Induced Seismicity in the UK and its relevance to Shale Gas Hydraulic Stimulation

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UK Onshore Hydrocarbon Basins
UK Seismic Activity
(Low Magnitude Shallow, Higher Magnitudes Deep)
Satellite Image of South Wales

Cynheidre Colliery

Swansea University
Longwall Coal Mining

Surface Subsidence
Bedding Plane Separation
Continuous Deformation Zone
Fractured Zone
Caved Zone
We detected many ‘impulsive’, ie rapid onset events which show clear P and S-waves. We are now certain that these originate from roof failure above, below and around the long-wall mine working.

The activity is closely correlated with the rate of coal extraction and we have detected these types of events from all collieries we have monitored in the UK and abroad.
Earthquakes beneath Sherwood Forest:
Seismicity Map of Sherwood Forest
Seismicity as a function of Depth

Variation in hypocentre depths Thoresby Take
Borehole Microseismic Monitoring
Longwall Coal Mining: typical seismicity.
And so to Frac!
Hydraulic Fracturing

Hydraulic fracturing, or “fracking,” involves the injection of more than a million gallons of water, sand and chemicals at high pressure down and across into horizontally drilled wells as far as 10,000 feet below the surface. The pressurized mixture causes the rock layer, in this case the Marcellus Shale, to crack. These fissures are held open by the sand particles so that natural gas from the shale can flow up the well.
Hydrofracturing Globally

- 100,000+ fracs already done in the US.
- Felt seismicity is extremely rare.
- Reported seismicity (Oklahoma) appears to be due to fluid reinjection rather than hydraulic stimulation.
- Microseismicity **does** occur and is used as the primary tool to monitor the success of the fraccing and extent of the fracture system.
Hydrofracturing in the UK

• Not new!!
  – Carried out for Geothermal Energy
  – Carried out for Coal Bed Methane
  – Microseismicity Monitored as long ago as 1988

Beckingham, Lincolnshire Hydrofrac Monitored by my (PS) Research Group (while at Liverpool) in 1988/1989 with BP!!
Cuadrilla Preese Hall 1 Borehole
Hydrofracturing Stages and Associated Seismicity at Preese Hall

<table>
<thead>
<tr>
<th>Stage</th>
<th>Description</th>
<th>Date</th>
<th>Perforations</th>
<th>Slickwater Volume</th>
<th>Proppant</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Depth</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Top (ft MD&lt;sub&gt;RKB&lt;/sub&gt;)</td>
<td>Bottom (ft MD&lt;sub&gt;RKB&lt;/sub&gt;)</td>
<td>Length (ft)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TVD&lt;sub&gt;SS&lt;/sub&gt;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>DFIT</td>
<td>26 March 2011</td>
<td>8,841</td>
<td>8,850</td>
<td>9</td>
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<tr>
<td></td>
<td>Job</td>
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<td>8,841</td>
<td>8,949</td>
<td>36</td>
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<td>2</td>
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<td>8,759</td>
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<td>Job</td>
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<td>8,700</td>
<td>8,583</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>01 April 2011</td>
<td></td>
<td></td>
<td>Magnitude 2.3 seismic event</td>
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<tr>
<td></td>
<td></td>
<td>04 April 2011</td>
<td></td>
<td></td>
<td>Deformed casing confirmed with caliper 8480-8640ft MD (just below zone 3)</td>
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<td>DFIT</td>
<td>08 April 2011</td>
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<td>8,020</td>
<td>8,052</td>
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<td></td>
<td></td>
<td>27 May 2011</td>
<td></td>
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<td>Magnitude 1.5 seismic event</td>
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<td>7,970</td>
<td>7,819</td>
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<td></td>
<td>Job</td>
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<td>7,970</td>
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<td>6</td>
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<td>7,670</td>
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<td>27</td>
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<td>TOTALS</td>
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<td>513</td>
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</table>
Blackpool Area Earthquakes
Surface GURALP 6TD Broadband, three component Seismometers
Blackpool Earthquakes

- Earthquake activity was caused by fluid injection into a fault zone.
- The fault failed repeatedly in a series of small earthquakes.
- The fault is yet to be identified.
- The injected volume and flow-back timing was an important controlling factor.

Overview of injection volume and seismicity during treatment stages. Earthquake activity closely correlates with stages 2 and 4. The largest event with 2.3 ML at 02:34 on 1/4/2011 occurred shortly after stage 2.

