Briefing Note

Induced Seismicity in the UK and its Relevance to Hydraulic Stimulation for Exploration for Shale Gas

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The continental crust of the UK has had a long and complex tectonic history, with a more recent phase of loading and unloading superimposed upon it from the advance and retreat of ice sheets during the last 10,000 years or so. It is crisscrossed by networks of faults, some of which move on a reasonably frequent basis with observable and often felt seismicity, such as the bounding faults of the Welsh Marches and others which have not had recorded seismicity in historic times but may be in a quasi-critical state, in which the rocks store energy which can be released by changes in stress or hydrogeological conditions. The crust can respond by failing in an earthquake, a release of elastic stored energy which can be, and often is, **NATURAL** seismicity; or can sometimes be due to human activities such as mining, deep quarrying, coal mining, hydrogeological extraction or fluid disposal and activities associated with non-conventional hydrocarbon extraction, which is described as **INDUCED** seismicity.

The magnitudes of the induced seismic events which occur in any region are partly due to the size of any **applied stimulation,** which must be sufficient to take ambient stress within the rocks beyond the point at which the yield point of the rock is exceeded, but are mainly determined by the **strength of the rock** being stressed. A good analogy is a stretched elastic band. Thick bands are hard to stretch and break but when they do they snap with a vengeance. Thin bands are easier to

stretch and snap and are far less energetic. It doesn't matter how hard you pull them as long as it is sufficient, they still snap with an energy defined by their material properties. Because of its complex tectonic history, the crust of the UK south of the Iapetus Suture, the boundary between "Geological England" and "Geological Scotland", is mostly rather weak and can rarely store sufficient energy for large seismic events; we consider a tectonic event with a magnitude 6 a VERY significant event here in the UK for our own domestic purposes, but these are minnows compared with earthquakes occurring elsewhere and are almost always generated in the middle crust (Basement rocks) at depths of around 15 km or so, where the crust is much stronger than the sedimentary cover which is the target for hydrocarbon activity.

Earthquakes follow a well established frequency-magnitude relationship, which states that in a given period of time the number of events of a given magnitude will be ten times less frequent than those of one unit of magnitude less. This is known as the Gutenberg-Richter relationship (see full explanation of this later) and means that large earthquakes are less frequent than small ones. Figure 1 shows the Gutenberg Richter relationship for the British Isles and plots the number of earthquakes which exceed a certain magnitude against that magnitude. From this we can see that on average, the UK experiences a magnitude 4 earthquake or greater every three-four years and a magnitude 5 earthquake roughly every twenty years. The recurrence interval for the largest earthquakes can be rather uncertain because these are constrained less well. The largest earthquake we might expect in the British Isles is around magnitude 6. Figure 2 shows earthquakes above 4 and earthquakes above magnitude 5 superimposed on a fault map of the UK. There are many, many faults and only a few earthquakes of significant magnitude, which tells us that most faults are not particularly active in the sense that we might think them to be.
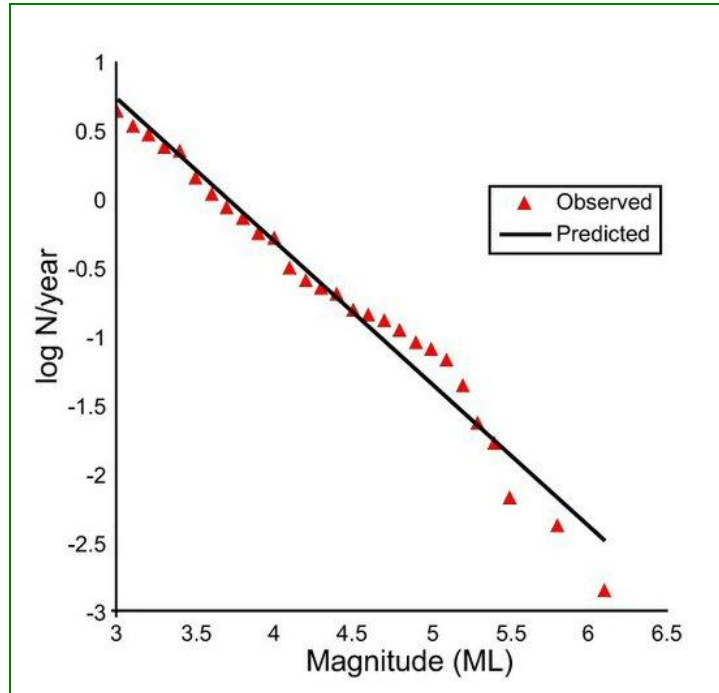
Figure 1.   Gutenberg-Richter Plot for larger British Earthquakes

