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

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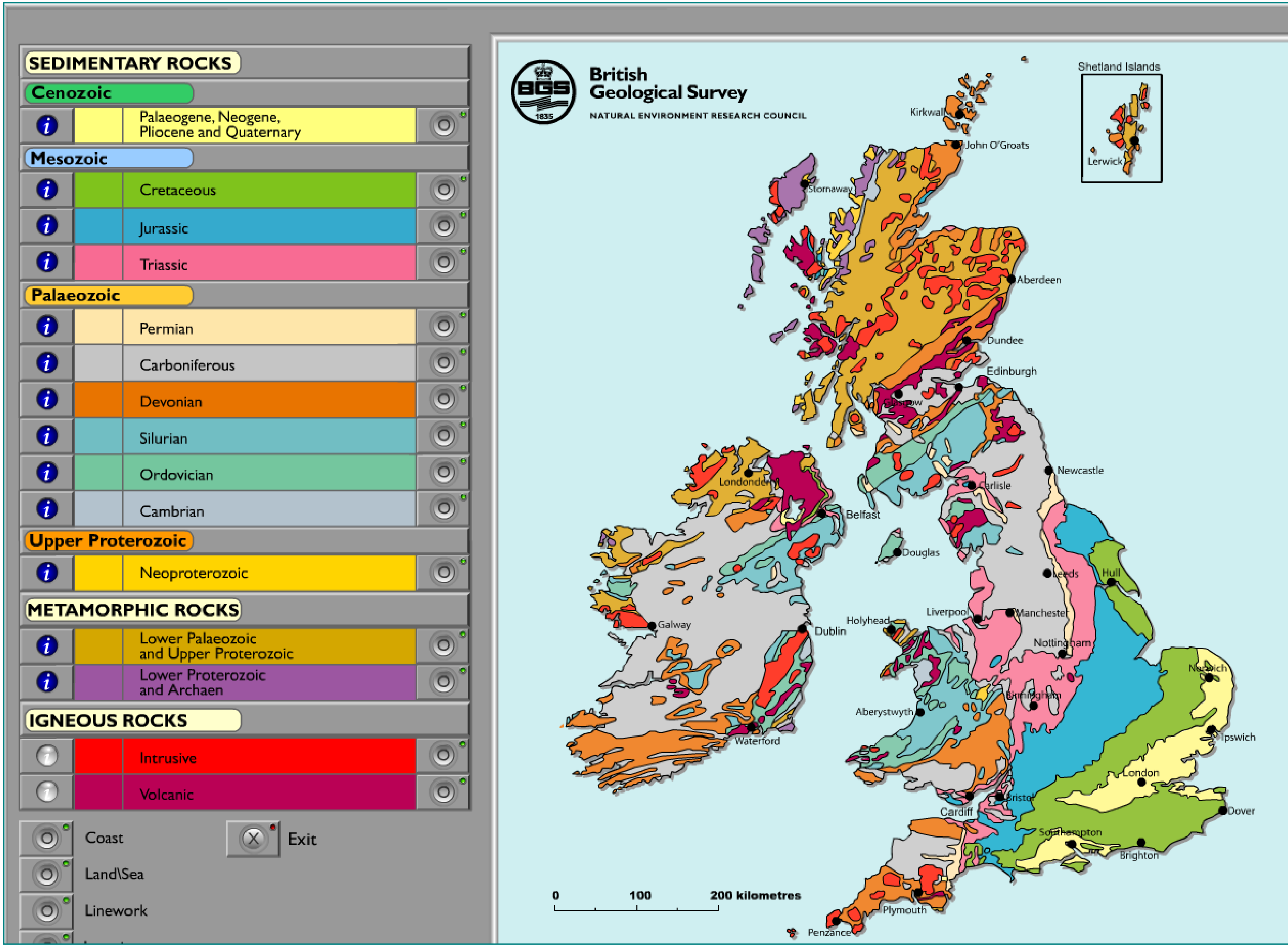
Keele University


SEDIMENTARY ROCKS
Cenozoic
Palaeogene, Neogene, Pliocene and Quaternary
Mesozoic
Cretaceous
Jurassic
Triassic
Palaeozoic
Permian
Carboniferous
Devonian
Silurian
Ordovician
Cambrian
Upper Proterozoic
Neoproterozoic
METAMORPHIC ROCKS
Lower Palaeozoic and Upper Proterozoic
Lower Proterozoic and Archaen
IGNEOUS ROCKS
Intrusive
Volcanic
Coast
Land\Sea
Linework
Exit
BGS
1835
British Geological Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL
Shetland Islands
Lerwick
Kirkwall
John O'Groats
Stornaway
Aberdeen
Dundee
Edinburgh
Newcastle
Carlisle
Belfast
Douglas
Leeds
Hull
Galway
Dublin
Holyhead
Liverpool
Manchester
Nottingham
Birmingham
Aberystwyth
Ipswich
Waterford
London
Cardiff
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Dover
Southampton
Brighton
Plymouth
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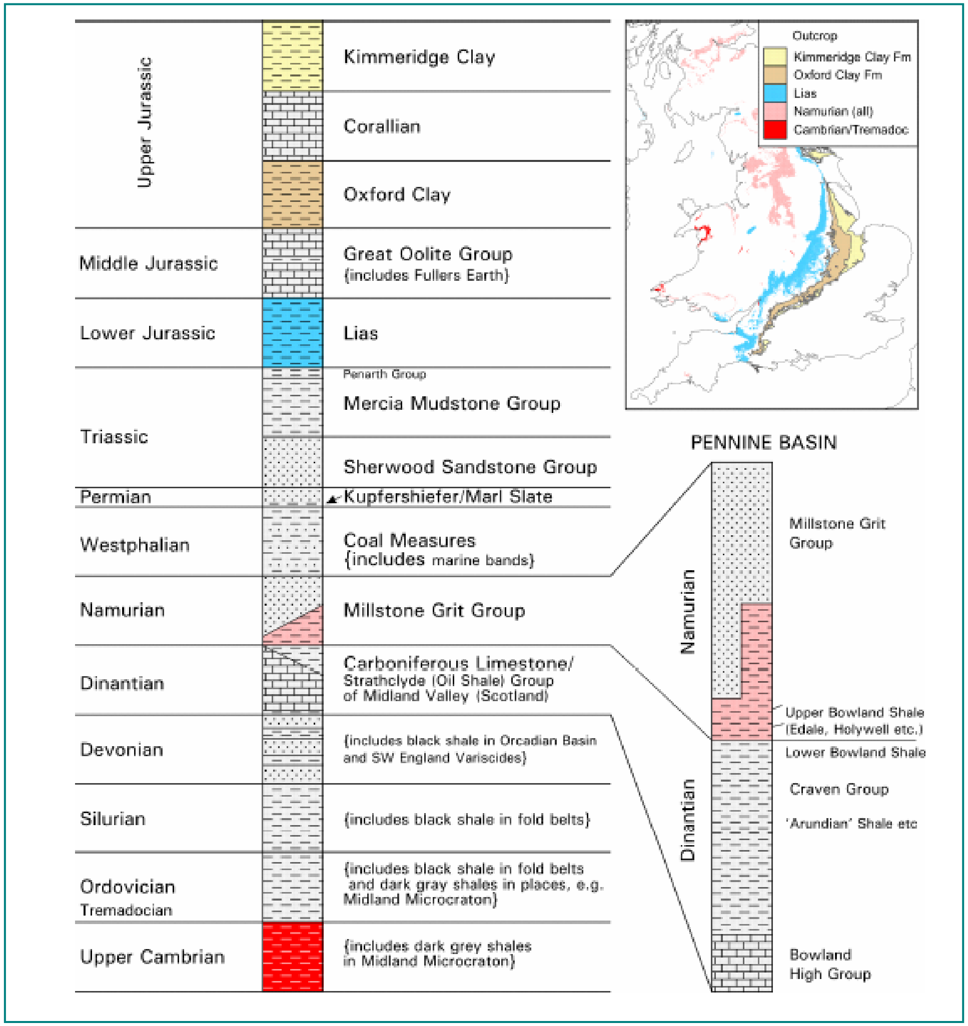
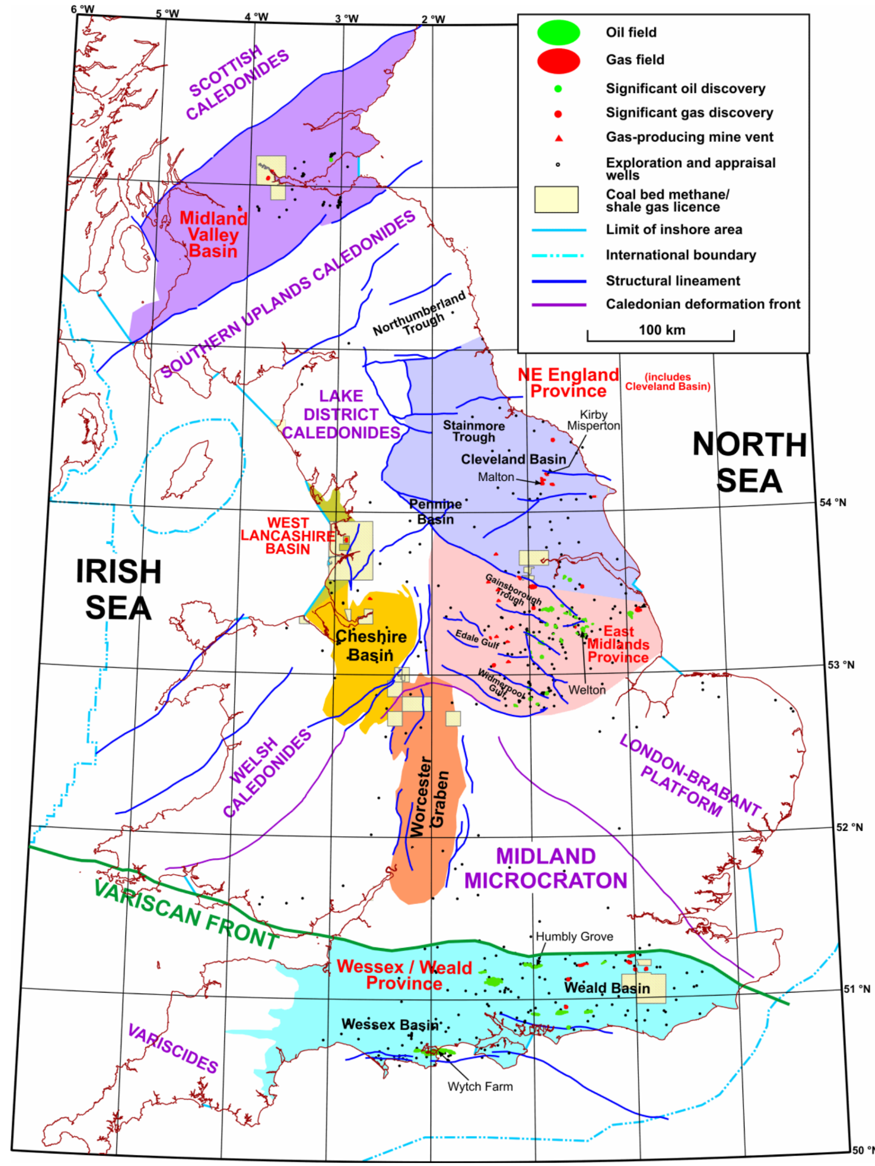
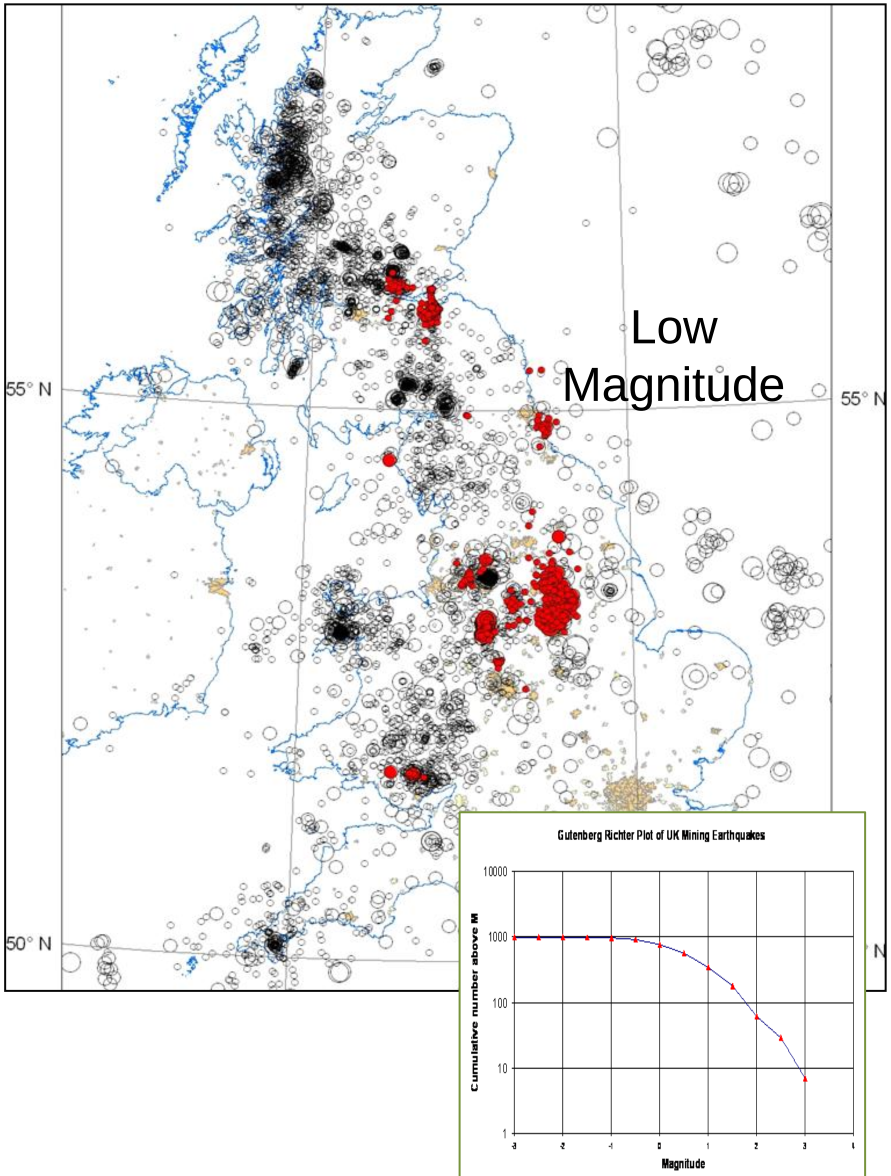
0
100
200 kilometres

