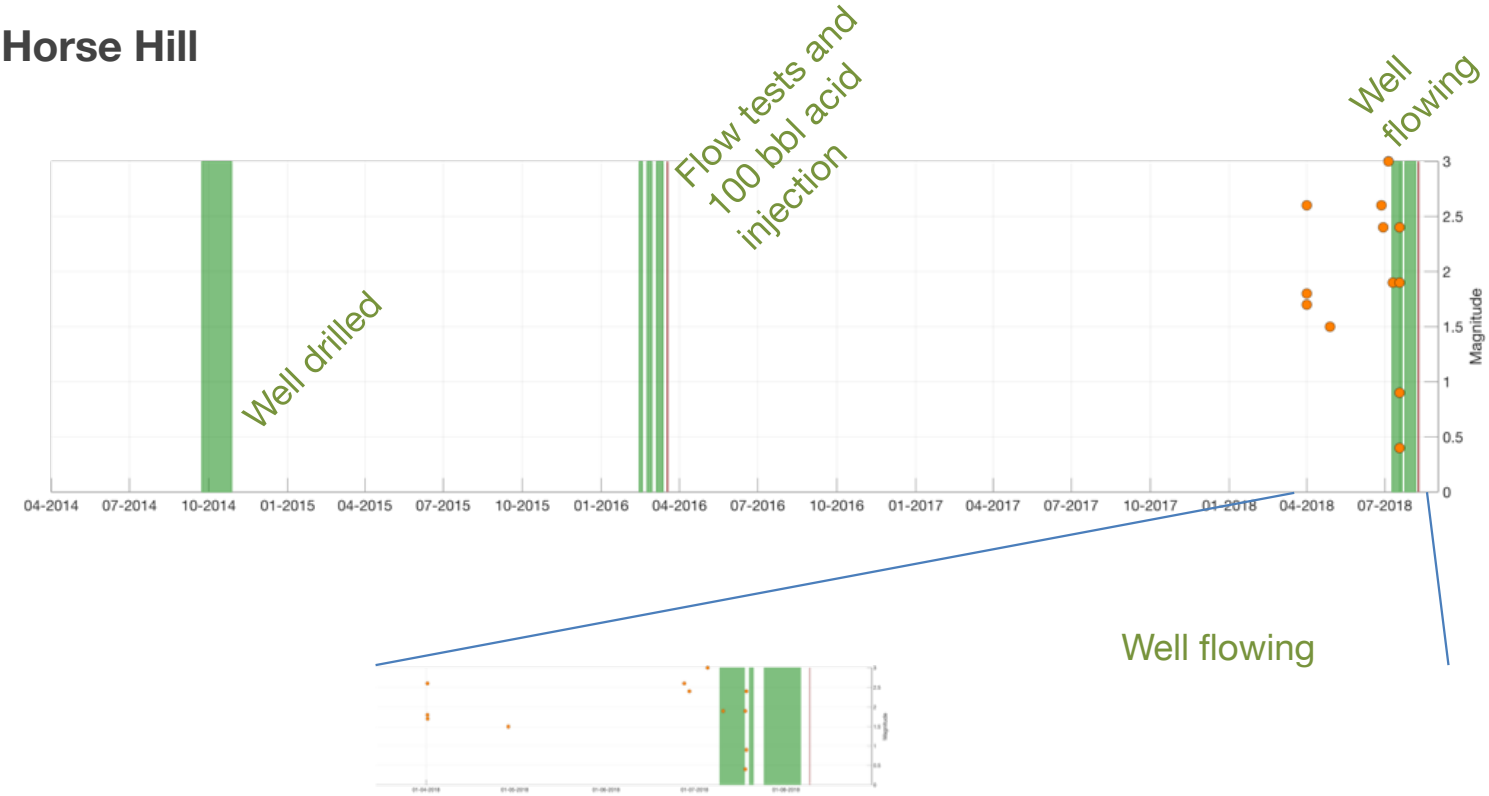


Temporal Correlation (Horse Hill)

Completion and flow testing at Horse Hill

- Well activities as provided by UKOG
- No correlation between seismicity and HH-1 well activities
- Seismicity begins > 2 years after the initial flow tests at HH, and is well underway before the latest activities began on 9th July



2. Is there a clear correlation between injection and seismicity?

Brockham

No.

While there is some apparent correlation with the restart of activities at Brockham, this field has both produced and injected at much higher rates in the past without causing seismicity.

Note also that production volumes have always exceeded injection volumes at Brockham, so any mechanism for seismicity must be based on extraction and subsidence mechanisms.

