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Public Engagements with Induced Seismicity: Lessons for Geothermal Energy in the UK's Net-Zero Transition

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ABSTRACT

The United Kingdom (UK) net-zero energy transition is driving research on the prospects and risks of new subsurface energy technologies—including Carbon Capture, Utilisation and Storage (CCUS), Mine-water Geothermal and Enhanced Geothermal Systems (EGS). However, as exemplified by the government's moratorium on hydraulic fracturing for shale gas, complex underground processes such as induced seismicity often exceed scientific predictions. Since earthquakes induced by fracking were perceptible to local residents, either directly or via seismic monitoring, they escalated public opposition and undermined efforts to secure a social license for the industry. Geo-energy operations—like many major human interventions into the subsurface—can produce earth tremors with the potential to generate controversies similar to fracking. The failure of fracking showed how simplistic representations of the subsurface may conceal substantial scientific uncertainties. Controversies around induced seismicity affirmed the key tenet of Science and Technology Studies: that regarding the public as misinformed and deficient of scientific understanding is ineffective in addressing such controversies. Rather, geoscience must actively engage with alternative forms of knowledge and first-hand experiences of subsurface events. This paper reports on the preliminary findings of a UKRI-funded research project on public engagement with induced seismicity. The overarching aim of this research is to identify transferable lessons from fracking-induced seismicity for new geo-energy projects, with a specific focus on EGS. The key objectives are to: (i) explore the social implications of a likely recasting of scientific networks, discourses and dissensus from the fracking controversy into the prospective geothermal industry; and (ii) examine how the public engages with scientific and political framings around induced seismicity, with a view to exploring opportunities for enhanced citizen participation in the co-production of geoscientific knowledge.

1. INTRODUCTION

The United Kingdom (UK) net-zero energy transition is driving research on the prospects and risks of new subsurface energy technologies—including Carbon Capture, Utilisation and Storage (CCUS), Mine-water Geothermal and Enhanced Geothermal Systems (EGS). However, as exemplified by the government's moratorium on hydraulic fracturing for shale gas, complex underground processes such as induced seismicity often exceed scientific predictions, undermining efforts to secure a social license for the industry. This paper reports on the preliminary findings of a pilot project, funded by the UK National Environment Research Council (NERC) and Economic and Social Research Council (ESRC) through the Unconventional Hydrocarbons in the UK Energy System (UKUH) Programme at Newcastle University. This project builds on work on the socio-economic impacts of unconventional hydrocarbons (e.g. Szolucha 2019, Williams and Sovacool 2019, Williams and Sovacool 2020) and public perceptions and acceptance of shale gas (e.g. Evensen *et al.* 2019), piloting critical inquiry of public engagement with induced seismicity. The overarching aim of the research is to identify transferable lessons from fracking-induced seismicity for new geo-energy controversies, with a specific focus on EGS, given the significance of public knowledge controversies around fracking-induced earthquakes and the potential socio-political implications of these tensions for EGS.

In November 2019, the UK government announced a moratorium on shale gas exploration in England, ending their decade-long support for developing domestic gas resources through hydraulic fracturing (fracking). The U-turn followed an investigation by the Oil and Gas Authority (OGA) into earth tremors triggered by fracking operations near Blackpool, Lancashire, which repeatedly breeched the regulatory magnitude threshold of 0.5 ML established in 2012. Generating considerable media attention for an already-controversial technology, the induced earthquakes led to repeated suspensions of drilling by the operator, Cuadrilla Resources, and proliferation of concern across communities adjacent to the site. Imposing the moratorium immediately, the Department for Business, Energy and Industrial Strategy (BEIS) conceded that future unacceptable impacts on the local community could not be ruled out, though they later qualified that the bar was effective unless further evidence is provided that extraction can be carried out safely.

Meanwhile, geothermal has emerged as a potentially significant component of the UK's low-carbon transition. Until recently, geothermal energy has been exploited only in tectonically active regions such as Iceland and Italy. EGS make it possible to target heat stored at greater depths through various methods, including hydraulic stimulation of the rock. This has expanded the prospects for geothermal production to other regions including France, Germany, and latterly the UK. However, EGS also produce earth tremors with the potential to generate controversies similar to fracking.