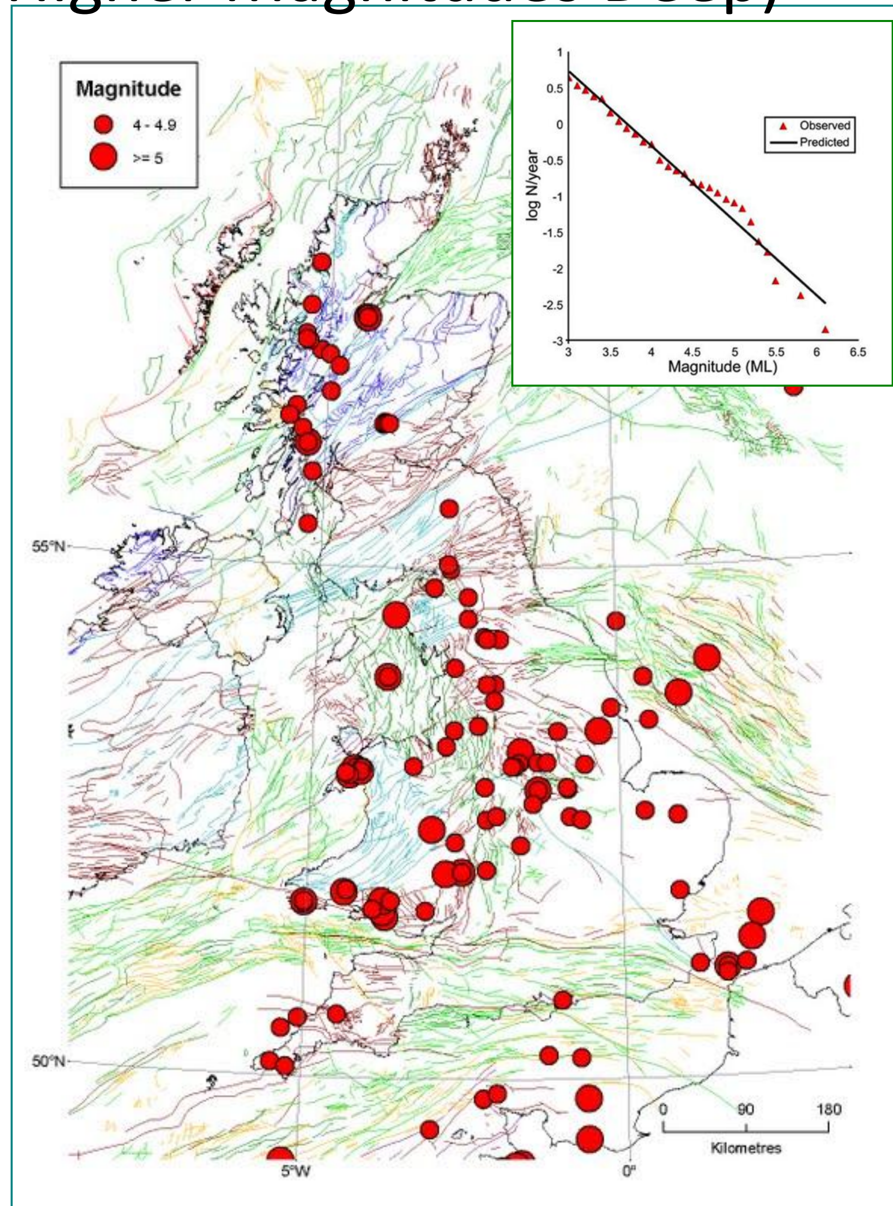
UK Onshore Hydrocarbon Basins



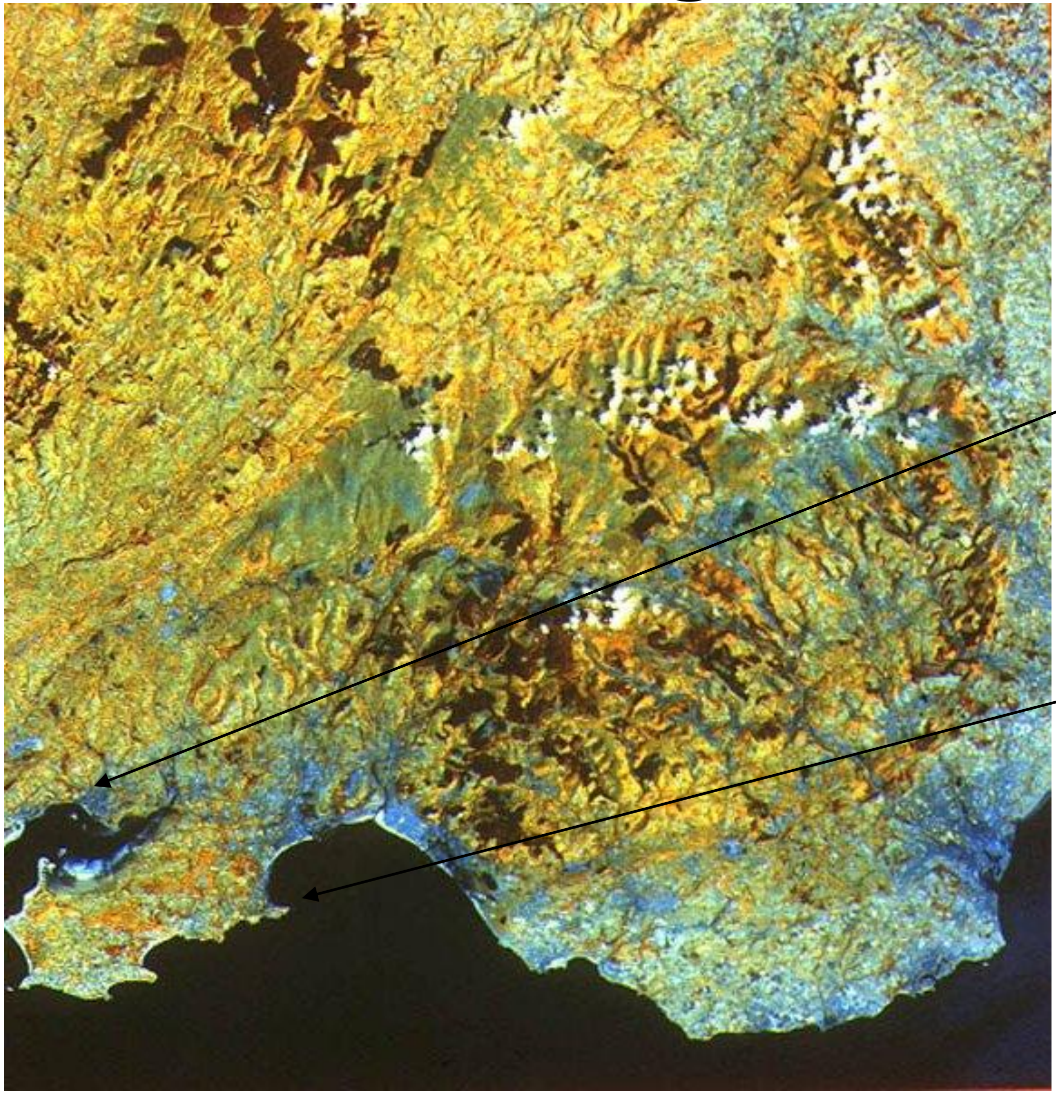


UK Seismic Activity
(Low Magnitude Shallow, Higher Magnitudes Deep)