2. Is there a clear correlation between injection and seismicity?

Horse Hill

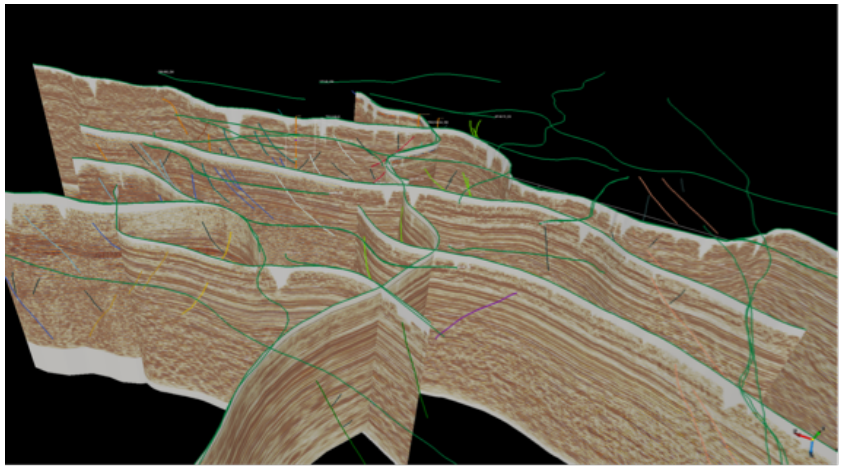
No.

The seismicity began > 2 years after the initial flow testing at Horse Hill, and was well underway before activities restarted in July 2018.

Fault Interpretation

Reflection seismic data has been used to identify faulting in the area of interest

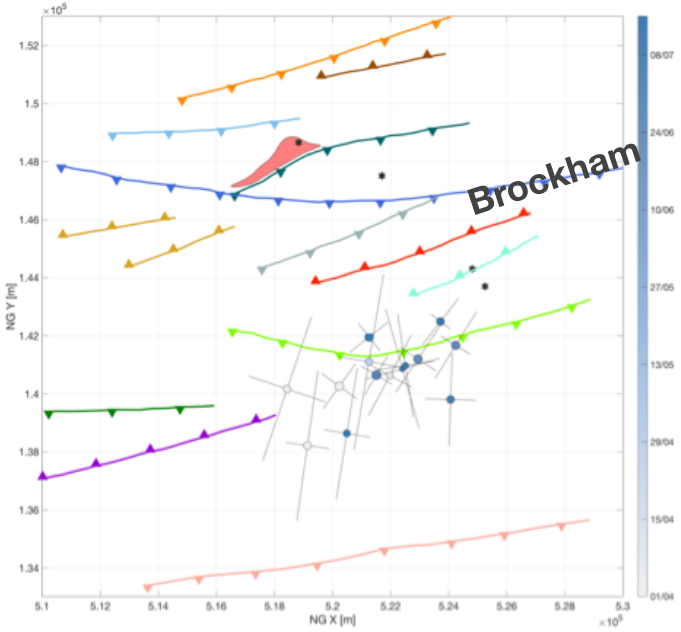
- 2D lines of various vintages (late 1970s – 1990)
- Variable quality, and with 2D data fault interpretations may not be unique



Summary Map

Seismicity in relation to nearby wells and faults

- Event epicentres are marked by coloured dots (with bars showing location uncertainties)
- Coloured lines show fault positions as interpreted from 2D seismic data – these are all dipping faults with dip-slip displacement (normal with varying degrees of reverse re-activation) trending roughly ESE-WSW, which matches the observed focal planes of the events
- Brockham Field and HH-1 well are also marked - Event positions match with the Newdigate Fault running to the S of HH-1 (light green). A possible W -> E migration of events is observed, moving towards the HH-1 well
- Events are shallow (500 – 1000 m depth)



Brockham

3a. Are epicentres near wells (< 5 km)?

No. Nearest events, and the Newdigate Fault, are c. 7 – 8 km from Brockham

3b. Do some earthquakes occur at or near injection depths?

Yes. Events are shallow (500 – 1000 m), within the zones of operation for Brockham

3c. If not, are there known geologic structures that may channel flow to the sites of earthquakes?

No geological structure that might provide a direct flow pathway to the earthquake sites has been identified (see following slides on potential for fluid flow)

Horse Hill

3a. Are epicentres near wells (< 5 km)?

Yes. Both the nearest events, and the presumed reactivated fault, are c. 1 – 2 km from HH-1.

