Southern UK Earthquakes

Brockham Site

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Angus Energy Plc

Since April 1st, 2018, a series of 7 small scale seismic events were detected by the British Geological Survey in southern England. These occurred on 1st April (Magnitudes 2.7, 1.8 & 1.7), 4th April (Magnitude 1.5), the 27th June (Magnitude 2.6), 29th June (Magnitude 2.4), and 5th July (Magnitude 3.0) all around the Surrey & Sussex area. Further tremors were recorded on the 10th & 18th July. The BGS installed further seismic monitoring stations in the region on the 11th/12th July.

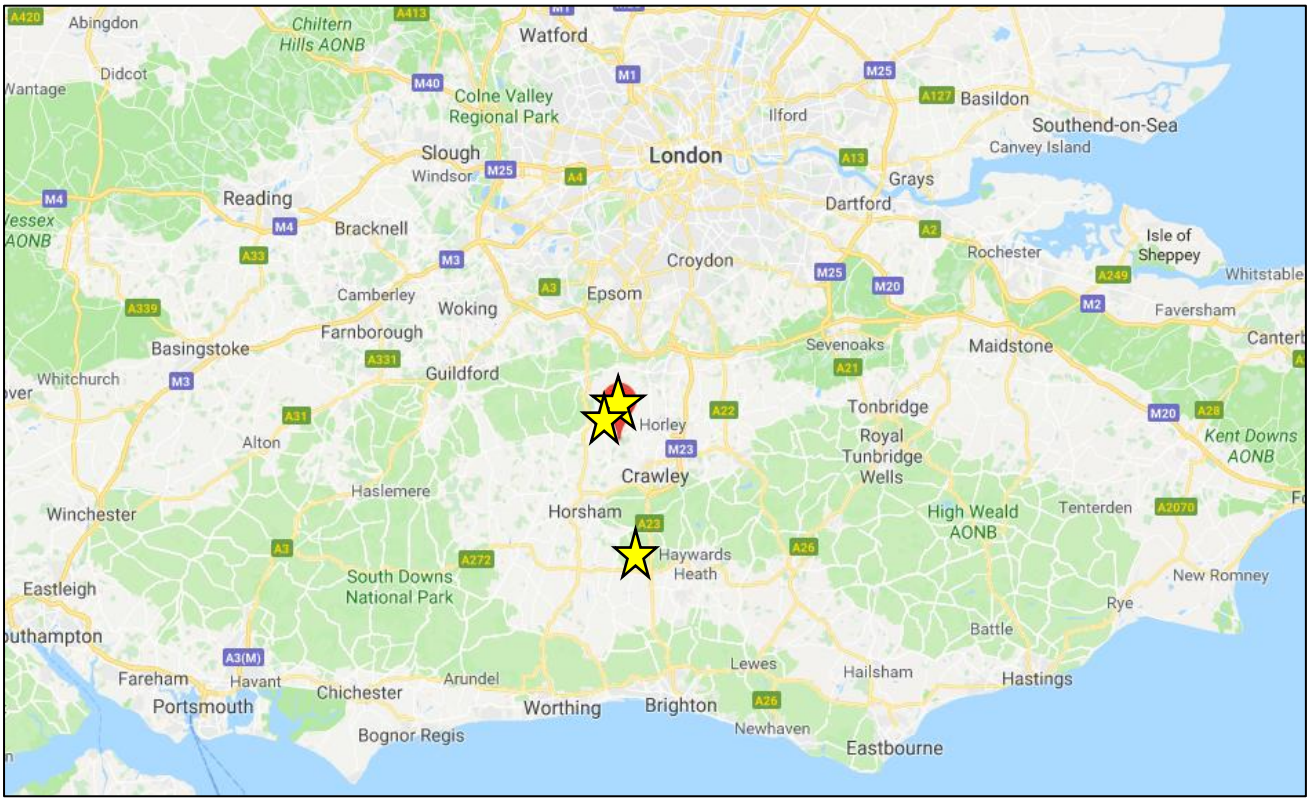

Fig. 1 – Earthquake epicentres for the 3 most recent major seismic events in the south of the UK (27th & 29th June tremors & the 5th July event)

Introduction & Background

Angus Energy operates three onshore oil and gas sites in the Weald Basin in the south of the UK, including the Brockham oil site in PL235. The site has been producing oil steadily for approximately 30 years without incident. Currently the Brockham 2 well (BRX2Y) produces oil from the Portland Sandstone reservoir. Water is also produced from the reservoir with the oil, and this produced water is replaced back into the reservoir via the water replacement well BRX3. It has been suggested that the replacement of water back into the Portland Sandstone reservoir is a cause of the seismic events seen in the last few weeks in southern UK. However, Angus Energy firmly believes that activities at the Brockham site have not caused any seismic activity.

