HYDRAULIC FRACTURING AND SEISMICITY RISKS IN THE UK

THE UNIVERSITY of EDINBURGH

Professor Stuart Haszeldine

School of Geosciences

Edinburgh Climate Change Institute

University of Edinburgh

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Stuart.Haszeldine@ed,ac,uk

Professional Background

1) My name is Professor Stuart Haszeldine. I am a Professor of Geology since 1999 at the University of Edinburgh. My expertise is in sedimentary rocks of the UK, with particular relevance to fossil fuels- coal, oil, gas, and the Transition to de-fossilised energy enabled by a system-wide combination of renewables, carbon capture and storage, fuel switching and nuclear power. This has included studies of sediments onshore and offshore of the UK, and close interaction with academic research relevant to commercial interests in conventional oil and gas exploration and extraction offshore. And in the years since 2010, the attempts to identify and extract shale gas and unconventional hydrocarbons from sedimentary rocks deeply buried beneath the onshore UK. This has resulted in detailed understanding of the geology and the reservoir engineering processes involved in large volume injection of highly pressured aqueous fluids for fracking of Lancashire, exploration for fracking in central Scotland, northern England, and the south and east of England.
2) My work has been widely recognised nationally and internationally. I was invited to be Fellow of the Royal Society of Edinburgh, Awarded Chartered Geologist, awarded the Scottish Science Prize, awarded the international William Smith Medal for applied geology by the Geological Society of London. Awarded the annual Medal of the Energy group of the Geological Society of London. Appointed Order of the British Empire. I am regularly invited as keynote, or research speaker at expert meetings in the UK and internationally. I am currently co-Director of the Edinburgh Climate Change Institute.
3) I have been involved in the study of small earthquakes which have been induced by depressurisation of oil and gas deposits during gas and oil production in Surrey (Horse Hill). I have also been involved in the study of earthquakes induced in Lancashire at Preston New Road and Preece Hall. I have provided expert evidence in a legal planning context to the Cumbria planning inquiry, which recommended against development of a £ multi-billion permanent store for radioactive waste. I provided evidence to Surrey Council on triggering of earthquakes at Horse Hill, closely linked to oil and gas production. And I provided expert evidence to the planning inquiry against development of a new subsea coal mine in west Cumbria.
4) My current focus since 2002 is on studies to define subsurface commercial geological storage of carbon dioxide (CO_2) to mitigate the global heating and climate change effects of fossil fuel

combustion. My research group in University of Edinburgh produced the first comprehensive map and audit of CO_2 storage available to the UK. This profoundly redirected UK Government policy, eventually investing the current £21 billion in Carbon Capture and Storage projects. Associated with my current research focus, I advise Westminster Government DESNZ (Department of Energy and Net Zero) through the CCUS Council. I have also advised UK Government through the Public Accounts Committee, Scottish Government through Net Zero, Energy and Transport Committee, and regular contact with civil servants who advise the Secretary of State (England) and the Cabinet Secretary (Scotland).

Purpose

5) I have been requested by Friends of the Earth to provide a written statement on the seismicity risks associated with hydraulic fracturing for hydrocarbons. The evidence which I have prepared and provide for this statement is true, and wherever possible is backed by public academic or peer reviewed publications. I confirm that the opinions expressed are my true and professional opinions. All views contained within this statement are attributed to me, the author, and do not necessarily reflect those of other institutions with which I am associated.

Hydraulic Fracturing

6) There are multiple processes used by business and industry which inject aqueous fluids into the subsurface. The primary aim of these processes is to improve the flow of fluids around a borehole which can assist, improve, or increase production of hydrocarbons (oil or methane gas). There is inconsistent terminology used nationally in the UK and by the international oil and gas industry, so I provide some short explanations for clarity of communication. Of particular interest are the distinctions between "Fracking", "Associated High Volume Fracturing", "Relevant Hydraulic Fracturing", "proppant squeeze", "acidization", "acid squeeze" "acid matrix" or "acid fracture". A more detailed discussion, and strong argument for a simpler and robust evidence-based definition is provided by Zalucka et al (2021). This is an important study, which may not have been read by regulators or Government. I refer to this study below, and an extract is enclosed with this statement.

Background to fracking and seismicity risks

7) In spite of predictions made by the British Geological Survey, that many Carboniferous and Jurassic mudrocks (shales) of the UK onshore are thermally mature and should produce abundant hydrocarbons, no commercial production has been found viable in the UK by using

fracking. In each of the three sites drilled for investigation by Cuadrilla at Preese Hall and Preston New Road, no net oil or gas was produced, and each of the three boreholes triggered earthquakes (induced seismicity) as a direct result of fracking; tremors were felt by residents at the surface across a 28km diameter. Several methods were attempted by the developer to eliminate these small earthquakes, but no method could predict their timing or location, which culminated in a 2.9M_L event. The Conservative government at the time instigated a moratorium on continued fracking in the UK, because fracking-related earthquakes remained unpredictable and increasing in energy.