3b. Do some earthquakes occur at or near injection depths?

Yes. Events are shallow (500 – 1000 m), within the zones of operation for HH-1.

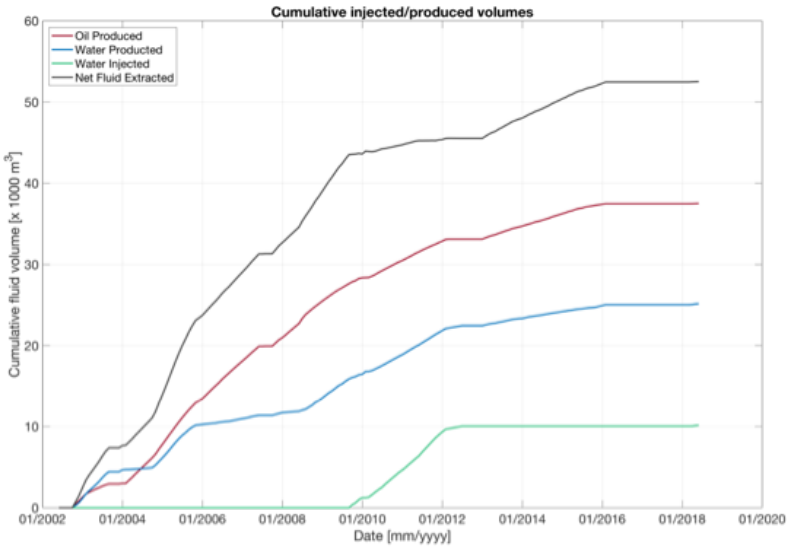
3c. If not, are there known geologic structures that may channel flow to the sites of earthquakes?

N/A. The events themselves are within 5 km.

Pressure Changes

Injection/Production rates at Brockham:

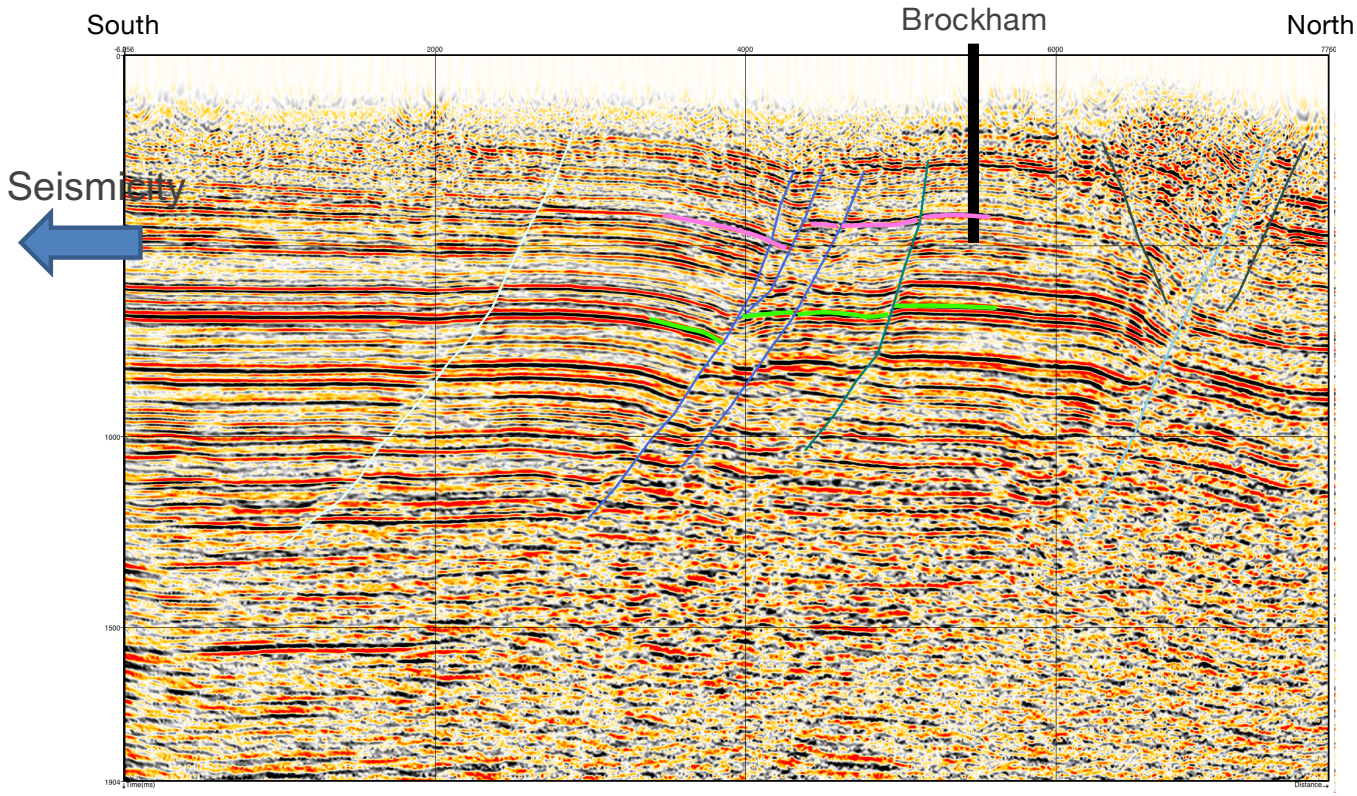
- Brockham has experienced significant production and injection volumes, with net fluid production far outstripping re-injection
- Therefore operating pressures at Brockham are expected to be well below initial conditions
- Any seismicity associated with Brockham must be caused by production effects.
- This is a viable mechanism (e.g. Groningen), but it is typically associated with significant subsidence. To our knowledge, no subsidence has been observed at Brockham.