Historical Earthquakes in the Weald Area

There has been a long history of earthquakes and seismic activity in the Weald region (as defined by Sussex, Surrey, East Hampshire & Kent) with recorded events stretching back to the 13th century. These events are summarised in the table below. The quality of the records is obviously limited by primitive technology, and it is likely that significantly more earthquakes would have occurred that were not recorded or felt by people. Indeed, the recent earthquakes on the 18th July were only detectable due to the new monitoring stations installed by the BGS. Small pre-tremors and aftershocks of around magnitude 0.4 are now detectable with current technology. It is therefore highly likely that many small seismic events over the last few hundred years have gone undetected.

Date	Location	Approx. Magnitude
4 January 1299	Weald Area	5-6
21 May 1382	Canterbury	5.8
1553	Chichester area	Not known
25 October 1734	Portsmouth	4.5
30 November 1811	Chichester	3.4
2 March 1831	Deal	3.1
Sept 1833 – Aug 1835	Chichester	Series of tremors around 3
January 23, 1834	Chillgrove	5
21 August 1864	Lewes	3.1
September 8 1937	Warnham	5-6
1 April 2018 to July 2018	Newdigate	1.5 - 3

Table. 1 – Historical earthquake data for the Weald Area. The basin has been seismically active for many centuries. **Source**: *Nature* **volume140**, page498 (18 September 1937) and other sources

The main takeaway point from this data is that all the above earthquakes occurred prior to any significant oil and gas activities in the Weald.

Well Integrity

With any seismic events occurring near a well, there can be well integrity issues. Angus Energy takes this very seriously and has since checked all our wells for any integrity issues and have found no damage. Annulus and tubing wellhead pressures are monitored daily by our site operators and there have been no changes to these since the earthquakes began. Furthermore, there have been no changes in well production rates that could be attributable to issues with well integrity. Such small magnitude earthquakes occurring at such a distance from the Brockham site make any damage to wells highly unlikely.

Geographical Location

The Brockham site is over 10km from the estimated epicentres of the recent earthquakes, and it is implausible to suggest activities at the Brockham site could create enough stress in the Earth to cause an earthquake this far away. Furthermore, no major operations have occurred at the Brockham site for at least 18 months.