8) The type of drilling that took place in Lancashire, drilling into the source rock and shale followed by very high volume and high pressure injection of fracking fluid around the new borehole, imposes extreme pressures on the reservoir rock, which is why the rock breaks to form new fractures[1]. The fluid pressure pre-existing before drilling can be generally predicted at many locations around the UK, and usually increases with depth. But the increased fluid pressure, from the natural pressure at the surface, to the pressure which fractures the rock, is much less predictable. That pre-existing pressure depends on multiple geological factors such as sediment type, ability to release porewater, and geological burial and uplift history. These differing and regionally variable geological histories mean that a vertical sequence of sediments in locality A, can end up with a very different burial and uplift history from the same sequence of sediments at Locality B. To fracture the rock, the pressure of fluid being pumped into the rock porespace needs to exceed the “Fracture pressure” at which the physical fabric of the rock fails. And/or the imposed physical stress on the rock needs to become larger than the failure strength – usually conceptualised as the minimum compressive strength of the rock – measured in a horizontal compass direction X or Y, or depth vertically Z.

9) In practical terms there are very few direct measurements in the UK of the compressive strength quantity or direction, so that is often discovered for the first time during measurements at a detailed site investigation. Inevitably that direction of minimum compressive strength depends on the geological burial history, followed by emergence uplift and erosion of sediments overlying a site and varies in compass direction and in magnitude at different sites – e.g. A compared to B referred to earlier. It is very well understood that fractures

[1] It also involved some lower volume fluid injections; see below.

and faults can be triggered by human activities which change the fluid pressure in a rock porespace (Foulger et al 2017) and there are many examples worldwide. In each case the site-specific direction of the newly triggered fault is determined by the direction of net compressive stress at that site, and the timing and location of triggering is controlled by the buildup of extra pore-fluid pressure on the weakest fracture surface or fault plane. Imposing a large and rapid increase in pore pressure by injecting fracking fluid can therefore trigger a small earthquake tremor when the critical pore pressure is exceeded, and the direction of a new fracture or fault is controlled by stress direction. Thus, injection of fracking fluid can trigger earthquakes by releasing the prior buildup of fluid pressure and the rock compression.

Current UK legal and planning definitions

10) The definition of fracking and the variants of fracking change with the definition of different types of borehole treatment, acidisation and the variants on those variants. The definitions are complex and contradictory in detail. The definition of hydraulic fracturing in National Planning Policy Guidance is as follows (NPPG 6 March 2014 Annex A):

"*Hydraulic fracturing is the process of opening and/or extending existing narrow fractures or creating new ones (fractures are typically hairline in width) in gas or oil-bearing rock, which allows gas or oil to flow into wellbores to be captured"*

11) This makes no distinction based on volume of fluid. However, under the Petroleum Act 1998 section 4B[2], "high volume fracking", named by the UK as Associated Hydraulic Fracturing, is defined by volume:

"Associated hydraulic fracturing" means hydraulic fracturing of shale or strata encased in shale which

(A) is carried out in connection with the use of the relevant well to search or bore for or get petroleum, and

(B) involves, or is expected to involve, the injection of

(bi) more than 1,000 cubic metres of fluid at each stage, or expected stage, of the hydraulic fracturing, or

(bii) more than 10,000 cubic metres of fluid in total."

[2] Which was inserted via section 50 of the Infrastructure Act 2015

12) This definition is not wide enough to include the acid squeeze, or “Low Volume” Fracturing of less than 1,000m3 for each stage which is currently being proposed at several UK sites for onshore. That is in spite of the very clear link on borehole fracking records in Preese Hall and Preston New Road from the short time between injecting pressurised fracking fluid at volumes much less than the 1,000 metres cubed fracking fluid volume, and the triggering of felt earthquakes as a trailing tail for several hours. That gap in legislation and definition was commented by Smythe and Haszeldine (2017[3]) but no action was taken by Government.

13) The cause and effect of High volume and Low volume injections of fracking fluids are scientifically similar – both impose very high fluid pressures which result in new fractures being formed in rock reservoir or a sealing shale. Judging by the statements from some government ministers, it seems they consider that fluid volumes used are a useful discriminator between triggering earthquakes and not triggering earthquakes. The closely measured data from Preese Hall and Preston New Road in the UK (see below) show that fluid volumes do not, however, provide a reliable indicator of earthquake triggering size, or timing.