Pressure Transfer

Seismic section through the Brockham Field

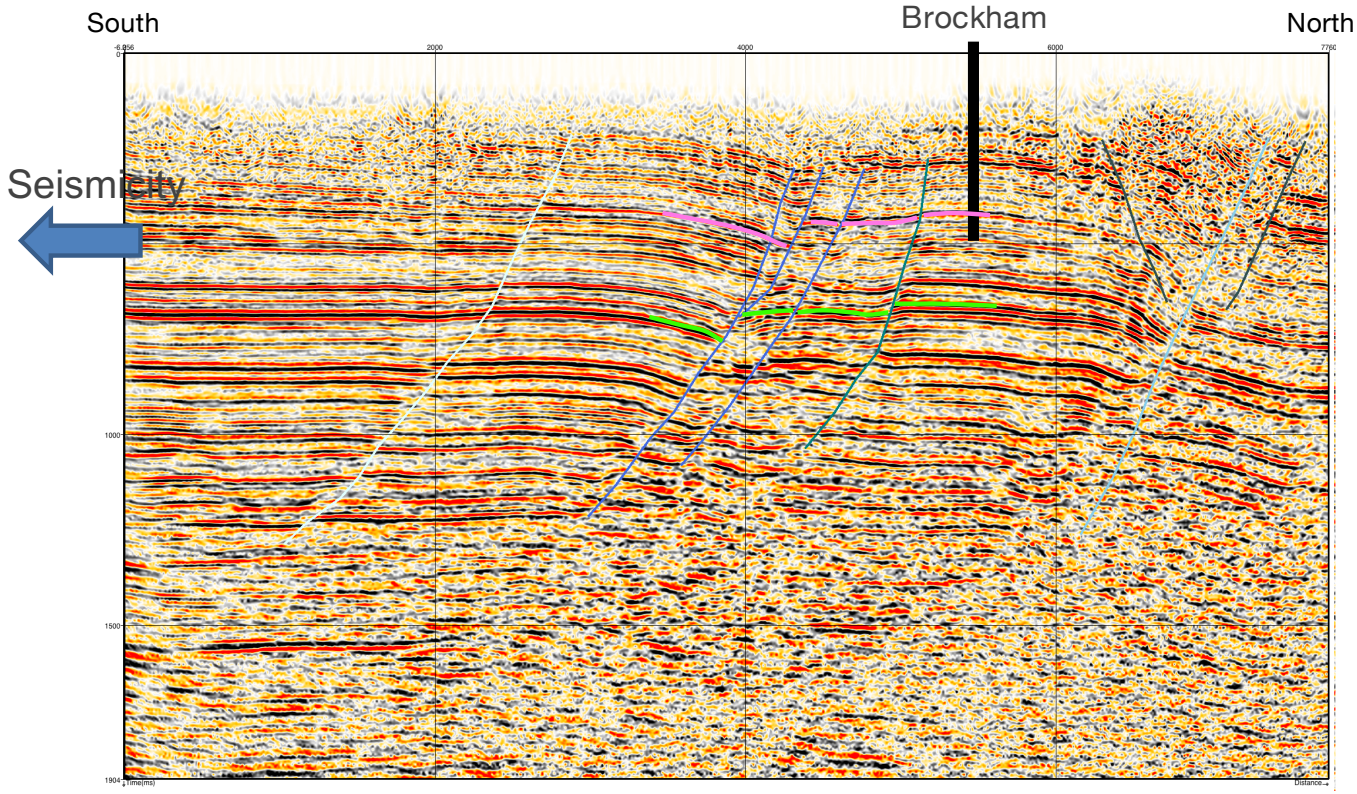
- Seismic section (BP-88-25) runnning N-S through the Brockham site. The Newdigate swarm is located to the south of this section
- The Brockham Field is fault-bounded (teal line). This fault must have some degree of sealing capacity, otherwise the HCs could not accumulate here.