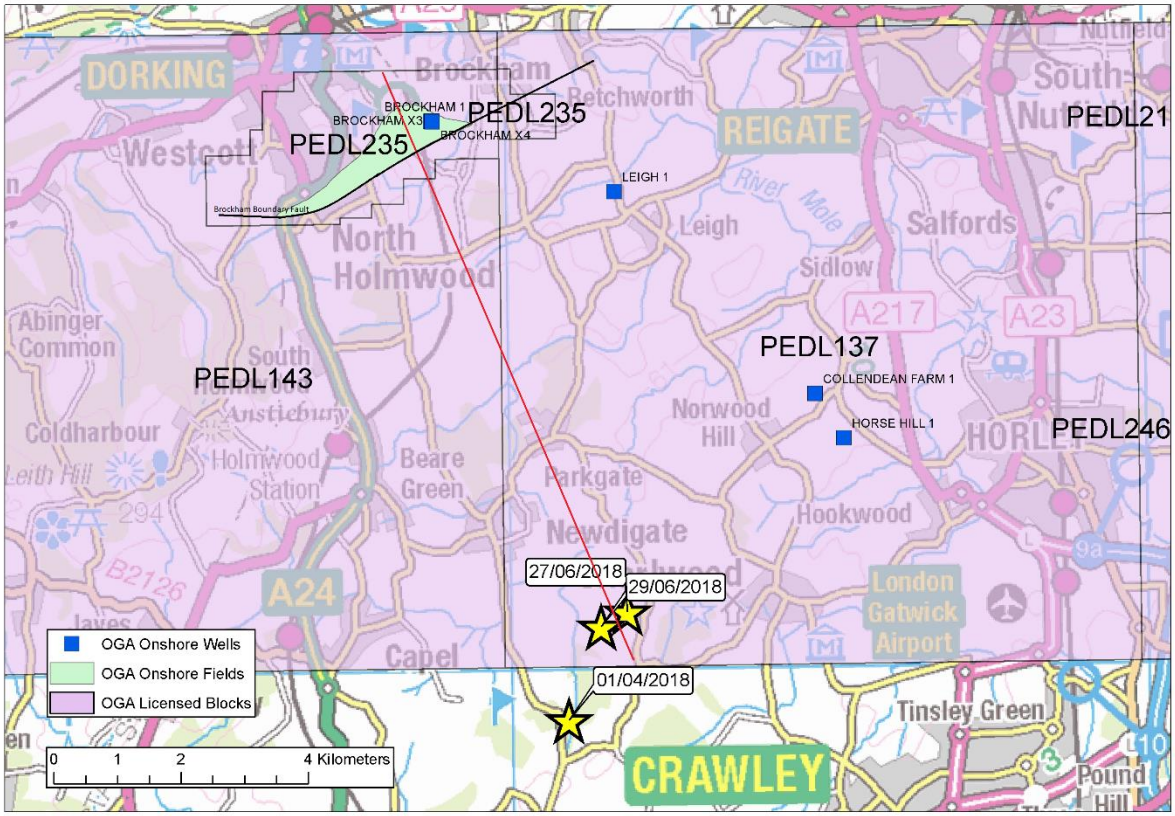

Fig. 2 – Regional location of the Brockham field from the earthquake epicentres. The black line represents the Brockham site bounding fault, and the red line is the line of section illustrated in figure 3 below

Structural Geology

Structural lineaments in the Weald Basin trend east – west, and the same trend is observed at Brockham. However, the epicentres of the earthquakes are to the south of the site, therefore even if operations at Brockham were to re-activate a fault the effects would not be seen so far south. Figures 2 & 3 below illustrate the location of the Brockham site from the earthquake epicentres, and the main NE-SW trending fault that bounds the Brockham field to the south is also marked. A cross section illustrates the considerable distance between the site and the epicentres, as well as the large vertical separation between the depth of activities at Brockham and the subsurface focus of the seismic events.

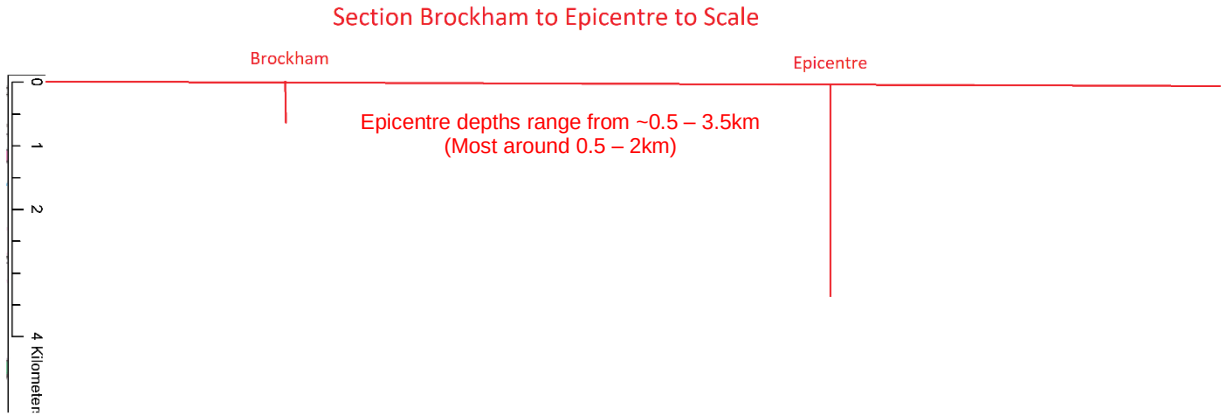

Fig. 3 – Illustrative cross section between the Brockham site and epicentres. Note the large vertical and horizontal separation between site activities and the range of depth of the seismic events.

Water Replacement

As previously mentioned, Angus Energy replaces produced water back into the Portland Sandstone reservoir, and this has been the normal operating process since 2007 when the BRX3 well was converted for this purpose. The rates of flow and pressures at which the water goes back into the Portland Sandstone are extremely low. Given that the reservoir has been producing fluids for approximately 30 years, the current reservoir pressure is now considerably lower than it was when the field was first discovered. As such, the reservoir pressure at ~600m depth is at approximately 1/3 of the pressure required to fracture the rock or to reactive any local faults. Therefore, the water replacement has not in the past, and cannot in the future reactive the boundary fault of the reservoir, let alone any other faults further away from the field. If the water replacement process was reactivating any faults, the epicentre of the earthquakes would be directly around the Brockham site.