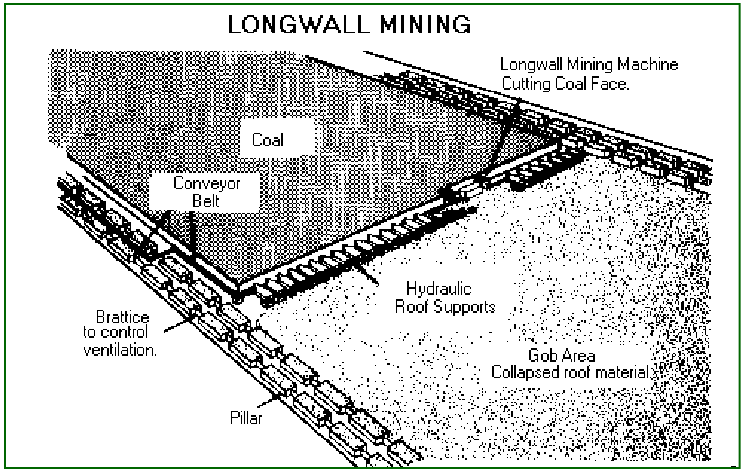
Satellite Image of South Wales

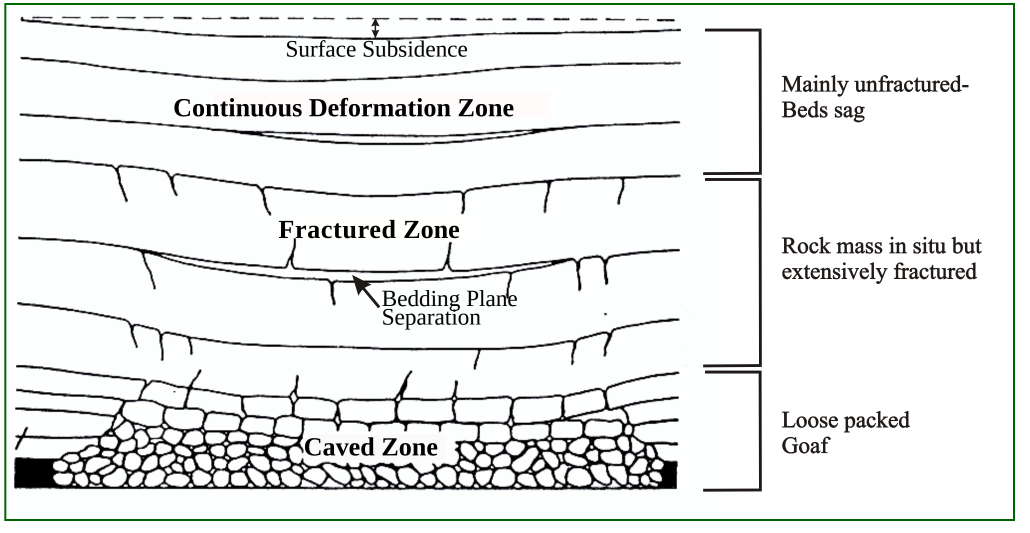


Cynheidre Colliery

Swansea University

Longwall Coal Mining

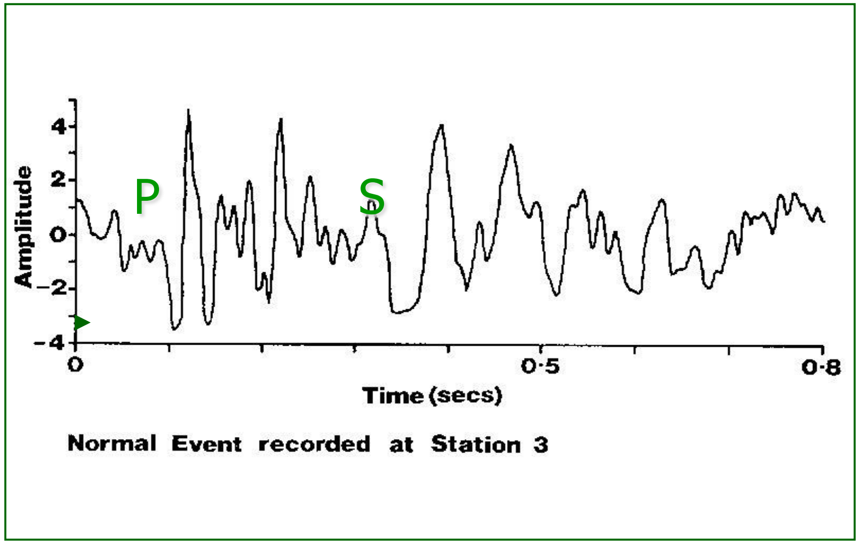




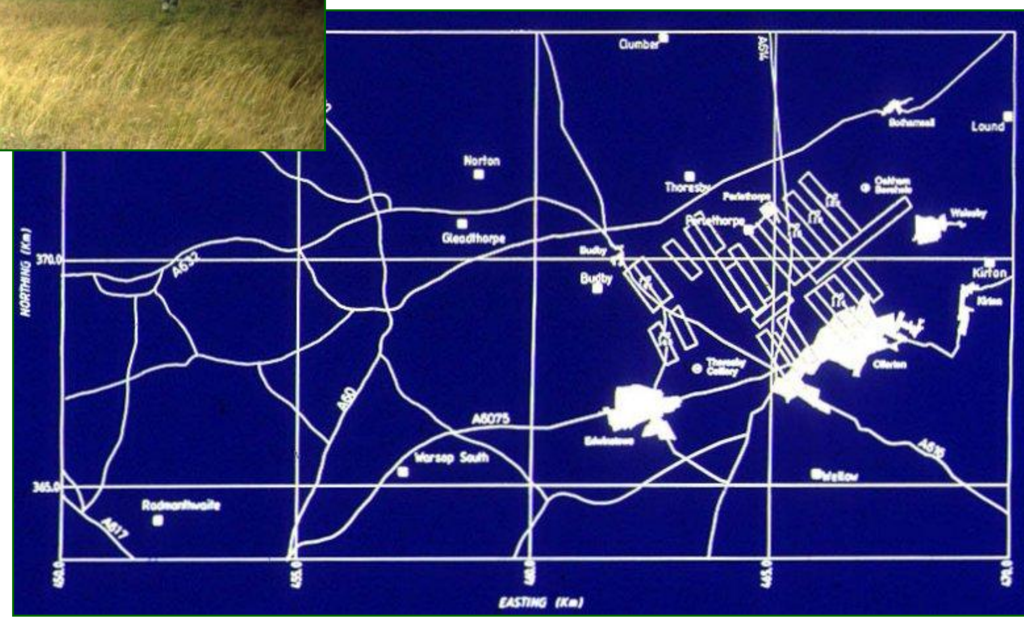
“Normal Mining Seismic Events”

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.

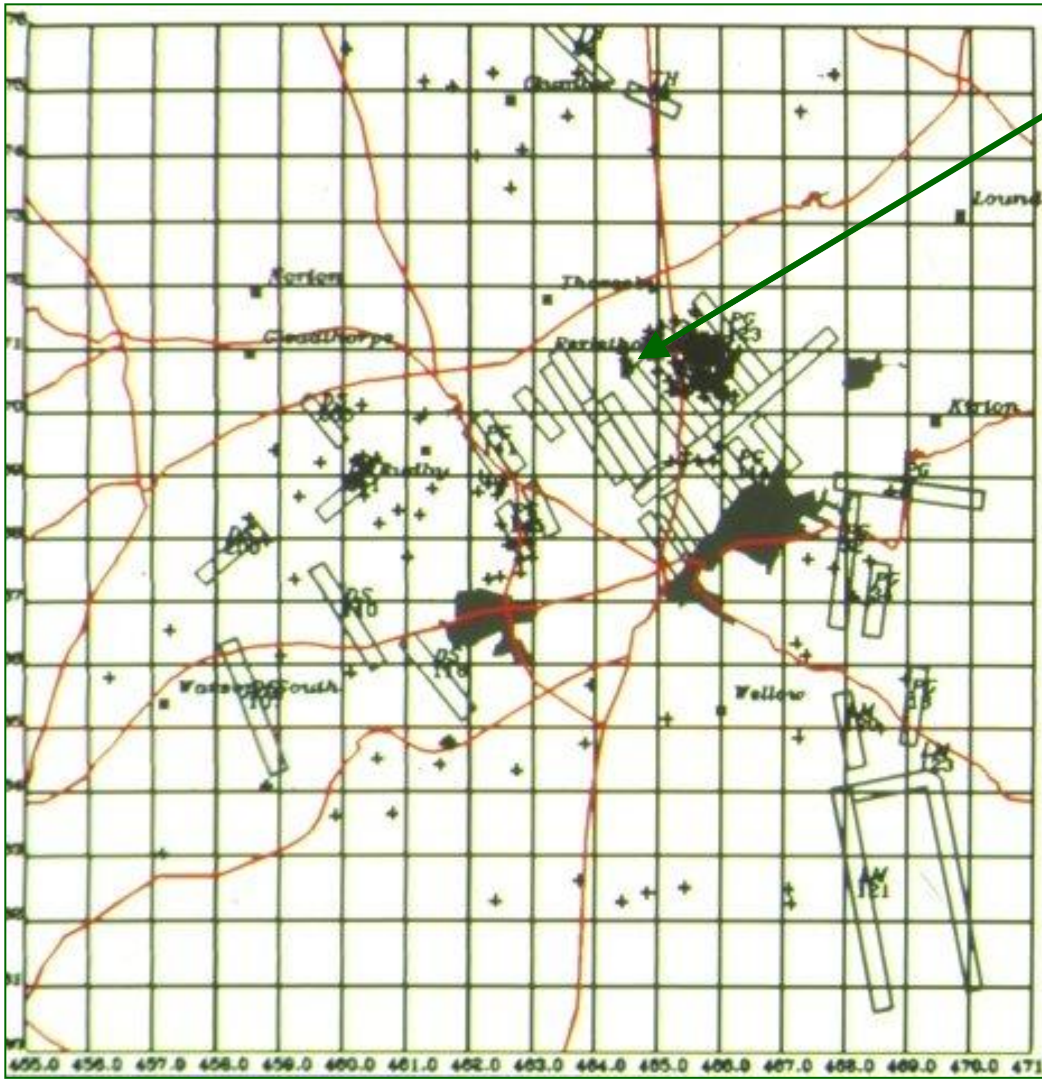
The activity is closely correlated with the rate of coal extraction and we have detected these types of events from all collieries we have monitored in the UK and abroad.

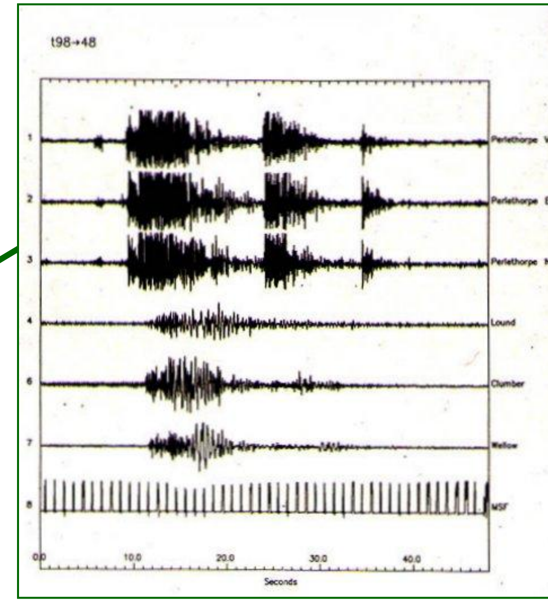


Earthquakes beneath Sherwood Forest:

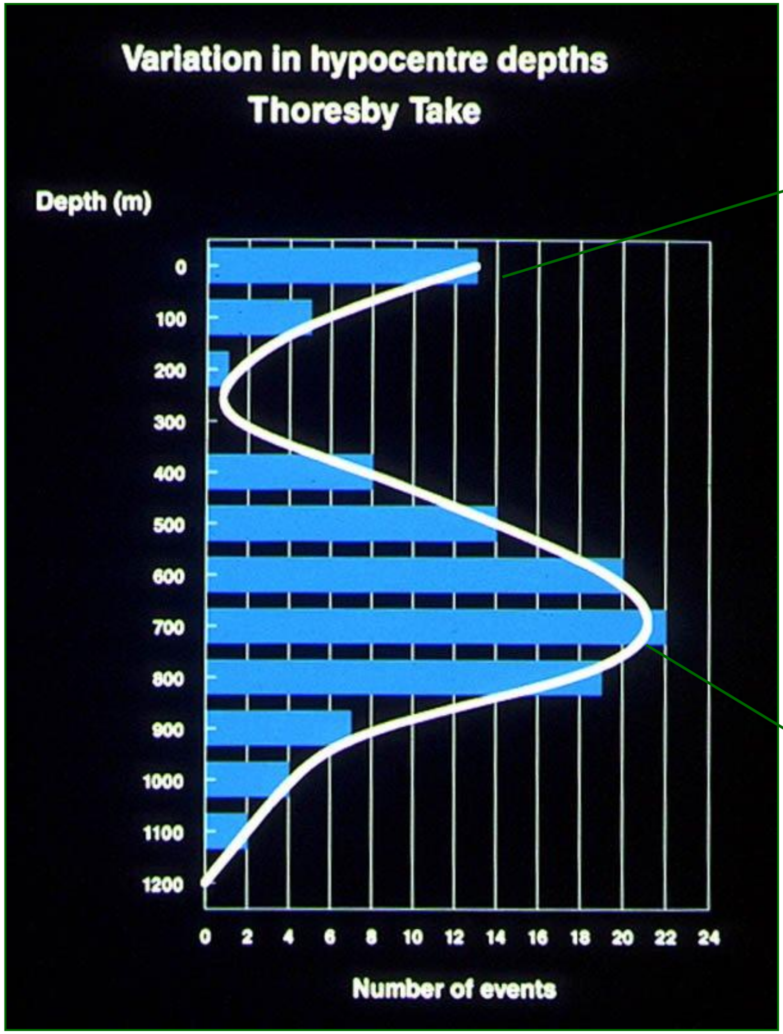


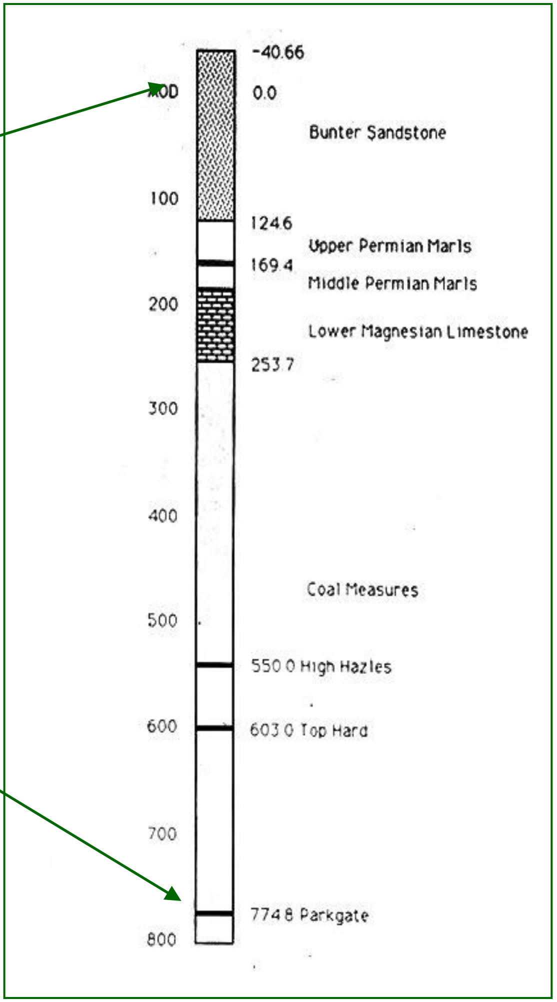
Seismicity Map of Sherwood Forest



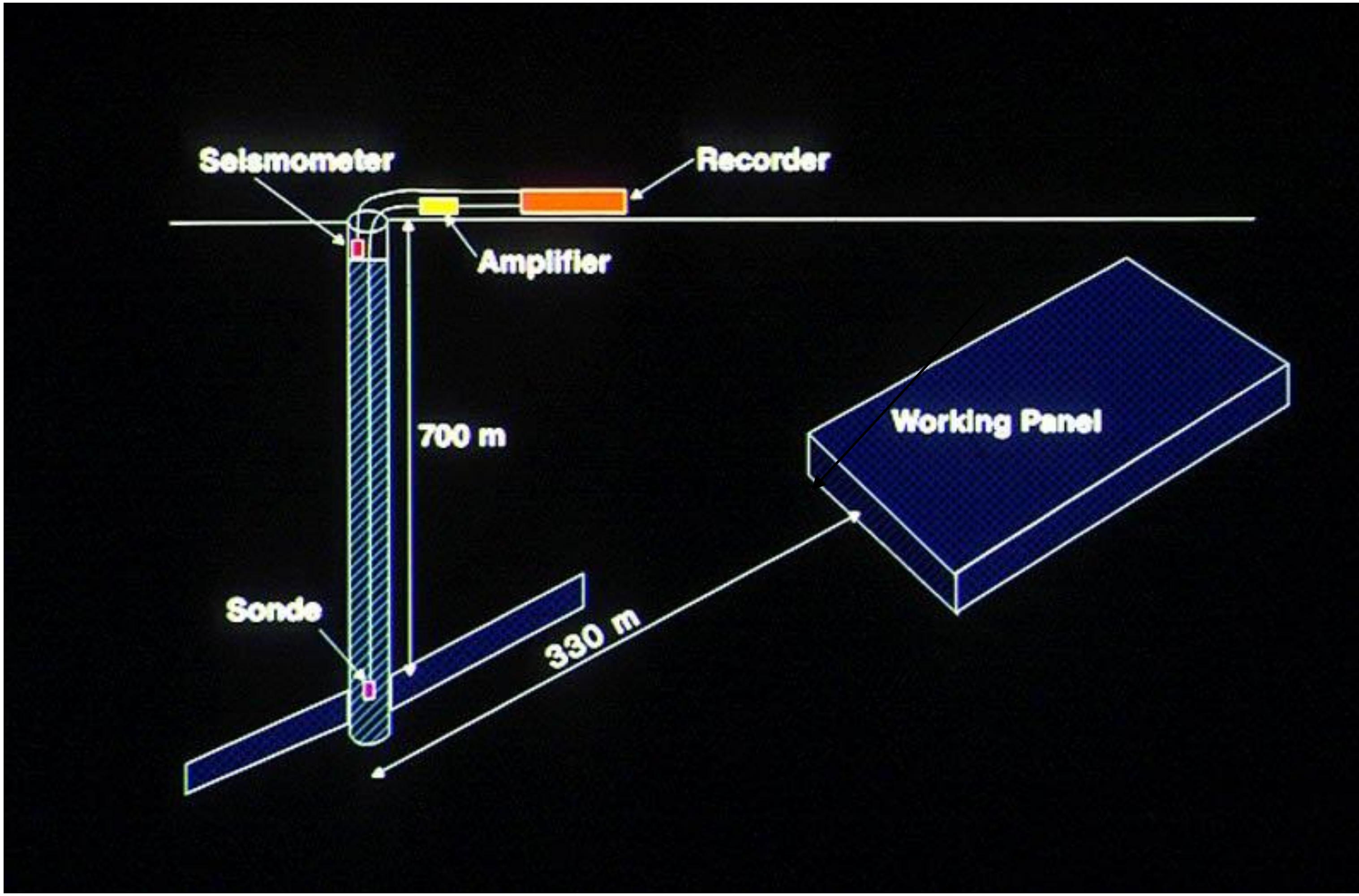


Seismicity as a function of Depth



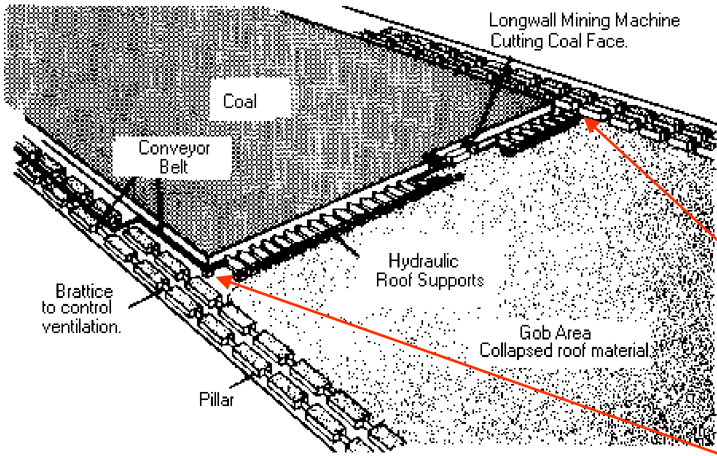


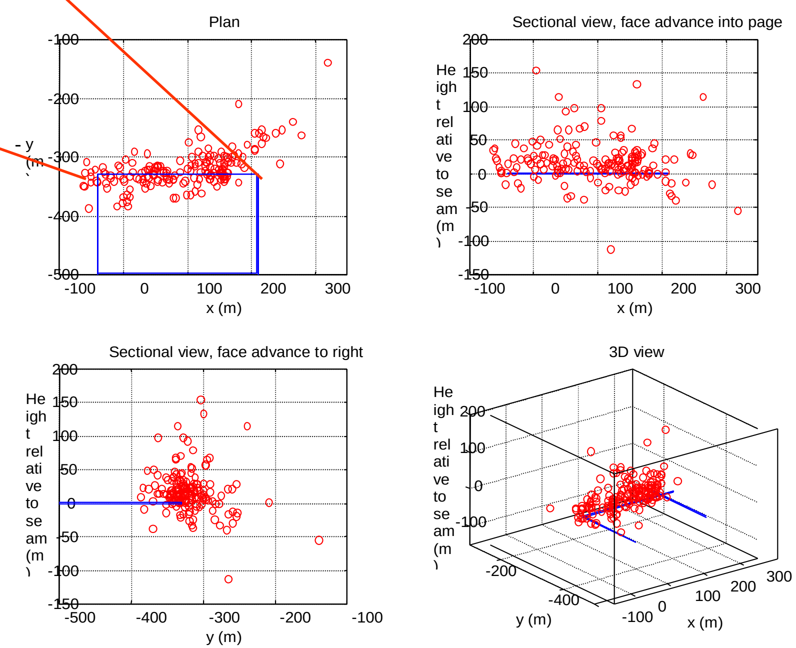
Borehole Microseismic Monitoring

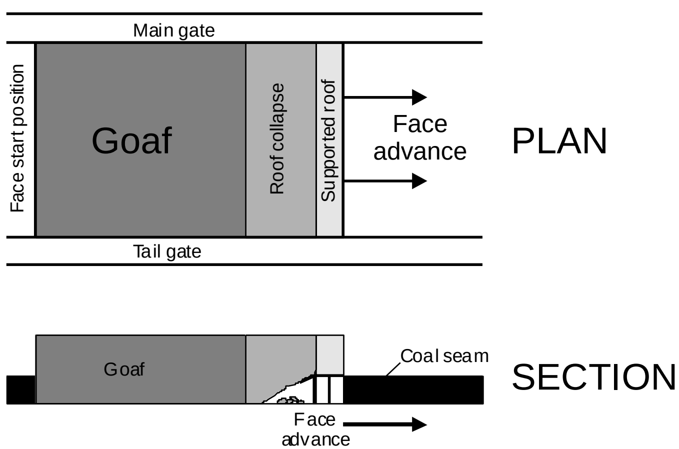


Longwall Coal Mining:typical seismicity

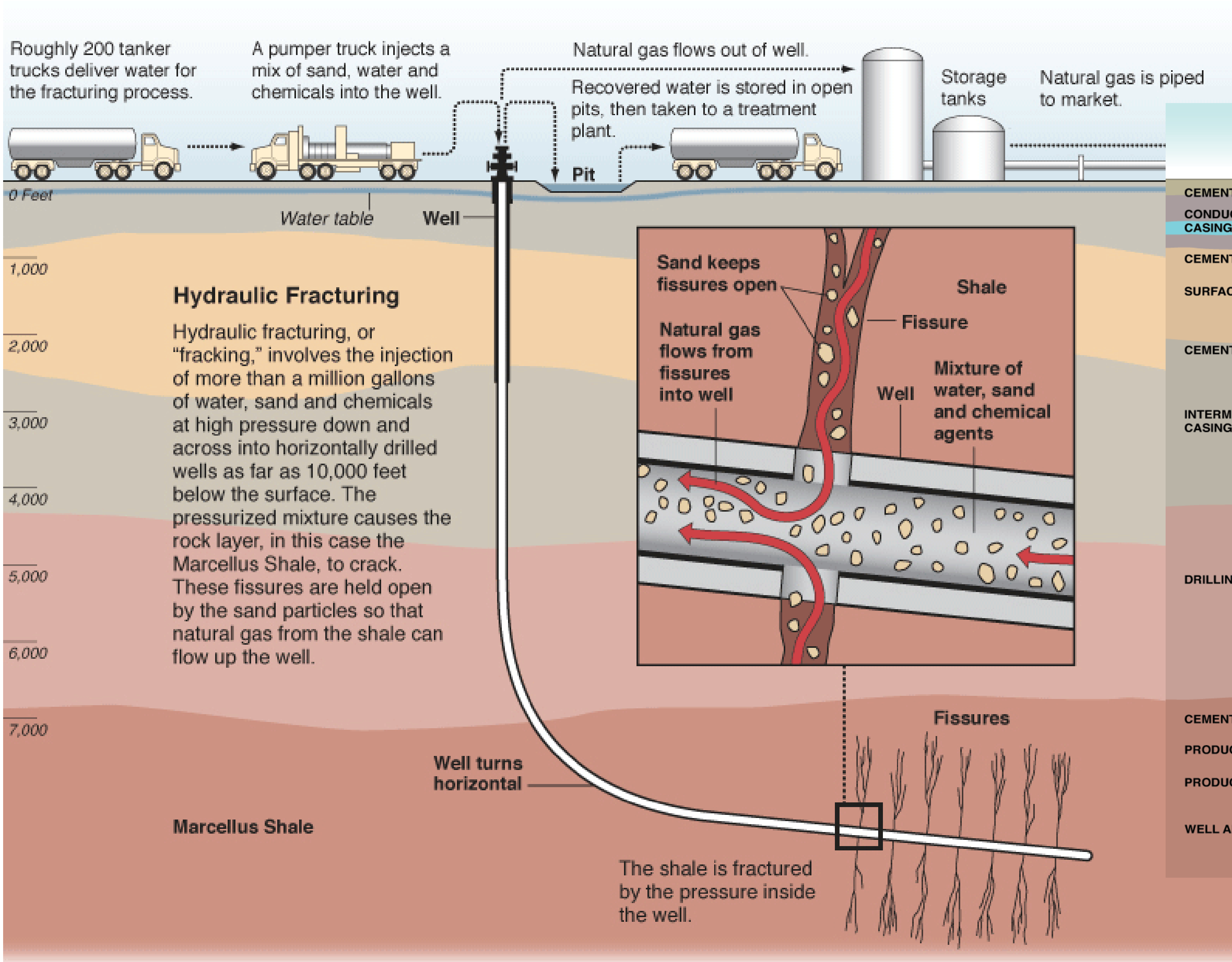
LONGWALL MINING



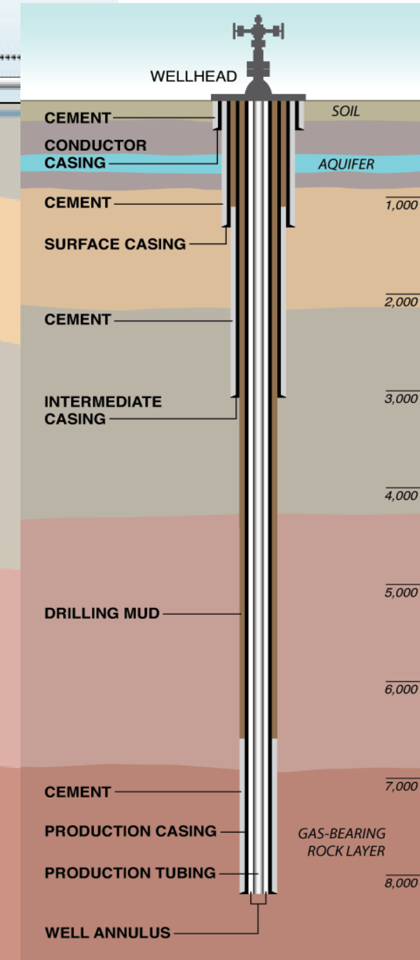




And so to Frac!