Epicentre of the Blackpool earthquakes (yellow star) in relation to the Preese Hall well. Depth is approximately 2250 m, which places the events close to the point of injection.
• In stages 2 and 4 the largest events occurred 10 hours after shut-in
• Unusually low number of small events
• Similar waveforms suggests highly repeatable source
Natural or Induced?

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Blackpool seismicity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Are these events the first known earthquakes of this character in the</td>
<td>Yes</td>
</tr>
<tr>
<td>region?</td>
<td></td>
</tr>
<tr>
<td>Is there a clear correlation between injection and seismicity?</td>
<td>Yes</td>
</tr>
<tr>
<td>Are epicenters near wells (within 5 km)</td>
<td>Yes</td>
</tr>
<tr>
<td>Do some earthquakes occur at or near injection depths?</td>
<td>Yes</td>
</tr>
<tr>
<td>Are changes in fluid pressures at well bottom sufficient to encourage</td>
<td>Probably</td>
</tr>
<tr>
<td>seismicity?</td>
<td></td>
</tr>
</tbody>
</table>
Is the earthquake activity at Preese Hall unique?

- Numerous examples of induced earthquakes in hydrocarbon fields and Enhanced Geothermal Systems (EGS)
- Induced micro-seismicity commonly used to image fracture networks and stimulated volumes
- Magnitudes of the induced earthquakes in reservoirs such as the Barnett Shale are typically less than 1 ML.

**BUT**

- Tectonic history and the present-day stress regime in the British Isles different.
- Many shale gas plays are in remote locations, with no monitoring.
- Recent evidence (Holland, 2011) suggests that there may be a issue for other reservoirs.
- Seismicity induced by fluid disposal (e.g. Frohlich et al., 2011).
Ground Vibration Recommendations

DIN 4150-3 Permissible German Vibration Limits

BS 7385 Permissible British Vibration Limits
Approximate Perception Distances from Natural and Induced Seismic Events of various magnitudes (US Nat. Acad. Sciences 2012)
Maximum Magnitude of Induced Events

- They happen in weaker, younger rocks, generally in sandstones of Carboniferous age, associated with coal mining.

- Hydrofracture related events occur in even weaker rocks which are shales of Carboniferous age.

- Inducing a significant seismic event requires an increase of the pore pressure above levels that have existed prior to fluid injection and over a region large enough to encompass a fault area consistent with the magnitude of the earthquake. It is not likely to exceed the magnitudes which we have seen of about 3 M_L at an expected depth of 2-3 km which results from a rupture area of about 0.060 km^2 (corresponding to 15 acres).
  
  - may be felt,
  - may in rare circumstances cause superficial damage (plaster)
  - will **not** cause structural damage.

- Possibility of other earthquakes during future fracture treatments can’t be ruled out as it is quite possible that there are critically stressed faults throughout the basin.
Our Detailed Comments (1)

• Although we agree that the events are attributable to the existence of an adjacent fault, the causative fault has not actually been identified, and more generally there is only a limited understanding of the fault systems in the basin.

• Also though some large scale structures have been mapped, earthquakes in the magnitude range 2 to 3 ML require only relatively small rupture areas, and so can occur on small faults. There might be other comparable faults at reservoir depths throughout the basin, given the tectonic history.

• A comprehensive 3-D seismic survey might better improve understanding of the nature and orientation of fault systems in the basin.
Our Detailed Comments (2)

• The observed seismicity at Preese Hall was induced by the hydraulic fracture treatments, the events are located close to the point of injection and the timing clearly corresponds to the treatment schedule.

• The similarity of seismic events suggests a highly repeatable source, i.e., a fault that failed repeatedly resulting in a number (c 50) of small earthquakes.

• There appear to be two possible scenarios:
  
  – the fault intersected the well-bore and fluid was directly injected into the fault during the treatment;

  – the fault may be a few hundred metres from the well-bore, but that fluid was able to flow into the fault through bedding planes in the reservoir that opened during stimulation as a result of the high pressures.

• There is little evidence for the former although this scenario is used in the numerical modelling. There is clear evidence both for bedding planes opening and for previous slip on the bedding planes.
“hydraulic fracturing leads to an array of induced fractures, some packed with proppant, others not, depending on factors such as leak-off rate, fluid viscosity, injection rate, and so on. The proppant bridges off in narrow secondary fractures, but the carrier fluid goes out much farther than the proppant.