Historically, the largest earthquake in the Lancashire region was a magnitude 4.4 earthquake near Lancaster in 1835 with a maximum intensity (the degree to which an earthquake is perceived by the local population) of 6 BGS). Little or no seismicity has ever been recorded from the Blackpool area but that says little about the state of preexisting stress as seismic events have been reported from south and north of this region where geology and stress fields are little different. The existing seismic reflection data have been interpreted with the principal known faults, but it is clear that there are other unnamed faults and significant structural discontinuities, which make the interpretation of this seismic data ambiguous.
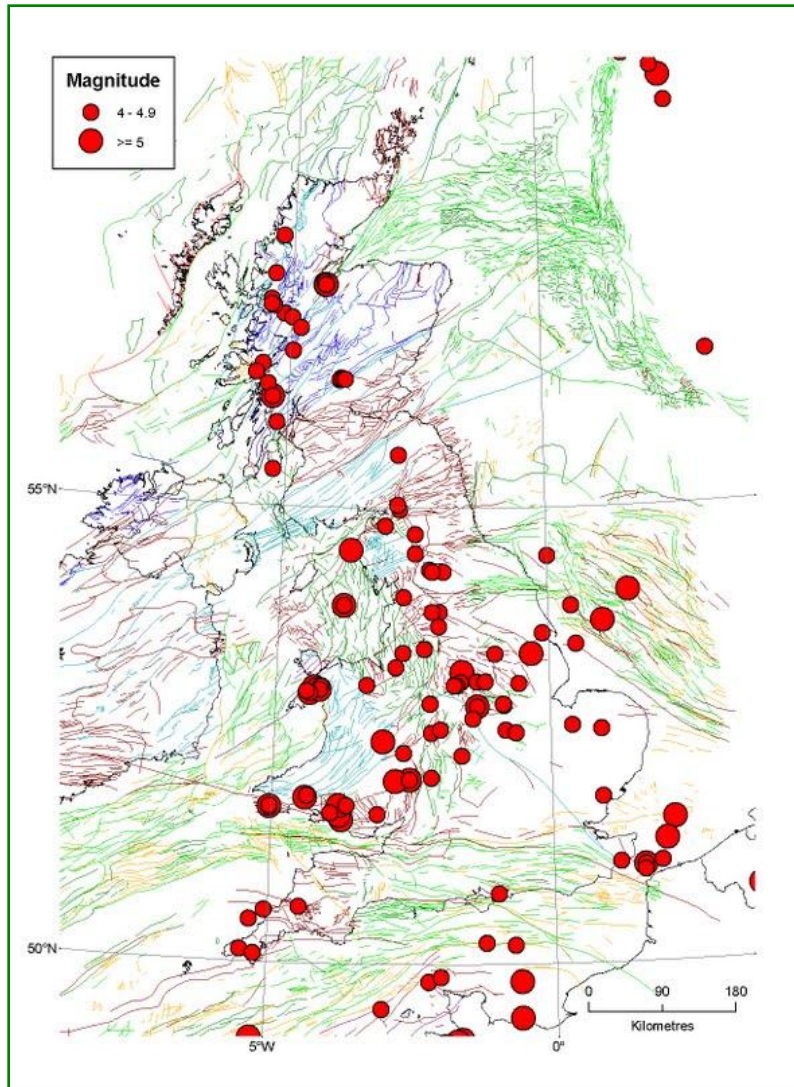
Figure 2. Fault pattern of the UK with the relatively few
earthquakes which have exceeded magnitude 4 superimposed

We agree that the hydrofracture process carried out in Lancashire at
Preese Hall was the trigger of the sequence of minor seismic events
observed near Blackpool between April and June 2011, with the highest
on April 1st 2011 with a magnitude of 2.4.However, the state of stress,
which was released by these events, was pre-existing, and the hydraulic
changes made in hydrofracturing were simply the perturbation which
initiated the sequence of events.   The sequence may have occurred

anyway at some later time (which may be of geological extent!) triggered by some other stress perturbation.