14) Examined below (Fig 1, Table 1) is measured data from the Cuadrilla boreholes in Preston New Road and Preese Hall in the UK showing that numerous earthquakes (including earthquakes felt by the public at the land surface overlying fracking) are directly triggered by fracking using fluid volumes much less than 1000 metres cubed. As I discuss below, it is very clear that high volume fluid injection can trigger earthquakes. But it is also clear that risk of seismicity cannot be ruled out through the use of “low” volume fluid injection (see below**)** [4]**.** The volumetric definition of high fluid volume fracking as at least 1000 metres cubed for each fracking stage and 10,000 metres cubed for an entire borehole is arbitrary when compared with legislation from other countries (Zalucka et al 2021[5]). The description "each" fracking stage means that just one fracking stage can be 900 metres cubed of fracking fluid and the entire well is no longer classified as "Associated Hydraulic Fracturing". The choice of 1,000 and 10,000 cubic

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[3] Smythe D. and Haszeldine S. 2017. Could fracking creep under the radar? Nature 393, 548. https://www.nature.com/articles/548393a.pdf?origin=ppub

[4] Ban on low volume fracking looks unlikely – DRILL OR DROP? In response to concerns expressed by Alison Hume MP that low volume fracking carries seismicity risks, The Minster for Energy Security and Net Zero stated in December 2025 “*the evidence base is not there at the moment, to suggest that low volume hydraulic fracturing activities have the same associated risks as fracking for shale gas”*

[5] Zaluka A, Goodenough A, Smythe DK (2021) Acid stimulation: fracking by stealth. Energy Policy 153, https://doi.org/10.1016/j.enpol.2021.112244

metre thresholds are unusually large and based on a 2012 consultancy report for the EC which was based on incomplete preliminary evidence AEA Technology plc 2012[6].

15) Based on the Zalucka study (2021; extract enclosed), Associated Hydraulic Fracturing could be defined as **"All well stimulation treatments of oil and gas wells which increase the permeability of the target rock to higher than 0.1 milli Darcies beyond a 1m radius from the borehole".** This would, in my view, simplify things considerably, and avoid the confusion that there is currently. I will now consider high volume hydraulic fracturing, proppant squeeze, matrix acidisation and fracture acidisation in turn, and the evidence base for induced seismicity in each.

High Volume hydraulic fracturing

16) High volume hydraulic fracturing for hydrocarbons is a process by which very large volumes of water are injected into a borehole at depths typically of 1 to 4km. The fluid contains additives to decrease chemical reactivity and to physically prop open fractures generated. The fluid is pressurised at the surface, sufficient to break apart bedrock at depth. This is the typical method of "Fracking" in the USA, and successfully forms networks of fractures and fluid flow to produce oil and methane gas from mudrocks where the hydrocarbons are generated, but have remained trapped in low permeability (low flow rate) rocks for geological timespans. This is the type of fracking which was used in Lancashire by Cuadrilla during 2011, 2018, 2019 (although, as I set out below, lower volumes of fluid were also used as part of these operations). Where the combination of site-specific fluid pressure and rock stress exists, fracking can induce earthquakes.

17) Key points to note on high volume fracking are:

- The extreme pressures used;
- The addition of large water volumes and proppant particles
- pumped into the subsurface;

[6] AEA Technology plc 2012. Support to the identification of potential risks for the environment and human health arising from hydrocarbons operations involving hydraulic fracturing in Europe before fracking had become fully investigated in Europe. Report commissioned by the European Commission DG Environment Number 070307/ENV.C.1/2011/604781/ENV.F1, 10 August 2012, ec.europa.eu/environment/integration/energy/pdf/fracking%20study.pdf.

- The intention to disturb the existing balance between pore fluid pressure and pre-existing rock stress to cause new fractures in deeply buried rocks; and
- The lack of recovery of about 50% of the injection fluid and the proppants used to keep fractures open.

18. There is good evidence that induced earthquakes are sometimes linked to fracking or to injection of large volumes of high pressure fluids. This is summarised in a recent global compilation Hydraulic Fracturing-Induced Seismicity by Schultz et al (2020)[7], and an encyclopaedic compilation by Foulger et al (2017[8]). I set out here some examples from North America and Spain of induced seismicity from fracking operations:
    - In Ohio, a direct link has been established between the disposal of wastewater, including hydraulic fracturing flowback fluids, and induced earthquakes in Ohio. While some Ohio incidents involved fracking flowback, many induced seismic events in the region are linked to the disposal of "produced water" (brine that comes up with oil and gas), rather than the initial fracking fluid itself. The primary culprit is the high-pressure injection of these fluids into deep disposal wells, which can increase pressure on, and cause slip along, deep, unmapped faults.
    - A 2011-2012 series of 109 earthquakes (magnitude 0.4–3.9) in Youngstown, Ohio, was directly linked to the Northstar 1 wastewater injection well. The quakes began 13 days after injection started and ceased shortly after the well was shut down by the Ohio Department of Natural Resources (ODNR).
    - In 2013-2015 more than 300 earthquakes (magnitude 0.7–2.1) occurred within 3 km of an active disposal well in southeastern Ohio.
    - Following the 2011 Youngstown events, the ODNR implemented stricter regulations for injection wells, particularly regarding seismic monitoring and siting wells near known faults. While 177 deep well injection sites were active in Ohio as of 2011, only specific wells, such as the Northstar 1, were conclusively linked to the tremors.