Graphic by Al Granberg



Graphic by Al Granberg

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

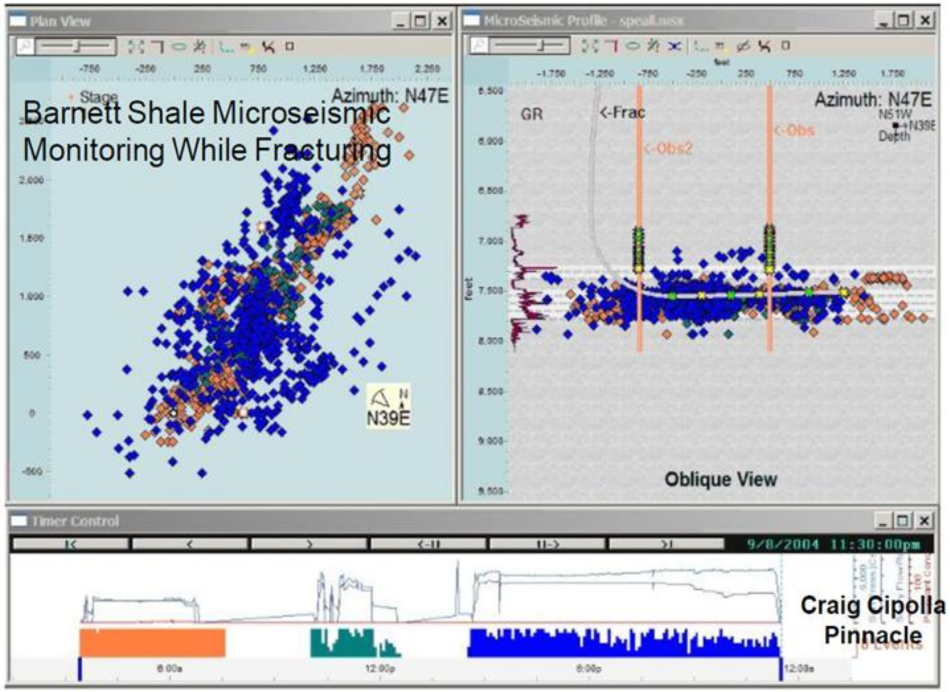
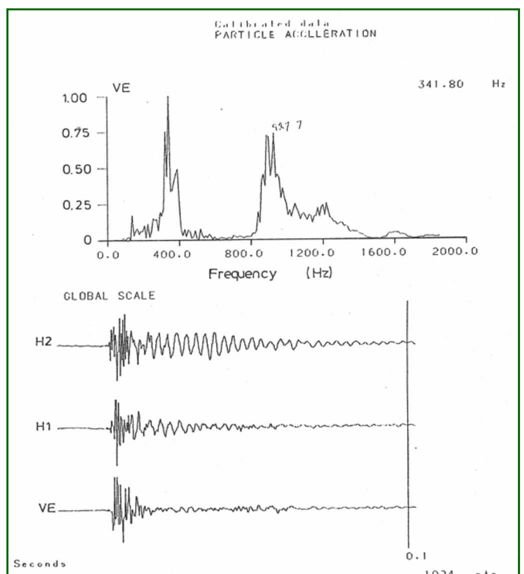


Figure 7: Microseismic Monitoring a Hydraulic Fracture Stimulation, Barnett Shale Gas [7]

Hydrofracturing in the UK

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



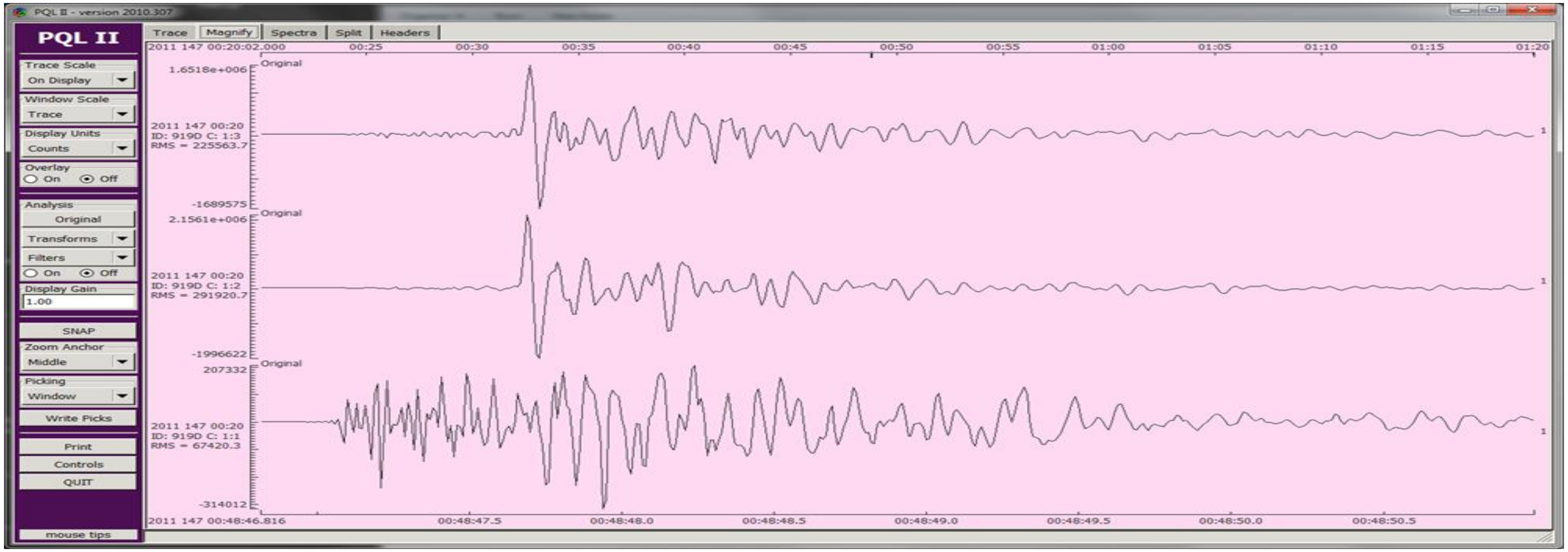
Beckingham, Lincolnshire Hydrofrac Monitored by my (PS) Research Group (while at Liverpool) in ***1988/1989*** with BP!!