Such interactions between tectonic features and anthropogenic activities associated with stimulation procedures used in hydrocarbon exploration of oil and more recently shale gas appear to be relatively rare (Holland 2011 reports a similar sequence with magnitudes from 1.0 to 2.8 in Oklahoma), but are not unknown; and induced seismicity from hard-rock and soft rock (coal, salt, gypsum, anhydrite and other minerals) are much more frequent.

It is quite difficult to measure stress in rock and requires complex procedures in deep boreholes. Much of our knowledge is in fact derived from observations of seismicity itself, as by looking at the frequencies present within the seismogram of the waves generated by an earthquake we can learn much about the source and the amount of stress which was released by that event. This is also true of induced seismicity and it is probably true to say that about 50% of the seismicity experienced in the UK in the last century was caused by coal mining activities. Despite the very large diminution of active coal mining we still experience occasional tremors, nearly always associated with post-mining hydrogeological recovery and mine flooding. These have been observed from every coalfield in the UK, and researchers at Keele University, which sits on one of the most seismically active coalfields in the UK, have recorded thousands and analysed many hundreds of these. They occur in the same Carboniferous geological formations from which shale gas is now being sought. The post-mining events, which are what we mostly see now, are often triggered by hydrogeological changes and are very relevant to the question of what the maximum expected seismic magnitude in this area might be. They range from the tiniest trembles of magnitude -3 which can only be detected very close to the source with sensitive

instruments but which are relatively frequent if unnoticed, through events of magnitude 1 which do not cause damage but can be noticed by a population which has become sensitised by experience, up to events which are detectable on seismic stations at tens of kilometers away and are reported by the BGS. The maximum reported appears to be a magnitude 3.2 in Midlothian and the magnitude at which a statistically significant number have been recorded is probably magnitude 3. They have been plotted as a Gutenberg-Richter plot but note that these would not even qualify to be on the Gutenberg-Richter plot for the UK which we showed earlier in Figure 1. There is a statistical probability of events perhaps as large as 3.5 but the probability is small and difficult to quantify and 3 is a better working hypothesis.

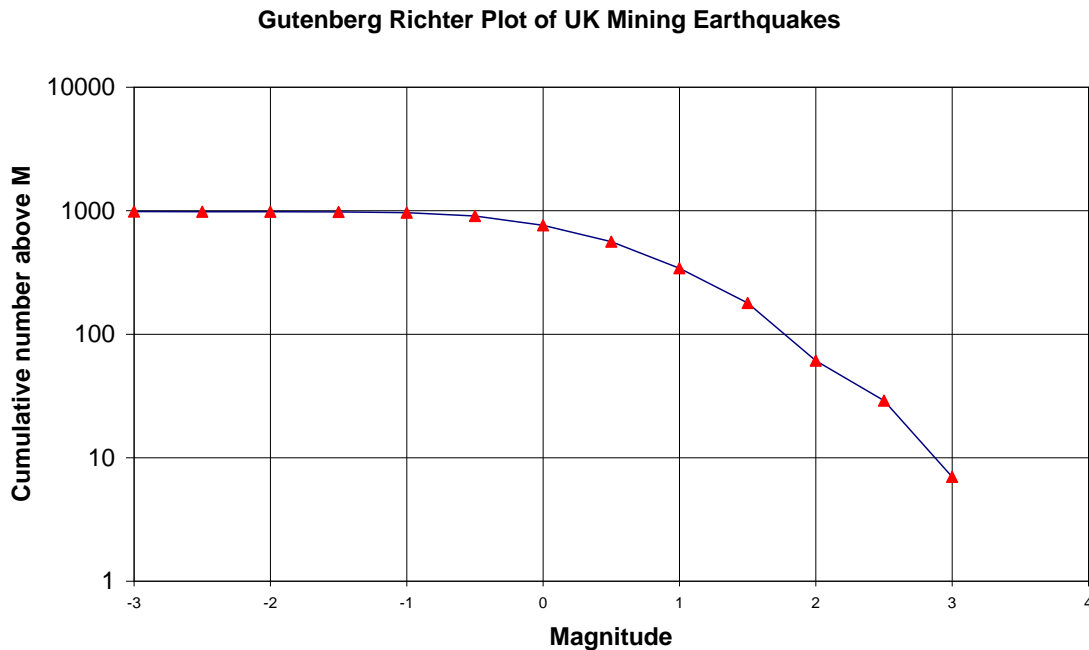**Gutenberg Richter Plot of UK Mining Earthquakes**

Figure 3. Gutenberg-Richter plot of the Frequency of Occurrence of Mining Induced Earthquakes above a specific magnitude. Data from various sources, mostly Styles P. (2011) and Redmayne et al (1998).