[7] Schultz, R., Skoumal, R. J., Brudzinski, M. R., Eaton, D., Baptie, B., & Ellsworth, W. (2020). Hydraulic fracturing-induced seismicity. Reviews of Geophysics, 58, e2019RG000695. https://doi.org/10.1029/2019RG000695

[8] Foulger, G. R., Wilson, M., Gluyas, J., Julian, B. R., & Davies, R. (2017). Global review of human-induced earthquakes. Earth-Science Reviews, 178. https://doi.org/10.1016/j.earscirev.2017.07.008

- Northern BC. CBC news 15 Feb 2025 The British Columbia Energy Regulator has toughened up its oversight of "induced" seismic activity after a series of earthquakes linked to hydraulic fracturing, or fracking, in the northeastern corner of the province.
- Offshore Spain. The 2013 Castor project offshore Spain, intended for gas storage rather than CO2, triggered significant earthquakes up to magnitude 4.1 by injecting gas into an old oil reservoir, activating the Amposta fault. This induced seismicity caused hundreds of tremors, leading to the project's permanent shutdown and highlighting risks for underground fluid injection. The injections increased pressure in the reservoir, causing the Amposta fault to creep and reactivating a deeper, unmapped fault in the crystalline basement project (Vilarrasa et al 2021[9]).

Proppant squeeze (AKA small/low volume hydraulic fracturing)

19. These are more established processes to improve fluid flow immediately around a borehole. Also known as small-scale fracking, but without a clear legal distinction or definition. The open borehole is packed above and below the zone of interest, and very high-pressure water-based fluids (and proppant) are injected to specifically exceed the strength of the reservoir rock and intentionally produce additional fractures to aid the production of oil and gas. This type of operation has been informally and verbally reported from several onshore boreholes in Scotland (Midlothian -1, 1999 Bargeddie -1 and Lawmuir-1). A distinction between two size scales of fracking was made previously by the Minister for Energy Security and Net Zero: *"I want to be clear on this Government's position towards hydraulic fracturing—both high-volume hydraulic fracturing for shale gas and more conventional low-volume hydraulic fracturing" (Shanks, Hansard* Column 150WH 10 Dec 2025).[10]

Evidence from Lancashire

20. The Cuadrilla site at Preston New Road, Lancashire, provides the best published example of a UK site, to my knowledge, which has recorded seismicity directly linked to fractures

[9] Víctor Vilarrasa, Silvia De Simone, Jesus Carrera, Antonio Villaseñor (2021) Unraveling the Causes of the Seismicity Induced by Underground Gas Storage at Castor, Spain. Geophysical Research Letters https://doi.org/10.1029/2020GL092038

[10] https://hansard.parliament.uk/commons/2025-12-10/debates/CF0A1C3C-EFAD-4F7E-B1DE-4A1F298872E8/Small-ScaleFrackingBan#:~:text=We%20have%20to%20see%20additional,conventional%20oil%20and%20gas%20operations.

caused by small volumes of high pressure fluid. By small volumes of fluid, I am referring to less than 1000m[3] per fracture stage, which is below the UK legal definition of high-volume fracking. These operations were intended to inject fracking fluids at pressures which would create new fractures in the shale rock. Operations in the PNR-1Z well were accompanied by seismicity (Clarke et al., 2019) that was recorded by both a dense network of surface sensors and by a downhole geophone array in the adjacent PNR-2 well. On 11Dec 2018, the largest PNR-1Z event had a magnitude of 1.5 ML. Also on 11 December 2018, the British Geological Survey received reports from five people in Blackpool who felt the earthquake. Seismicity is observed to move from west to east from shallow to deeper along the borehole, corresponding to different incremental stages of operations along the horizontal borehole.