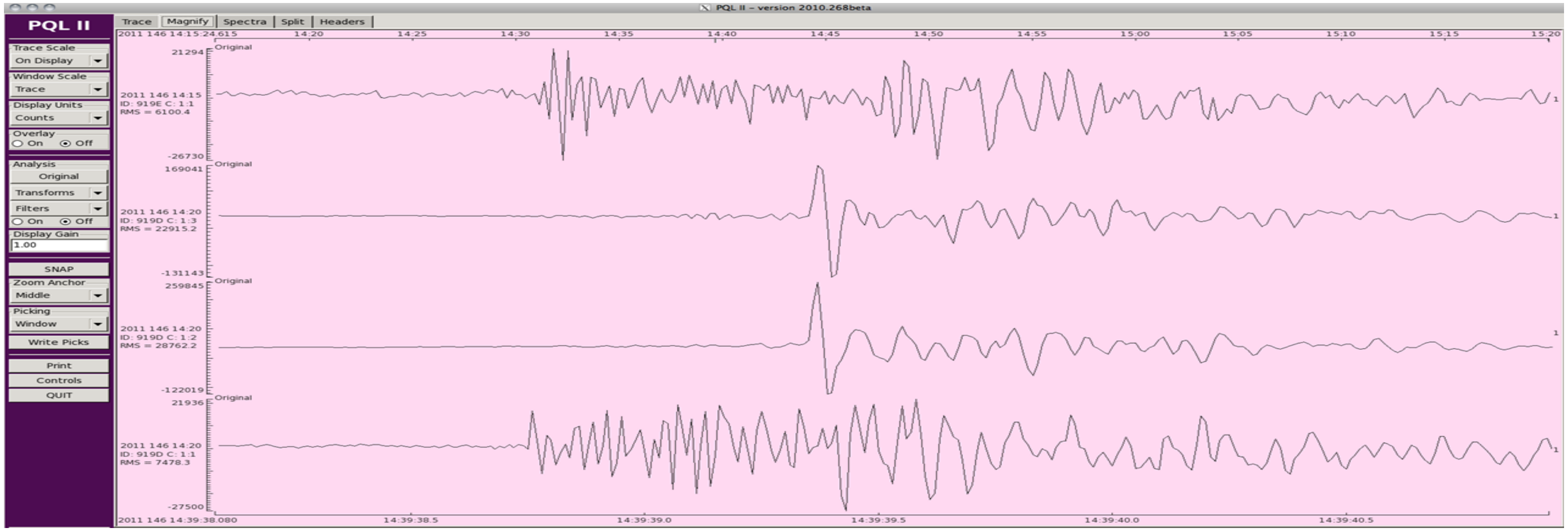
Cuadrilla Preese Hall 1 Borehole

Hydrofracturing Stages and Associated Seismicity at Preese Hall

Stage	Description	Date	Perforations					Slickwater Volume			Proppant	
			Depth			Length	Number					
			Top	Bottom								
			ft MD $_{RKB}$	*ft MD $_{RKB}$*	*ft TVD $_{SS}$*	*ft*		*Gallons US*	*m^3*	*bbls US*	*lbm*	*mton*
1	DFIT	**26 March 2011**	8,841	8,850		9	27	34,314	130	817		
	Job	**28 March 2011**	8,841	8,949	8,730	36	108	485,856	1,839	11,568	226,240	101
2	DFIT	**30 March 2011**	8,700	8,759	8,583	27	81	24,780	94	590		
	Job	**31 March 2011**						593,040	2,245	14,120	262,080	117
		01 April 2011	**Magnitude 2.3 seismic event**									
		04 April 2011	**Deformed casing confirmed with caliper 8480-8640ft MD (just below zone 3)**									
3	DFIT	**08 April 2011**	8,420	8,489	8,340	27	81	10,668	40	254		
	Job	**09 April 2011**						200,634	759	4,777	116,480	52
4	DFIT	**25 May 2011**	8,020	8,259	8,052	27	81	21,084	80	502		
	Job	**26 May 2011**						423,696	1,604	10,088	183,680	82
		27 May 2011	**Magnitude 1.5 seismic event**									
5	DFIT	**27 May 2011**	7,970	7,819	7,823	27	81	11,760	45	280		
	Job	**27 May 2011**						402,780	1,525	9,590	248,640	111
6	DFIT	**31 May 2011**	7,670	7,789	7,666	27	81	10,290	39	245		
TOTALS							**513**	**2,218,902**	**8,399**	**52,831**	**1,037,120**	**463**

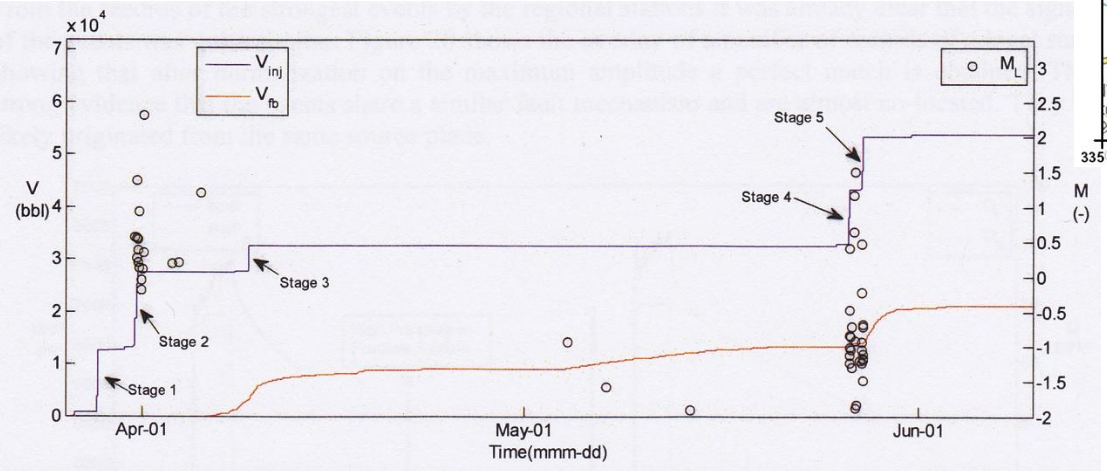
Blackpool Area Earthquakes
Surface GURALP 6TD Broadband, three component Seismometers



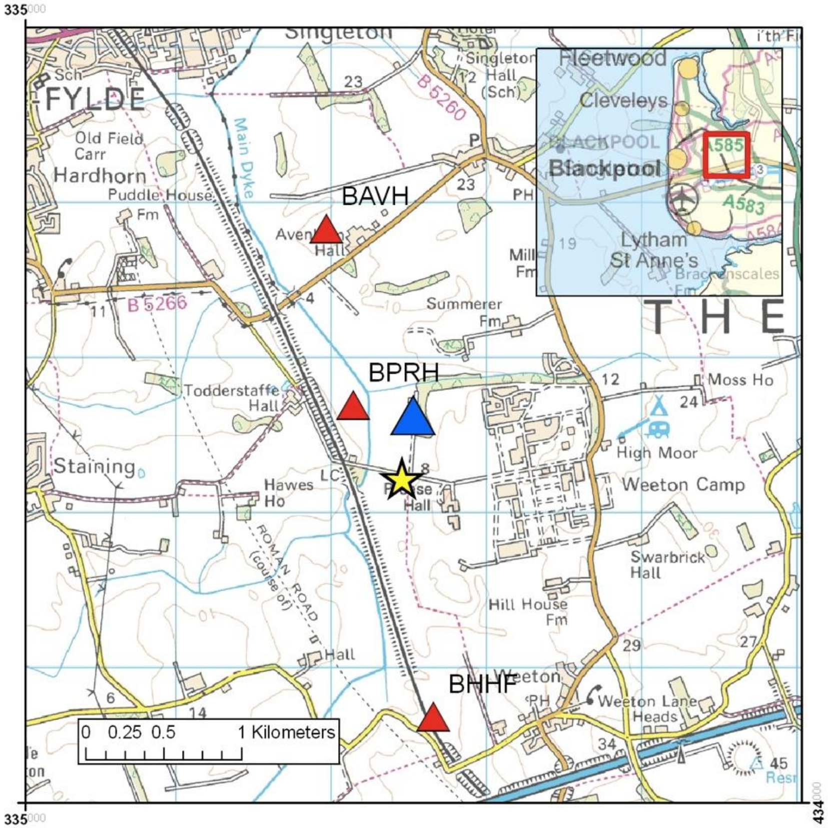


Blackpool Earthquakes

- 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

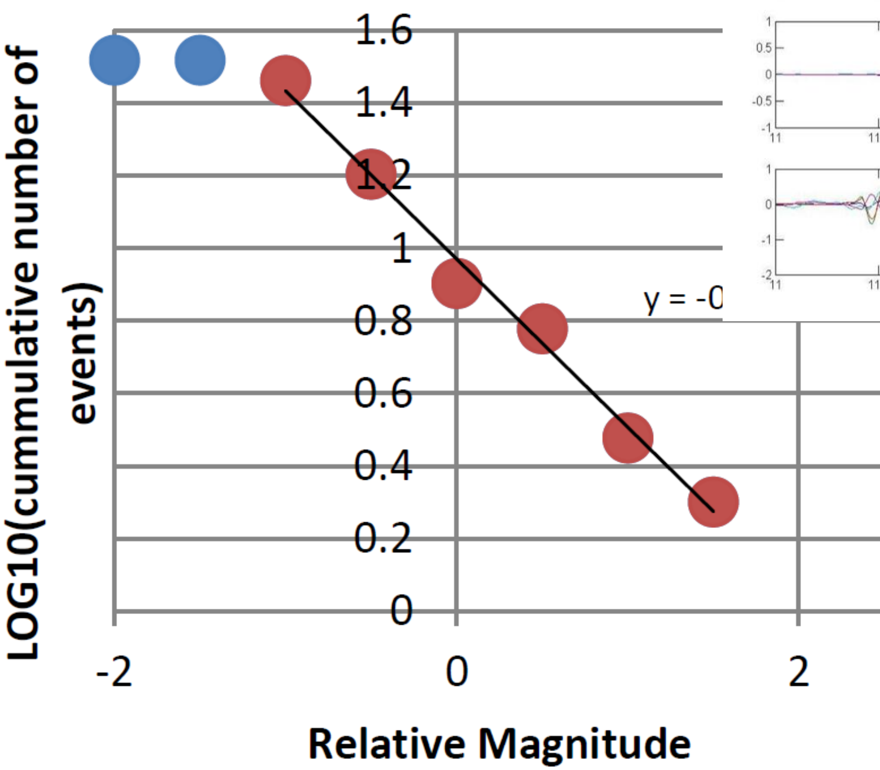


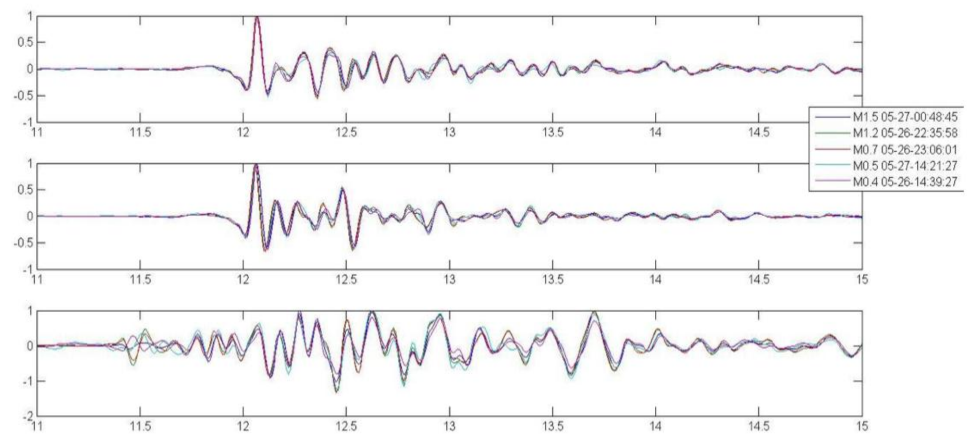
Overview of injection volume and seismicity during treatment stages. Earthquake activity closely correlates with stages 2 and 4. The largest event with 2.3 ML at 02:34 on 1/4/2011 occurred shortly after stage 2.