In this area, shale gas has been found in the rocks which immediately underlie the Coal Measures rocks, which are of lowest Carboniferous in age and are known in the UK as the Bowland Shale. They are of similar strength if not indeed weaker than the coal bearing strata and therefore we expect them to produce similar size earthquakes if stressed, i.e. probably much less than a maximum magnitude of about 3. They may contain enormous quantities of methane gas but have very little permeability, the property which allows easy flow of gas and water, and so it is common in the US and elsewhere to stimulate new additional fractures by injecting high pressure water; this is "hydraulic fracturing", sometimes known as hydrofracturing or "fraccing".   Hydrofracturing, the intentional injection of fluids (waters, foams and gels) at high pressure (5000+ psi) to create new fractures, is a relatively minor perturbation to the ambient stress field, and acoustic emission (rock noise) of very low levels is always recorded from this process. This acoustic emission is often used as a tool for monitoring the progress and extent of the extensive fracture networks created which increase permeability, the ease with which oil and gas and water can flow through the subsurface, which is the intended outcome of this activity. However, hydofracturing is such a small perturbation it is rarely a hazard when it is used to enhance permeability in oil and gas or other types of fluid extraction activities. Lawrence Berkeley Laboratory states "To our knowledge hydrofracturing to intentionally create permeability rarely creates unwanted induced seismicity large enough to be detected on the surface with very sensitive sensors, let alone be a hazard or annoyance"

http://esd.lbl.gov/research/projects/induced_seismicity/oil&gas/.

It should be noted that this is also true in the UK.   Although hydrofracturing has not previously come to public attention here, many hydrofracs have already taken place in several parts of the England and

Wales, both for geothermal and hydrocarbon stimulation, without inducing felt seismicity. During the "hot dry rock" experiment in Cornwall, over 11,000 microseismic events were detected between 1982-1987. Nearly all of these were too small to be felt, although the largest had a magnitude of 2.0 (12/07/1987) and was weakly felt with an intensity of 3.

Despite the previous history, it is clear that in Lancashire we have had a short sequence of induced seismic events triggered by hydraulic fracturing in shale formations, which did reach perceptible magnitudes. It is important that we understand how this has occurred, how we can mitigate any further felt seismicity and what procedures we put in place to monitor and control this process.

How do we measure how big an Earthquake is?

In order to be able to determine risk of damage to structures, recurrence interval (when will we get another one of a certain size), ground shaking and a host of other useful parameters, we have to be able to put some kind of a number on the size of an earthquake. There are two ways of doing this. The first, which is the old tried and tested method, which in fact has been in play ever since the first human experienced an earthquake, is the question 'how much did the earth move for you then…'?; in other words, the perceptibility and the amount of damage done. Small, but shallow, earthquakes can be felt quite strongly and conversely deep but large earthquakes may not be felt as strongly as we might suspect. The measure which we use for this is called the **Intensity** and it is a subjective scale assessed by asking people the question above, framed perhaps in a slightly different way, through a questionnaire called a macroseismic survey which asks them for their experiences; did they note any damage, did hanging objects swing etc.

Intensity

There have been several version of this through the past century or so and perhaps most people will have heard of the Modified Mercalli Scale but are less likely to have encountered a later Medvedev-Sponheuer-Karnik scale (MSK-64). We have now left poor Mercalli unmodified and we have what is known as the **EMS** or **European Macroseismic Scale**.