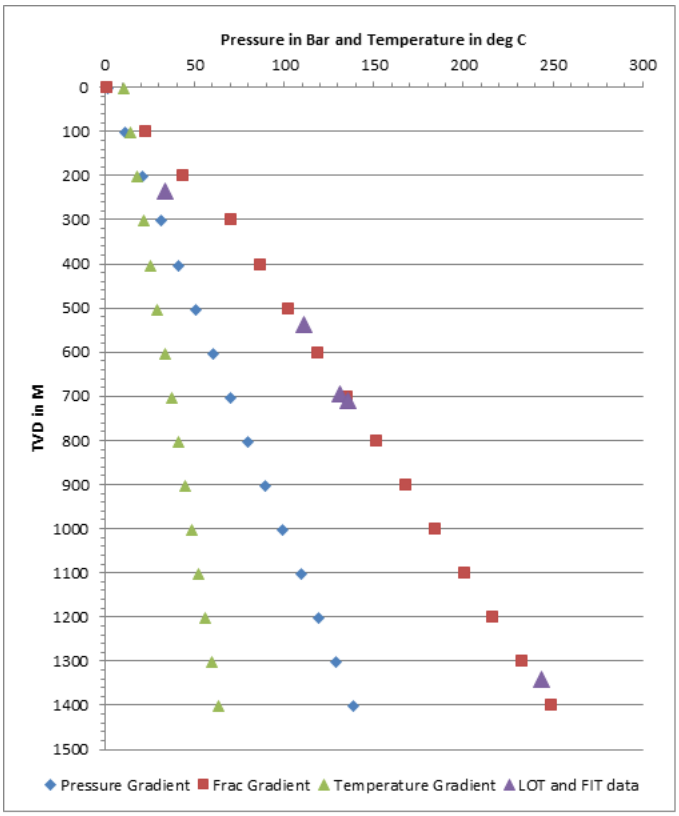

Fig. 4 – Graph to show the gradients within the well at Brockham. As shown, the pressure gradient (blue diamonds) is considerably below the fracture gradient (red squares) for the surrounding rock

The graphs and tables below illustrate the production history of the Brockham site. Over the life of the field, considerably more oil has been produced than water. In fact, cumulative oil production is approximately 230,000 bbls, and cumulative water production is approximately 70-80,000 bbls. Between 2012 – 2015 produced water at the Lidsey site was also injected at Brockham, with total produced water in this period being approximately 26,000 bbls. Even when combined with the 70-80,000 bbls from Brockham the amount of fluid replaced into the reservoir is considerably less than has been produced. Therefore, as described above, the pressure in the reservoir is considerably lower than it was in the past, and the replacement of water back in to the reservoir is not increasing the pressure due to more fluids being produced than put back in. Therefore, this will not lead to any possible fault reactivation and subsequent seismic activity.