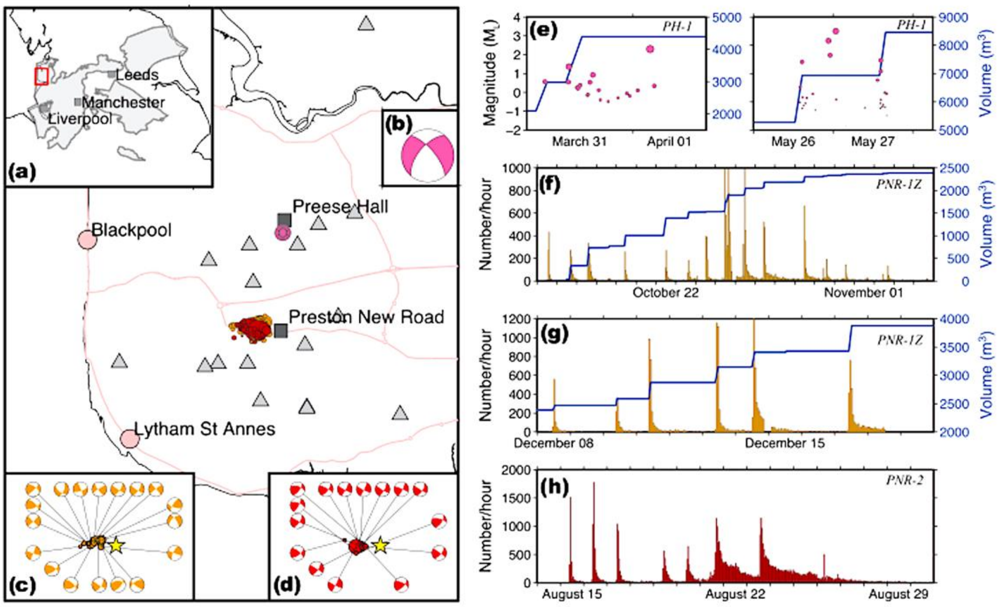


Figure 5. Map of HF-induced earthquakes in the United Kingdom. (a) Seismicity recorded during operations at Preese Hall in 2011 (pink circles) and at Preston New Road in 2018 (orange circles) and 2019 (red circles). Locations of Preese Hall (PH-1) and Preston New Road sites (PNR-1Z and PNR-2) are shown by gray squares, and gray triangles show locations of surface seismometers. The shaded area in the inset depicts regions of shale gas across North England. Red rectangle shows area of larger map. (b) The focal mechanisms for the magnitude −0.2 M_L event at Preese Hall on 2 August 2011 (Clarke et al., 2014). (c and d) Focal mechanisms calculated for selected events during operations at Preston New Road in 2018 and 2019, respectively. (e) HF stage completion volume (blue line) and induced seismicity (pink circles) for HF Stages 2, 4, and 5 at Preese Hall, Blackpool (PH-1). (f–h) HF stage completion volume (blue lines) and histograms of the number of events per hour recorded by downhole microseismic arrays during operations in PNR-1Z in October 2018, PNR-1Z in December 2018, and PNR-2 in August 2019.

Fig 1 taken from Schultz et al 2020. Data from Preese Hall 2011, Preston New Road 2018, 2019, Shows similarity of focal mechanisms (globes) for PH (Fig 5b), then PNR-1 (Fig 5c) and PNR-2 (Fig 5d). Blue lines are the incremental fluid volumes during fracking. Fig 5e shows high volume fracking in PH-1, contrasting with much smaller increments of low volume fracking for PNR-1 5f, and PNR-2 5g.

21. Detailed compilations of the three boreholes are presented by Schultz et al 2020 (reproduced here as Figure 1; above) and by a careful analysis and compilation in Zalucka et al (2020) reproduced as Table 1 (below).
22. During the completion of PNR-2 in August 2019, the published Hydraulic Fracture Plan states that the approach was similar to PNR-1Z, with a planned maximum injected volume of 765 m^3 in any single stage. **This planned volume was below the threshold in the Petroleum Act 1998** (see above). Under existing UK law, these activities would therefore be regarded by Regulators as "low-volume fracking".
23. The seismic events at PNR-2 initially showed strong temporal association with hydraulic fracturing stages, as there are relatively few events outside these periods—suggesting that the events are triggered by injection, and decay rapidly with time after stimulation stops. On 26 August 2019, following a seven-stage process (August 15–23) which saw 2,485m3 of fluid injected down PNR 2 well (including 422m3 on 17/8/19), a 2.9Ml earthquake occurred at Preston New Road. Following this, operations were suspended, and the fracking moratorium in place now was introduced. An article published by Drill or Drop (29 May 2020[11]) refers to the British Geological Survey's response to a freedom of information request at the time, which confirms reports of damage from eight postcode areas in the region following this earthquake (Figure 2, below).