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?

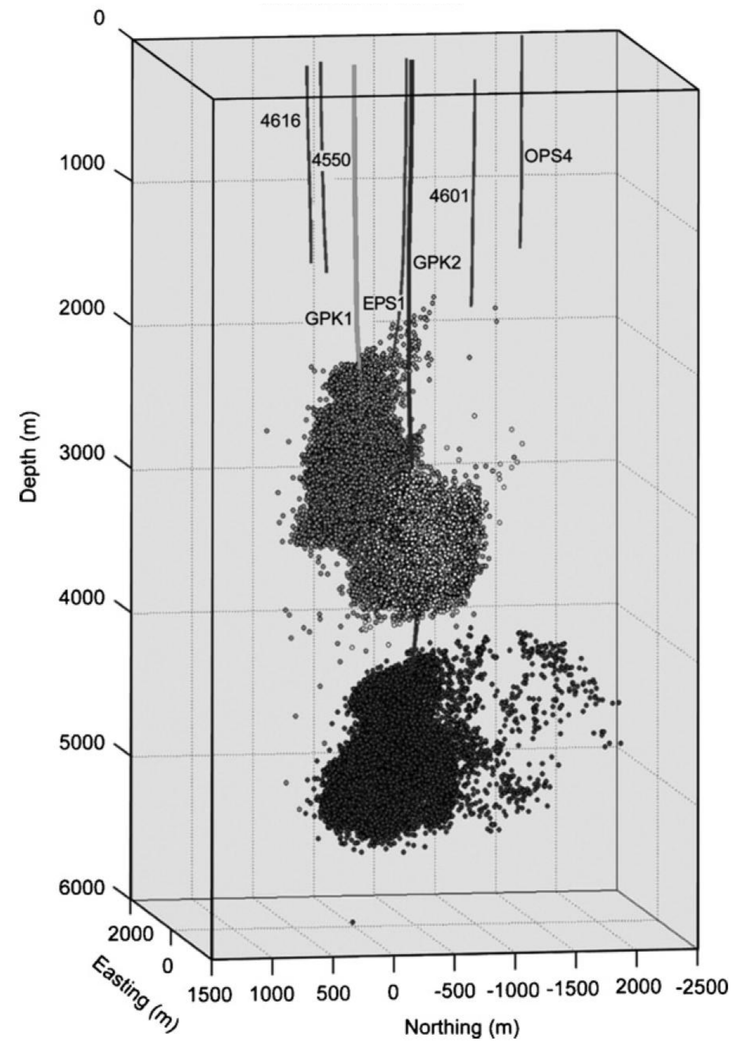
Criterion Davis and Frohlich (1993)	**Blackpool seismicity**
Are these events the first known earthquakes of this character in the region?	Yes
Is there a clear correlation between injection and seismicity?	Yes
Are epicenters near wells (within 5 km)	Yes
Do some earthquakes occur at or near injection depths?	Yes
Are changes in fluid pressures at well bottom sufficient to encourage seismicity?	Probably

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

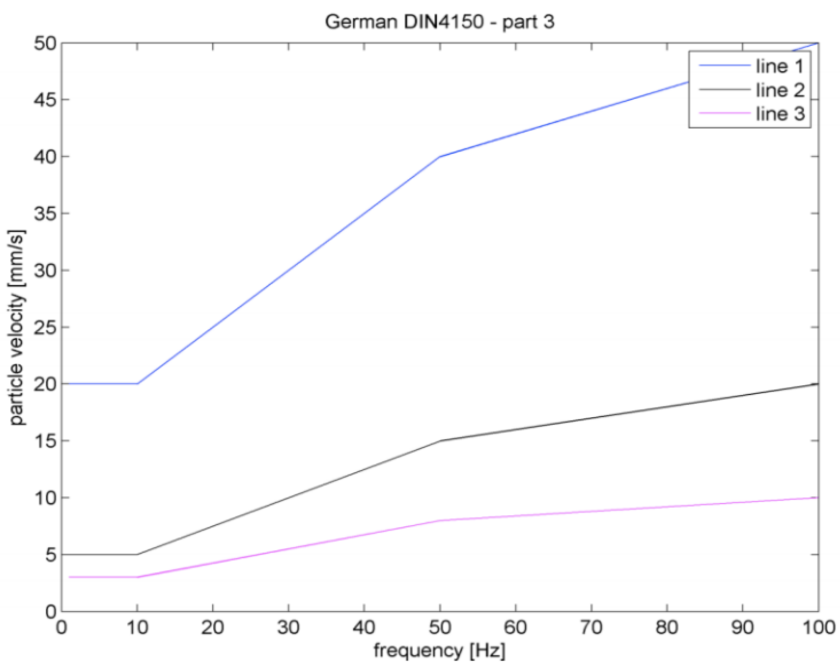
- Tectonic history and the present-day stress regime in the British Isles different.
- Many shale gas plays are in remote locations, with no monitoring.
- Recent evidence (Holland, 2011) suggests that there may be a issue for other reservoirs.
- Seismicity induced by fluid disposal (e.g. Frohlich et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



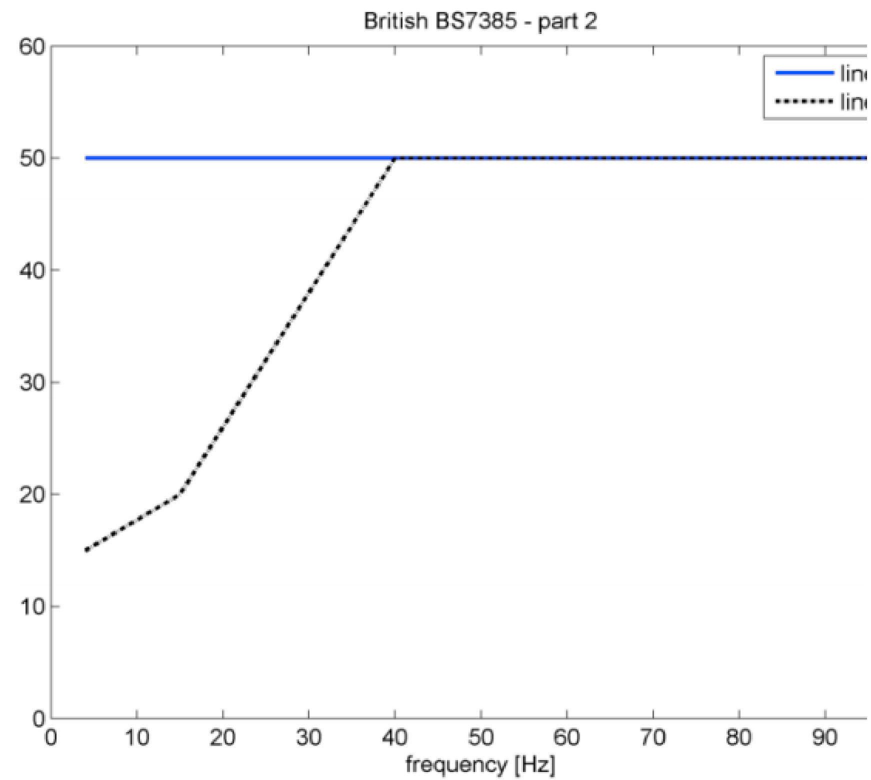
Induced earthquakes with magnitude as large as 3.5 ML are well documented in Enhanced Geothermal Systems (EGS), where the injected volumes may be much larger and the reservoir rocks are much stronger.

Ground Vibration Recommendations

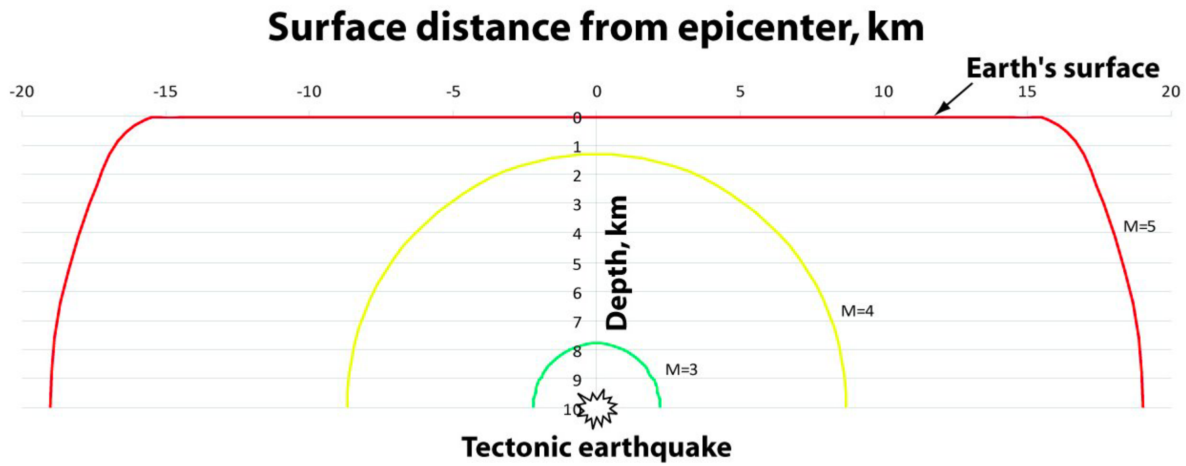
DIN 4150-3 Permissible German Vibration Limits

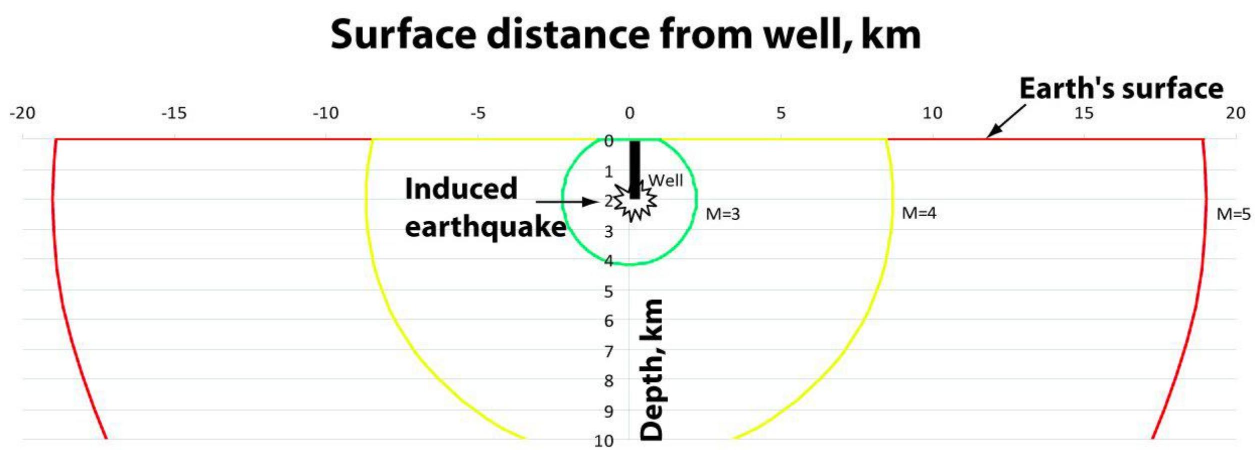


BS 7385 Permissible British Vibration Limits



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 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