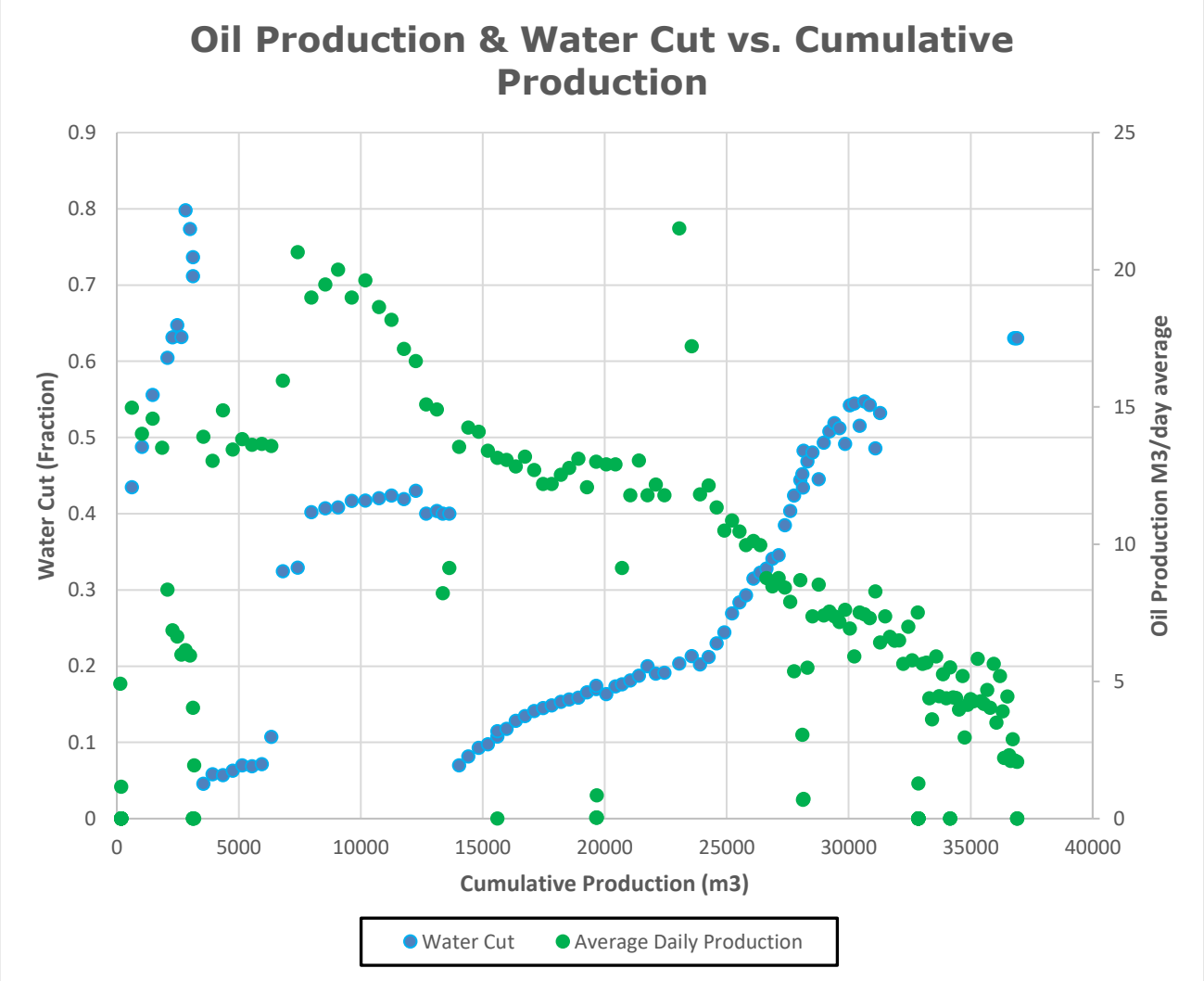

Fig. 5 – Graph showing cumulative oil production at the Brockham field. Cumulative oil production has currently reached approximately 230,000 bbls of oil (~36.5k M3)

In Summary, water replacement at Brockham cannot lead to seismic activity as it is not increasing the pressure in the reservoir due to more fluids being produced than replaced.

Expert Opinion

Further to the reasons outlined above, Angus Energy has also sought expert opinions on the seismic activity, most notably from Dr James Verdon of the University of Bristol, who is a specialist in Geomechanical Behaviour of Subsurface Reservoirs. His research has focused particularly on fault reactivation and induced seismicity during subsurface fluid injection, so he is well placed to comment on these events.

Dr Verdon referred us to a well known scientific paper authored by Scott D. Davis & Cliff Frohlich entitled 'Did (or will) fluid injection cause earthquakes? – Criteria for a rational assessment'. The paper is a widely used source for assessing the impact of water replacement on fault reactivation and sets out a series of logical questions to help ascertain as to whether an event is induced or not. The questions and how they relate to the Brockham field are outlined below. (N.B. The full paper is referenced at the end of this report, and a full .pdf of the paper can be provided on request).

Background Seismicity

1. **Are these events the first known earthquakes of this character in the region?**
   As far as we are aware, yes, however this is largely due to the fact that there has never been significant monitoring in the area, with BGS records only extending back to 1970 at best

Temporal Correlation

2. **Is there a clear correlation between injection and seismicity?**
   NO – no new activity has started at Brockham since the seismic events were recorded. As previously discussed water replacement has been ongoing for 10+ years at the site and therefore there is no temporal correlation with activities at Brockham and the events

Spatial Correlation

3a. Are epicentres near wells (within 5km)?
NO – epicentres are approximately double this distance away (~10km)

3b. Do some earthquakes at or near injection depths?
Yes – recent depths have been between 500 – 1000m

3c. If not, are there known geologic structures that may channel flow to sites of earthquakes?
NO – the main southerly bounding fault at the site is sealing. This has been proven as if it was not sealing there would be no oil accumulation in the first place

Injection Practices

4a. Are changes in fluid pressure at well bottoms sufficient to encourage seismicity?
YES – but only if assuming a depletion/significant subsidence mechanism.

4b. Are changes in fluid pressure at hypocentral locations sufficient to encourage seismicity?
NO - It is extremely unlikely that the very small changes in pore pressure could transmit any stresses to over 10km away

In summary, following the clearly laid out questions for determining the cause of these seismic events, it appears very clear that any association with the Brockham oil site is highly unlikely.

References:

Davis, S. D., & Frohlich, C. (1993). Did (or will) fluid injection cause earthquakes? - criteria for a rational assessment. *Seismological Research Letters*, *64*(3-4), 207-224.