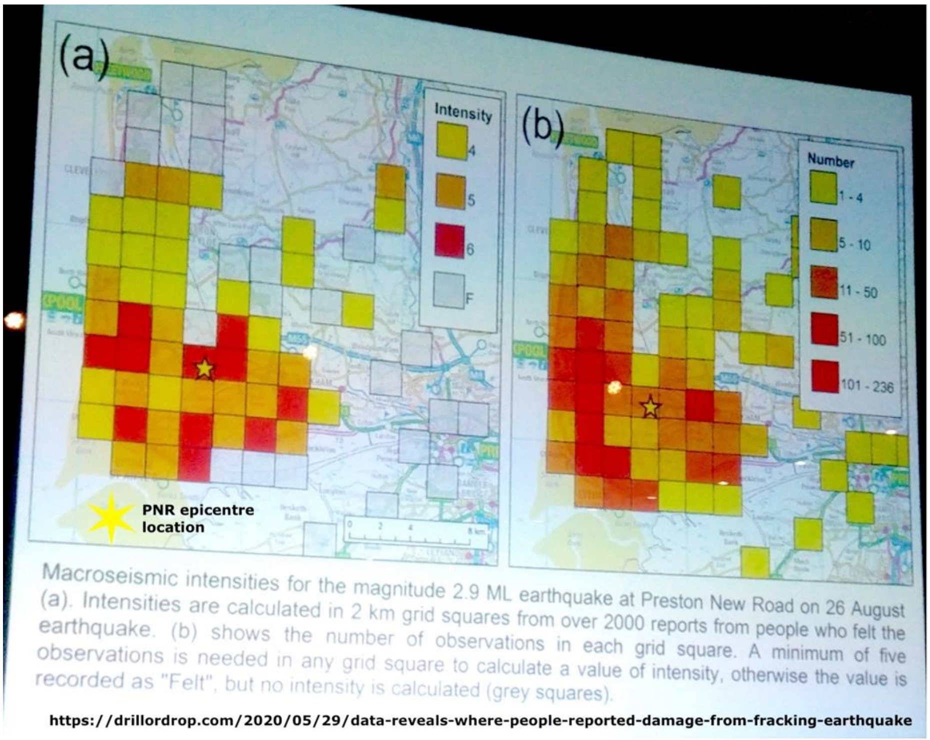
[11] https://drillordrop.com/2020/05/29/data-reveals-where-people-reported-damage-from-fracking-earthquake/

Zalucka, Goodenough, Smythe 2021 *Energy Policy 153 (2021) 112244*

Table 1
Frack fluid volumes and earthquake triggering at the three UK HVHF wells.

Well	Preese Hall 1	PNR 1	PNR 2
Start date	2011/03/26	2018/10/15	2019/08/13
End date	2011/05/31	2018/12/17	2019/08/23
Percentage of stages fracked	n/a	36%	16%
Total fluid volume (cu. m)	8399	3869	2485
Fluid used as percentage of fluid permitted	n/a	12%	7%
Average fluid volume of main frack (cu. m)	1594	218	355
Maximum volume of main frack	2245	417	432
Number of main fracks	5	17	7
Number of recorded induced tremors	2	56	134
Largest induced tremor (M_L)	2.3	1.5	2.9
Date of largest tremor	2011/04/01	2018/12/11	2019/08/26
Main fracking start date	2011/03/28	2018/10/16	2019/08/15
Recorded seismic event start	2011/04/01	2018/10/18	2019/08/15
Magnitude of first recorded events (M_L)	2.3	−0.2, −0.8, −0.3	−0.2
Total fluid volume injected before start of seismic events (cu. m)	4308	483–876.5	2.5–305.9

Table 1 compilation of basic data at Preese Hall and Preston New Road-1 2018, and Preston New Road 2 2019 From Zalucka et al 2021. Volumes of fluid used in fracks in PNR-1 Oct-Dec 2018 and PNR-2 Aug 2019 are similar 417-432 m^3. But produce similar largest tremors M_L 2.3, 1.5, 2.9



Maps showing the intensity of the 2.9ML earth tremor based on reports to the British Geological Survey. Source: Brian Baptie, BGS

Figure 2 BGS data following 2000 reports of the PNR-2 "felt" earthquake following 26 Aug 2019 M_L 2.9 earthquake. 197 reports of damage were made, in an area of 28 x 28 km (784 km^2). A clustering south of the PNR epicentre (star), is possibly due to shallow soil containing wet sand which transmits ground shake effects. Elongation of intensity south to north may indicate additional fault trends – but is not seen in the instrumented data

24. It is therefore clear from what happened at PNR, that "small" fluid volumes, injected for the purpose of fracking the rock to produce hydrocarbons, can cause seismicity if the geological setting is susceptible and already stressed close to the point of fracture. There is currently no known method to predict timing of this seismicity, nor to predict the magnitude of earthquake induced. The responsibility therefore currently lies with a developer to provide evidence that small volumes of high-pressure fluid, injected to fracture and acidise the shale rock or the reservoir rock, will not cause earthquakes. At present the balance of probability firmly supports the expectation that fracking with small fluid volumes less than 1000m^3 can cause seismicity. It should be noted, also, that the mitigation measures that were put in place at PNR-2 did not prevent the earthquake which occurred in August 2019.
25. In summary, fracking with lower fluid volumes (including proppant squeeze) is intentionally configured to modify fluid pressures within a deep reservoir. That modification of fluid pressure is intended to form new fractures in the reservoir rock, and so does carry risks of triggering an earthquake.