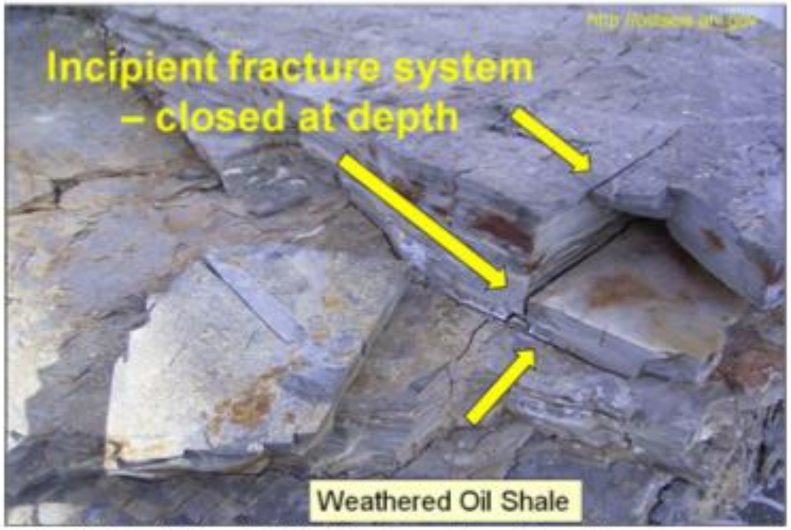
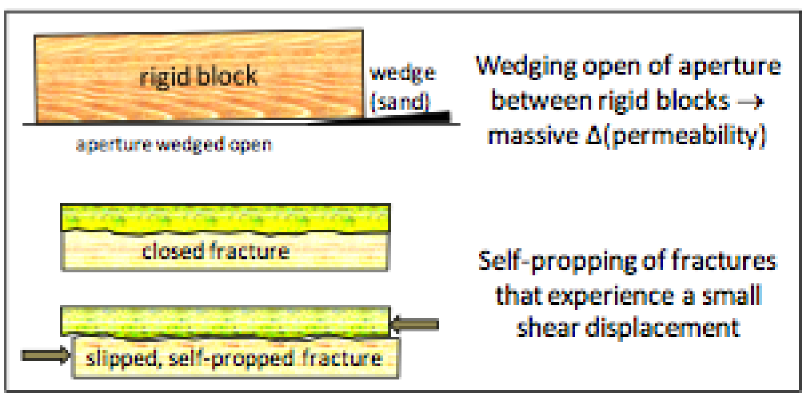


Figure 3: Weathered Colorado Oil Shale in a Quarry Floor. (Most of these fractures are fully closed at depth, but are planes of weakness, and therefore are "incipient" fractures.)

Slickensided and Polished Bedding Surfaces at two levels in the Preese Hall Borehole
Left 8185 Feet MD: Right 6835 Feet MD



"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.

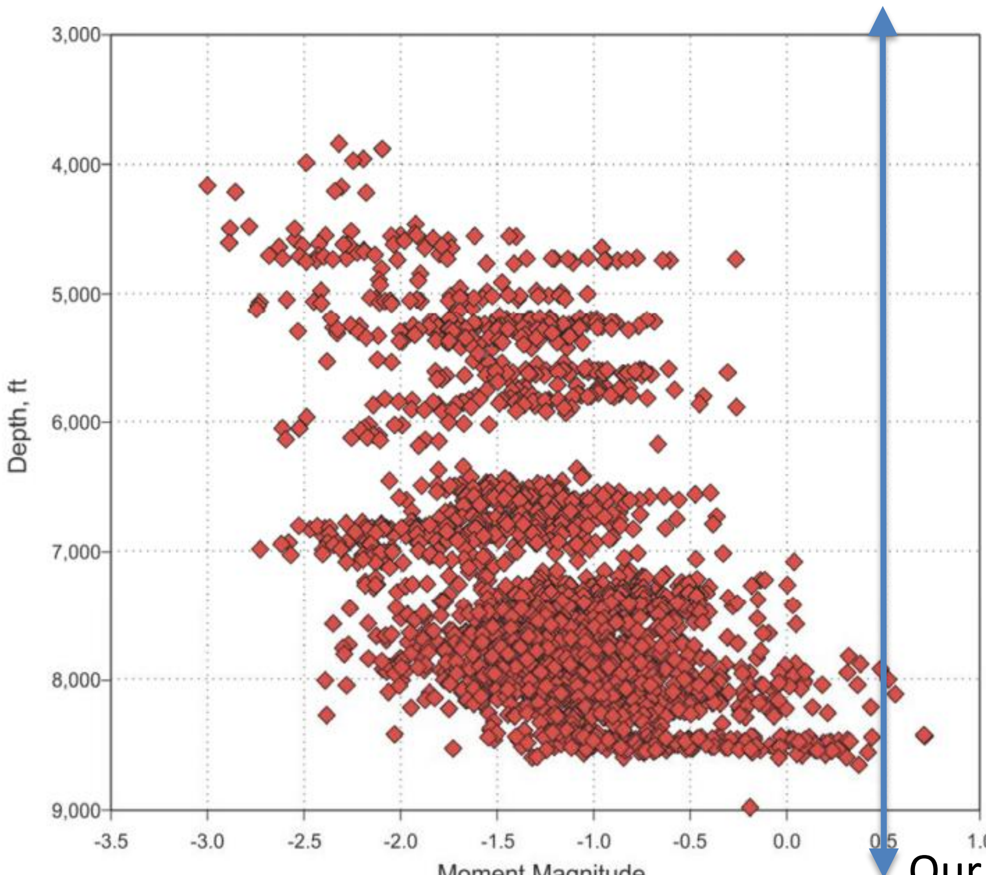
- The potential for upward fluid migration seems overstated, based on microseismic shale gas data from the main US plays. Further analysis in this report seems to indicate that fracture containment was good, with little vertical height growth.

We conclude that an effective mitigation strategy is a necessary pre-requisite for commencing operations and offer our own recommendations, for future operational best practice and monitoring.

Our Recommendations for Mitigation of Hazards (1)

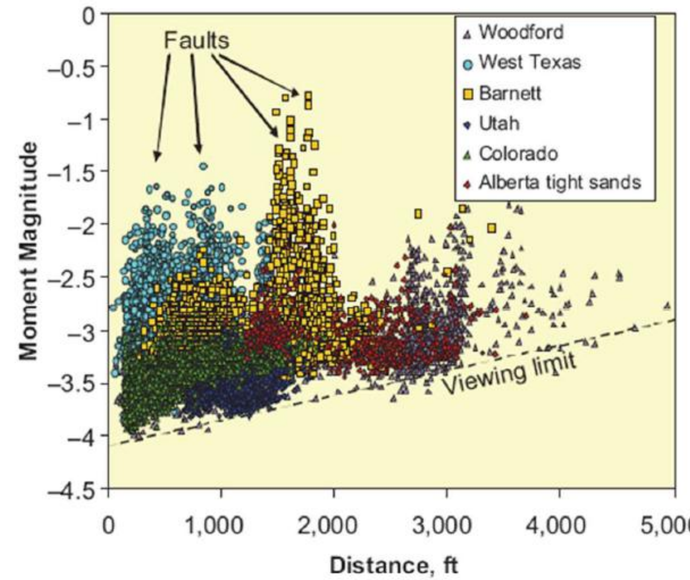
- Hydraulic fracture growth in the reservoir was poorly constrained by the available data from the treatments in April and May 2011.
  - We recommend that detailed analysis of microseismic activity is used to monitor fracture growth in the next hydraulic fracture treatment to better understand the nature 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 sub-surface stress **before, during and after** Hydraulic fracturing

Maximum Magnitudes of events generated from Hydrofracture in the Barnett Shale, US (after Warpinski, 2009 2011)



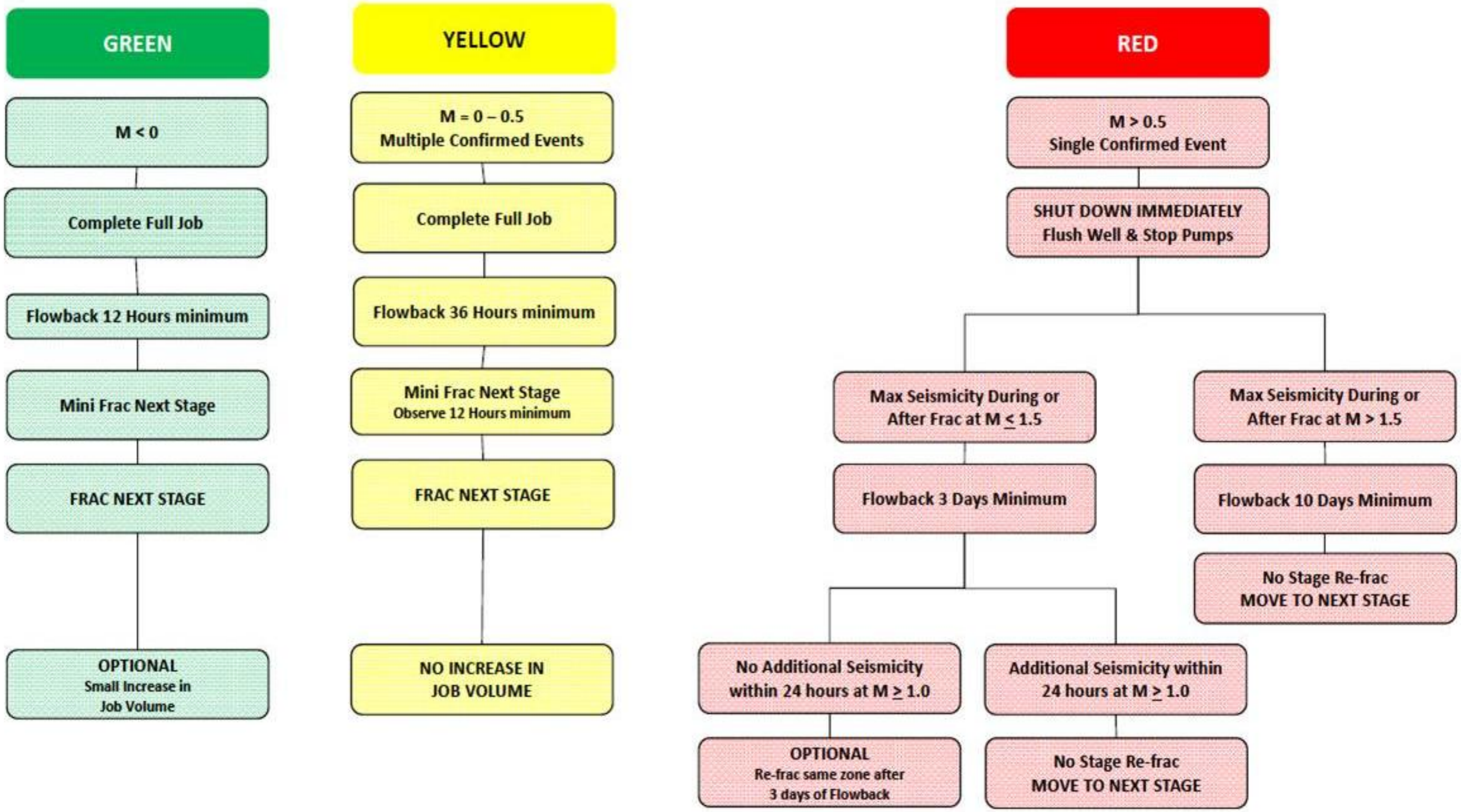
Our Threshold for Action

Fig. 1—Barnett shale maximum moment magnitude results for monitored stages through mid 2011.



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

Proposed Traffic Light System with Thresholds



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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