This fluid pressurizes a large volume, induces slippage on existing or existing features (and extensional opening) and results in detectable microseismic activity”
We conclude

Given the sparse nature of the available seismic data the Cuadrilla report can only address the **major** questions but provides some useful insights into the relationship between operations and seismic activity.

We generally agree with the main conclusions about the nature and mechanism of the seismic activity, but we have the following concerns:

- The stated low probability of earthquakes during future treatments. There is insufficient data to justify the stated low probability of encountering a similarly unique scenario in any future wells.

- The potential for upward fluid migration seems overstated, based on microseismic shale gas data from the main US plays. Further analysis in this report seems to indicate that fracture containment was good, with little vertical height growth.

**We conclude that an effective mitigation strategy is a necessary prerequisite for commencing operations and offer our own recommendations, for future operational best practice and monitoring.**
Our Recommendations for Mitigation of Hazards (1)

• Hydraulic fracture growth in the reservoir was poorly constrained by the available data from the treatments in April and May 2011.

  – We recommend that detailed analysis of microseismic activity is used to monitor fracture growth in the next hydraulic fracture treatment to better understand the nature and extent of possible fracture growth in the Bowland Shale reservoir and the hazards associated with this.

  – Microseismic data should be recorded using either a dense array of near-surface sensors, or an array of borehole sensors for both a traffic-light system and detailed understanding of subsurface stress before, during and after Hydraulic fracturing.
Maximum Magnitudes of events generated from Hydrofracture in the Barnett Shale, US (after Warpinski, 2009 2011)

![Graph showing moment magnitude vs depth for different shale formations.](image)

Eagleford?
Woodford Shale max. 0.8
Marcellus Shale max. 0.7
Barnett Shale max. 0.4
Fayetteville max. -0.1
Haynesville max. -0.2
West Texas Barnett max. -1.0
Bakken max. -1.5
Montney avg. -2.7
Piceance max. -3.0

Fig. 1—Barnett shale maximum moment magnitude results for monitored stages through mid 2011.
Proposed Traffic Light System with Thresholds

**GREEN**
- $M < 0$
- Complete Full Job
- Flowback 12 Hours minimum
- Mini Frac Next Stage
- FRAC NEXT STAGE
- OPTIONAL: Small Increase in Job Volume

**YELLOW**
- $M = 0 - 0.5$
  - Multiple Confirmed Events
- Complete Full Job
  - Flowback 36 Hours minimum
  - Mini Frac Next Stage
  - FRAC NEXT STAGE
- NO INCREASE IN JOB VOLUME

**RED**
- $M > 0.5$
  - Single Confirmed Event
  - SHUT DOWN IMMEDIATELY
    - Flush Well & Stop Pumps
  - Max Seismicity During or After Frac at $M \leq 1.5$
    - Flowback 3 Days Minimum
  - Max Seismicity During or After Frac at $M > 1.5$
    - Flowback 10 Days Minimum
    - No Stage Re-frac
      - MOVE TO NEXT STAGE
  - No Additional Seismicity within 24 hours at $M \geq 1.0$
    - Additional Seismicity within 24 hours at $M \geq 1.0$
      - No Stage Re-frac
        - MOVE TO NEXT STAGE

OPTIONAL:
- Re-frac same zone after 3 days of Flowback
Our Recommendations for Mitigation of Hazards (3)

• The number of fluid injection induced earthquakes above a given magnitude will increase approximately proportionally to the injected fluid volume,

• Therefore reducing volumes and implementing flow back should reduce the probability of significant earthquakes.

• We therefore recommend that future fracture treatments should initially be modified to reduce the probability of future induced earthquakes, by:
  – reducing the injected fluid volume
  – initiating immediate flow back post-frac.
Proposals for any future HF operations elsewhere in the UK (*and elsewhere?*)

We recommend a detailed analysis of potential seismic hazards *prior* to spudding the well. This should include:

- Appropriate baseline seismic monitoring to establish background seismicity in the area of interest.

- Characterisation of any possible active faults in the region using all available geological and geophysical data.

- Application of suitable ground motion prediction models to assess the potential impact of any induced earthquakes
European Shale Gas and CBM plays

Figure 3.7: Major unconventional natural gas resources in Europe

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