Low volume hydraulic fracturing at Burniston

26. Friends of the Earth have sent me links to Europa Oil and Gas Ltd's application for planning permission for hydrocarbon appraisal at Burniston, North Yorkshire and to their application for an environmental permit for this project. Given the proposed volumes of injected fluid, this project is not subject to the fracking moratorium. The developer seeks to use low volume hydraulic fracturing in this project, also known as a proppant squeeze. The proposed overall fluid volume – according to the waste management plan in the environmental permit application (p36) – is between 1,200 and 2,000m3, and 60 tonnes of proppant over 4 separate treatments" (or 300-500m3 on average). These volumes then, do not meet the threshold for "associated hydraulic fracturing". But they are higher than those used at PNR by Cuadrilla in the seven-day period running up to the 2.9ML seismic event in 2019.
27. The type of rock at the Burniston site is not shale. According to the Environment Agency environmental permit application (p5), the target formations are claimed to be Carboniferous Sandstones (primary target formation; clearly shown on the diagram at the base of proposed borehole), Permian Brotherton Limestone (Plattendolomite) and the Kirkham Abbey (Hauptdolomite) formations (secondary target formations). [12] The officer's report also states: *The proposed borehole is a single conventional gas well targeting* ***conventional tight gas sands***. *The sands at depths of over 2.0 km would require stimulating (enhanced productivity) through a proppant squeeze operation*. The Permian carbonate rocks are likely to be dolomites – a mineral grown during burial which often results in a very low permeability as a minor reservoir – less than 10% porosity and 1% milliDarcy permeability and so needs natural fracturing to enable hydrocarbon production. This is a small and poor target reservoir compared to underlying mid Carboniferous sandstones – typically 10% porosity and 10-100 milliDarcy permeability which would not require essential stimulation. The Carboniferous shales are typically extremely impermeable 0.05 milliDarcy to 10^{-9} milliDarcy. On this basis, in my view, the risk of

[12] https://consult.environment-agency.gov.uk/psc/yo13-0db-europa-oil-gas-limited/supporting_documents/Application Bespoke A001 03 Non Technical Summary 250425.pdf

seismicity induced or triggered from proposed operations at Burniston, cannot simply be ruled out.

Matrix Acidisation

28. Matrix acidisation at low pressure is a technique routinely used in the groundwater extraction industries at shallow burial depths of tens to a few hundreds of metres. This uses a concentrated solution of hydrochloric acid and is particularly favoured for limestones (such as chalk aquifers) where water flow through the rock mass can be greatly enhanced by dissolution of a small percentage of the rock matrix in the rock surrounding the borehole steel casing. The technique uses simple engineering to deliver the acid directly to a zone of interest, and allow the acid to slowly percolate into the reservoir rock during several days, before the acid is recovered. The hydrochloric acid (HCl) flows into porespace driven by its density greater than water, ranging from slightly above water 1.05 for 10Wt% HCl, to about 1.20 g/cm3 for 35 Wt% HCl. If the entire column of fluid from reservoir to surface was HCl, with 20% increased density, reservoir pressure would increase by just 20% greater than a water column due to increased density of the fluid column, compared with compressors driving a 250% pressure increase for fracking.
29. Carbonates are much more geochemically reactive to hydrochloric acid than silicate sandstones, consequently the technique is primarily used on carbonates. Acidisation may sometimes be used to remove drilling debris of sand or silt size fragments of the reservoir which have been left behind after drilling when mud circulation stops – or after many months or several years of production to remediate a reservoir back to its natural flow properties. Key points on matrix acidisation are:

- Minimal extra fluid pressure is imposed;
- Small volumes of chemically reactive acid are used not immense volumes of water;
- The acid can be delivered by a downhole tubing which can emplace small volumes of acid directly to where it is needed; and
- No additional fractures are produced.

Fracture acidization (also known as acid fracturing).

30. This name is often applied in an unclear way. This additional type of acidization is often used in oil and gas exploration and particularly to enhance production of hydrocarbons.

This is used where a borehole crosses a reservoir and so is inevitably at much deeper burial depths than matrix acidization for aquifers. An important distinction is that additional fluid pressure may be used to push acid into the rock formation, but with very small volumes of fluid and at pressures much less than required for fracking. In deep geothermal applications (Enhanced Geothermal Systems; “EGS”) there have been several occurrences of induced seismicity – some delayed by days after the fluid injection and offset by several km. The relationship between induced seismicity and acid fracture injection is driven by the alteration of subsurface stress fields and pore pressure, which can reactivate pre-existing faults. While acid fracturing is less frequently cited than hydraulic fracturing in large-scale seismic event reports, it shares identical triggering mechanisms when used for permeability enhancement in reservoirs like EGS or carbonate formations. EGS (such as United Downs in the UK) are usually in crystalline rock, not sediments and are much deeper than fracking at 4 or 6km, and do not produce hydrocarbons – just heat. I refer here to some examples of examples of seismicity with EGS deep burial fracture acidisation:

- **Basel Deep Heat Mining Project (Switzerland, 2006)**: One of the most studied cases involving both hydraulic and **acid stimulations** in granitic rock. A magnitude M_L3.4 earthquake occurred five hours after injection was stopped, leading to the project's cancellation.
- **Pohang EGS (South Korea, 2017)**: While primarily involving hydraulic stimulation, the project used cyclic injection protocols similar to those applied in acidizing operations. It triggered a M_L5.4 earthquake two months after the final stimulation, the largest ever associated with EGS.
- **Vendenheim (France, 2021)**: A M_L3.9 earthquake occurred six months after a circulation test in an EGS project that utilized stimulation techniques, resulting in the project's permanent closure

Gas and oil production triggering earthquakes

31. **Horse Hill, Surrey (2019)**. The effects of fluid pressure change during oil or gas production can be linked to triggering earthquakes.[13] At the Horse Hill field in Surrey (UKOG 2026), oil and gas reservoired in the upper Jurassic Portland porous carbonate sandstone and

[13] https://www.youtube.com/watch?v=cRXyUclQpjw

fractured Kimmeridge shales was initially produced rapidly from a discovery borehole, "the Gatwick Gusher". The discovery borehole was shut in for many months before being reactivated for an extended period to test gas and oil flow rates. The start of testing coincided within hours to a cluster of seismic activity April 2018 – 2019 with tens of small earthquakes. These earthquakes were claimed to be a natural coincidence by the oilfield developer, supported by an expert panel assembled by the Oil and Gas Authority (now North Sea Transition Authority). But that simple proposal was contested by Haszeldine & Cavanagh (2018[14]) with the hypothesis that depressurisation of free methane gas increased stress on faults in the reservoir. And a prediction that continued oil and gas production would continue to trigger earthquakes – which is what happened through most of 2019 (Cavanagh Gilfillan Haszeldine 2019). Similar processes caused by oil production have been proposed by Westaway 2020[15], and by Fox and Meredith 2025[16].

Discussion of potential resolution

32. The UK regulations are illogical in their differential treatment of high volume fracking, low volume fracking, matrix acidization, fracture acidization. That may enable a regulator ban on fracking to be circumvented by developers who could define their stimulation of boreholes to avoid legal definitions.
33. As I set out above, existing evidence from closely monitored commercial attempts at Preese Hall, Preston New Road -1 and Preston New Road-2 show that earthquakes from large volume fracking and small volume fracking are equally large and equally unpredictable. Regulatory permission for low volume fracking does not remove the risk of unpredictable earthquakes.

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[14] Haszeldine, S., Cavanagh, A., 2018. Weald Basin 2018 Earthquake Cluster Analysis: Does Horse Hill meet Davis & Frohlich (1993) criteria for induced earthquakes? https://www.ogauthority.co.uk/media/5173/10-weald-basin-earthquakes-induced-ogaworkshop-haszeldine-cavanagh-oct-2018-low-res.pdf

[15] Westaway R . (2020) Seismicity at Newdigate, Surrey, during 2018-2019: A candidate mechanism indicating causation by nearby oil production. *ESS Open Archive* . April 28, 2020. DOI: 10.1002/essoar.10502953.1

[16] Fox, M. and Meredith, P.G., 2025. Were the Newdigate Earthquakes, Southern England, of 2018–2019 triggered by oil extraction?. *Geological Magazine*, *161*, p.e23

Conclusions

34. Fracking with large volumes of fluid (more than 1000m^3 per stage) is currently banned in the UK, because of a clear association with triggered earthquakes. The UK government chose a definition of fracking in the Petroleum Act 1998, based on volume of injected fluid.
35. Fracking with low volumes of fluid (less than 1000m^3 per stage) is classified differently in the UK, apparently on the basis that it does not cause seismicity. That is, however, contradicted by evidence from UK fracking at Preese Hall and Preston New Road.
36. In USA and Canada, and Spain, there are many examples of earthquakes being linked to fracking and water injections, for disposal of waste water, or for hydrocarbon production. The time gap between fluid intervention and earthquake may be hours, days or multiple months, so cause and effect may be harder to prove.
37. About 5 types of fracking or acidization intervention to increase hydrocarbon production have been used in the UK. There is substantial confusion in the legal and planning definitions of fracking in the UK.
38. A more reliable definition of fracking which simplifies terminology and responsibility could be that proposed by Zalucka et al (Energy Policy 2021). Associated Hydraulic Fracturing could be defined as ***"All well stimulation treatments of oil and gas wells which increase the permeability of the target rock to higher than 0.1 milli Darcies beyond a 1m radius from the borehole".*** That would close the loophole in the current phase of onshore exploration and extraction, where unconventional oil and gas can be pursued using acidization or small volume fracking under the guise of conventional hydrocarbon exploration and production.

Professor Stuart Haszeldine

School of Geosciences

Edinburgh Climate Change Institute

University of Edinburgh

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