Pressure Transfer

Seismic section through the Brockham Field

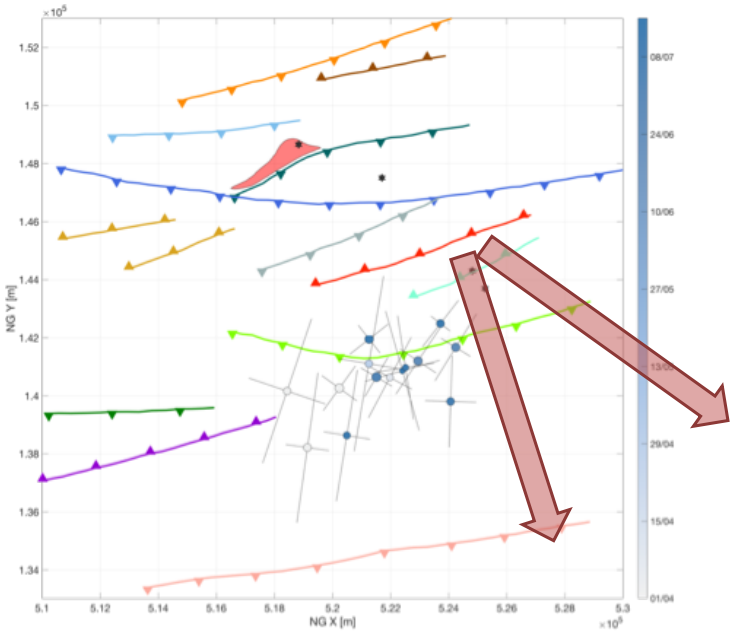
- A larger fault (blue line) is found to the S, with significant offset through the Upper Jurassic layers. This would prevent pressure changes in the Brockham Field being transferred to the south, since the Portland unit is not continuous unit
- A third smaller fault (light grey line) is also present, providing a further baffle



Pressure Transfer

Pressure communication between wells?

- If pressure changes from Brockham are affecting the Newdigate Fault, then they must also be observable (in the form of substantial pore pressure reductions) at the HH-1 well
- To our knowledge this has not been observed



Horse Hill Injection/Production

Are not publically available for Horse Hill (may be commercially sensitive)

Reported stable flow rates of 80 – 200 m^3 p/d (500 – 1,000 bopd) (UKOG investor reports)

Acid wash conducted in 2016 using c. 100 bbls of fluid.

Extracted volumes are larger than small volume of acid injected in 2016. Injection (i.e. pressure increase) is not a viable triggering mechanism. Extracted volumes are far too small to have caused subsidence (and thereby production-induced seismicity).

$$R_{inv} = 0.029\sqrt{\frac{kt}{\phi\mu c}}$$

Brockham

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

Yes (assuming a depletion/subsidence triggering mechanism). The Brockham Field is likely to have experienced substantial pressure reductions associated with the net fluid extraction. Depletion can cause seismicity, although it is usually accompanied by significant subsidence in such cases.

4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

No. The seismicity is c. 8 km away, across several faults that have demonstrated sealing capacity (the oilfield itself is fault-bounded), and which produce significant offset across the Portland Sandstone unit. Pressure changes in the Brockham Field are therefore unlikely to be transferred to the event hypocentres. Pressure communication at this scales would also result in inter-well communication, which has not been observed.

Horse Hill

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

Unlikely. Acid injection took place > 2 years before the sequence began, using very small volumes that are unlikely to trigger activity. Volume extracted is larger than that injected, so any triggering mechanism must be depletion-based, which typically requires large production volumes and associated subsidence.

4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

No. The radius of investigation from limited pumping is likely to be significantly smaller than the distance from the well to the event hypocentres and/or the Newdigate Fault.

Diagnostic Questions: Brockham

1. Are these events the first known earthquakes of this character in the region?

Maybe

2. Is there a clear correlation between injection and seismicity?

No

3a. Are epicentres near wells (< 5 km)?