EMS Short form	Experience
I. Not felt	Not felt, even under the most favourable circumstances.
II. Scarcely felt	Vibration is felt only by individual people at rest in houses, especially on upper floors of buildings.
III. Weak	The vibration is weak and is felt indoors by a few people. People at rest feel a swaying or light trembling.
IV. Largely observed	The earthquake is felt indoors by many people, outdoors by very few. A few people are awakened. The level of vibration is not frightening. Windows, doors and dishes rattle. Hanging objects swing.
V. Strong	The earthquake is felt indoors by most, outdoors by few. Many sleeping people awake. A few run outdoors. Buildings tremble throughout. Hanging objects swing considerably. China and glasses clatter together. The vibration is strong. Topheavy objects topple over. Doors and windows swing open or shut.
VI. Slightly damaging	Felt by most indoors and by many outdoors. Many people in buildings are frightened and run outdoors. Small objects fall. Slight damage to many ordinary buildings; for example, fine cracks in plaster and small pieces of plaster fall.
VII. Damaging	Most people are frightened and run outdoors. Furniture is shifted and objects fall from shelves in large numbers. Many ordinary buildings suffer moderate damage: small cracks in walls; partial collapse of chimneys.
VIII. Heavily damaging	Furniture may be overturned. Many ordinary buildings suffer damage: chimneys fall; large cracks appear in walls and a few buildings may partially collapse.
IX. Destructive	Monuments and columns fall or are twisted. Many ordinary buildings partially collapse and a few collapse completely.
X. Very destructive	Many ordinary buildings collapse.
XI. Devastating	Most ordinary buildings collapse.
XII. Completely devastating	Practically all structures above and below ground are heavily damaged or destroyed.

which ranges from I (not felt which isn't very helpful) to XII when everything has been devastated and you might not feel much like filling in a questionnaire! However, this is a very well thought out descriptor, which can relate to both Geophysicists and Engineers in a meaningful way

Magnitude

Seismologists, of course want something a bit more quantitative than this, and so they invented **magnitude** which is an instrumental measure of an earthquake, based on the amplitude of the ground displacement and the distance from the earthquake and initially, at least, on the type of seismometer on which you recorded the earthquake. This gave rise to the much-misunderstood Richter Scale of magnitudes which is a logarithmic scale with no upper and lower limits despite what the media presume! Seismologists refer to this kind of assessment as Local Magnitude M_L and while it is very useful for most smaller earthquakes (including all of those felt in the UK it should be noted) it is not very informative for the very largest earthquakes where we need a new measure based on the area of the slip and how far the rupture moved together with knowledge of the elastic properties of the Earth and this is called Moment Magnitude M_W. There are a plethora of other scales based on different parts of the earthquake seismogram but the M_L and M_W scales cover everything (and more), which most folks need to know.

There is no exact relationship between Intensity and Magnitude but USGS suggest the following general comparison.

http://earthquake.usgs.gov/learn/topics/mag_vs_int.php

Magnitude	Typical Maximum Modified Mercalli Intensity
1.0 - 3.0	I
3.0 - 3.9	II - III
4.0 - 4.9	IV - V
5.0 - 5.9	VI - VII
6.0 - 6.9	VII - IX
7.0 and higher	**VIII** or higher

Gutenberg Richter Plots

Beno Gutenberg and Chuck Richter (he of the magnitude scale) were two of the greats of post-war seismology and they give their names to a graph which relates the frequency of occurrence of earthquakes to their size measured on the magnitude scale and shows some interesting properties.

Plotting the Log_{10} (number of earthquakes) against their magnitude seems to show a linear relationship between these two parameters and if we go a step further and make this a cumulative plot of the number of earthquakes each year which have magnitude M or greater, we see that this quantity which we call N(M) is given by the following equation which is a straight line of the form: y=mx+c or more accurately: y=c-mx.

$$Log_{10}N(M) = a - bM$$

While a, the intercept on the $Log_{10}(n)$ axis varies significantly, b is almost always close to 1 which says that that every time we increase magnitude by 1, the number of larger magnitude events goes down by a factor of 10 or conversely for every step down in magnitude the number of smaller events increases by a factor of 10. This relationship seems to hold true for all earthquakes globally with a b value of about 1.

This b value will vary a little when you consider subsets of events from different regions but is remarkably consistent for earthquakes from all over the world.

However, there **are** some times when the b value does change and that has some significance as this happens when we have a sequence of seismic events which are after-shocks of a larger event and here we often see that the b value is much higher than 1 indicating that that there are

more small events than we might have expected for each change down of 1 on the magnitude scale. We have to be a little careful because we can only be confident about our G-R plot if we can be sure that we are detecting all of the earthquake of a certain size (we call this the completeness of the catalogue). When we have earthquake swarms they also seem to have higher b values and so do volcanic seismic events. Many, many papers have been published on this topic and almost as many explanations voiced. However, high b values (greater than 1) do seem to indicate variable physical properties in the region generating the seismic events (high heterogeneity is how its described). Hydrofracturing microseismicity often seems to have a b-values which are much higher than 1 (sometimes exceeding 2)

http://www.cseg.ca/events/mug/2012/20120228-Goodway.cfm

References

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