No

3b. Do some earthquakes occur at or near injection depths?

Yes

3c. If not, are there known geologic structures that may channel flow to the sites of earthquakes?

No

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

Yes (but depletion)

4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

No

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3a. Are epicentres near wells (< 5 km)?

Yes

3b. Do some earthquakes occur at or near injection depths?

Yes

3c. If not, are there known geologic structures that may channel flow to the sites of earthquakes?

N/A

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?

Unlikely

4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?

No

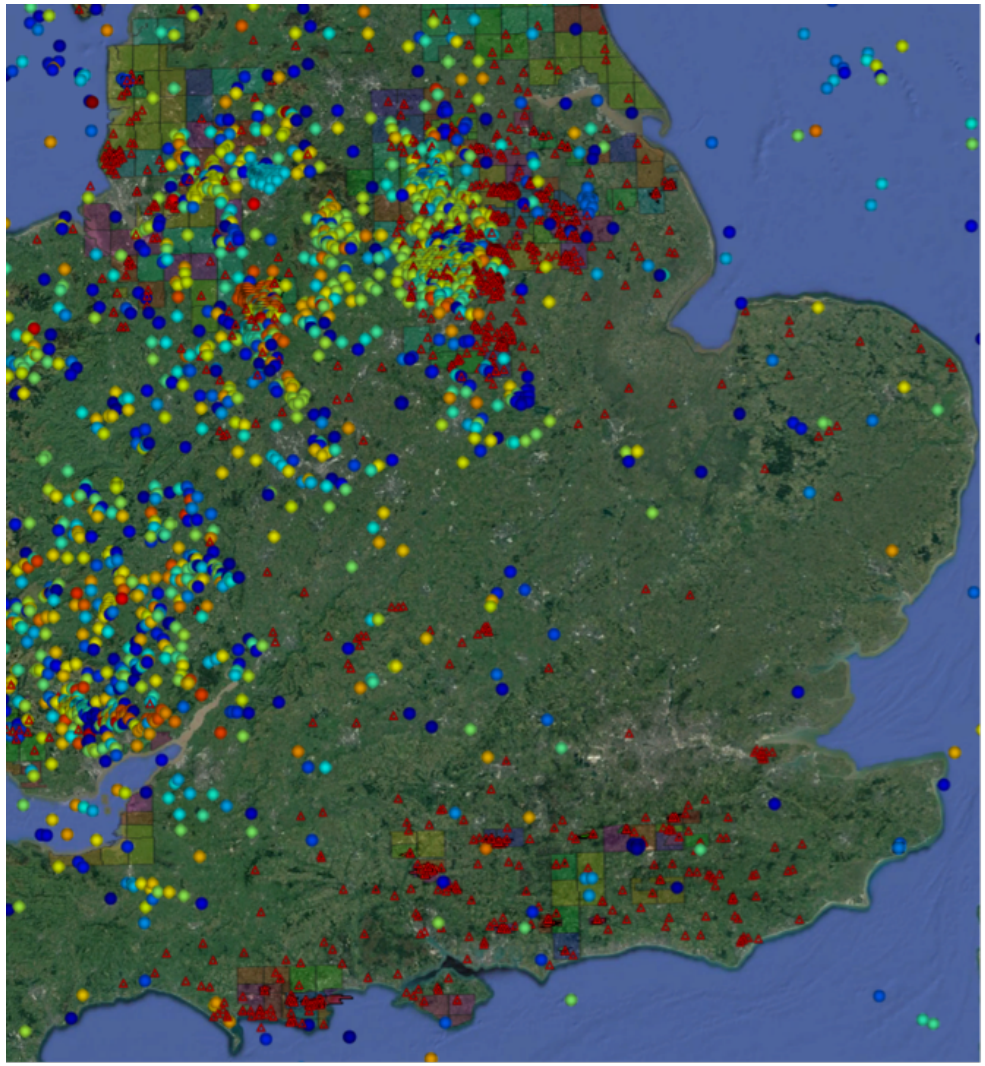
Well Integrity

Seismicity near to oil wells is not uncommon, even in the UK

We are not aware of any reported loss of wellbore integrity as a result of seismicity, unless an active fault passes across or very close to the wellbore (e.g. Cuadrilla events, 2011)

In this case the active fault does not pass across or close to either wellbore, so wellbore integrity issues are not expected

Nevertheless, operators should continue to monitor wellbore integrity, especially if further seismicity occurs on the fault.



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