The failure of fracking showed how simplistic representations of the subsurface may conceal substantial scientific uncertainties. When earth tremors persisted irrespective of stringent regulations and suspensions, public resistance to fracking escalated. Controversies around induced seismicity affirmed the key tenet of STS: that regarding the public as misinformed and deficient of scientific understanding is ineffective in addressing such controversies. Rather, geoscience must actively engage with alternative forms of knowledge and first-hand experiences of subsurface events.

While a number have analysed the competing frames around shale gas in the UK (e.g. Williams and Sovacool 2019, Williams and Sovacool 2020), there has been relatively little research on public engagement with the operations of geoscientific expertise and discursive political practices in respect to induced seismicity (Maguire 2020, Trutnevyte and Ejderyan 2018). Addressing this gap, this project explores the prospects for incorporating alternative sources of seismological knowledge and political agency in geo-energy policy, focussing empirically on the United Downs Deep Geothermal Power project (UDDGP) in Cornwall. The UDDGP targets radiothermal granites at a depth of around 4.5 kilometres, pumping water into fractures with relatively high permeability (Gluyas *et al.* 2018). A seismic monitoring and control protocol has been implemented, using British Standards for vibration in buildings and Cornwall Council's planning guidelines for blasting, quarrying and mining activity.

The key objectives of this pilot research are to: (a) explore the social implications of a likely recasting of scientific networks, discourses and dissensus from the fracking controversy into the prospective geothermal industry; and (b) examine how the public engages with scientific and political framings around induced seismicity, with a view to exploring opportunities for enhanced citizen participation in the co-production of geoscientific knowledge. To meet these objectives, the methodological approach entails:

(1) analysis of expert and political discourses around shale gas, induced seismicity and EGS;
(2) in-depth interviews with key informants from the scientific, policy, and business sectors concerned with prospective EGS projects;
(3) a workshop, inviting public participants in addition to the above groups

This paper reports on the preliminary findings of the above-introduced research. First, it explores how human-induced earth tremors came to acquire major salience in the regulation and contestation of fracking in the UK, effectively deciding the industry's fate. It analyses how the spatial and temporal regulation of induced seismicity enabled the continuous deferral of shale gas production. Specifically, it is argued that suspensions and moratoria manifest as unspecified periods of time, during which both the subsurface and knowledge of subsurface phenomena are expected to stablilise, allowing exploration to resume. Secondly, this paper shows how speculative claims for a UK shale gas bonanza have been ultimately confounded by the recurrence of seismic events, which may have implications for EGS as a potential part of the transition to net-zero.

2. FRACKING AND INDUCED SEISMICITY IN THE UK: HISTORY OF A REGULATORY PROBLEM

The first high-volume hydraulic fracturing operations on UK soil were conducted by Cuadrilla at Preese Hall, Lancashire in March 2011. The injections were almost immediately followed by a series of earthquakes in the area. On 1st April, a tremor with magnitude 2.3 ML was detected after the second injection. On 27th May, a further 1.5 ML event was detected following the fourth treatment. As a result of the latter earthquake, the concrete and steel shell that prevents escape of pollutants from the well was found to be deformed. These tremors—each occurring after approximately the same interval, 10 hours following the injections—were immediately linked to the hydraulic fracturing operations. As the quakes were above the predicted range of magnitudes, the Department of Energy and Climate Change (DECC, subsequently BEIS) directed Cuadrilla to suspend operations so that the cause could be investigated.

Following the events at Preese Hall, despite sporadic attempts to resume activities, the inability to mitigate induced seismic events has left the industry in a state of suspension for most of the past decade. During this time, a series of scientific investigations have sought to understand the nature of the incidents and the implications for future shale gas development. This began with a series of studies commissioned by Cuadrilla, culminating in a synthesis report by De Pater and Baisch (2011), which focused on three aspects of the Preese Hall case. First, data obtained from the BGS regional seismic monitoring network and two temporary stations installed close to the site was used to determine locations and mechanisms of the seismic events. The report identified a pre-existing seismic fault in close vicinity to the well as the *probable* hypocentre for the two earthquakes. Strong evidence showed that the timing of the events was governed by the fluid flow into this fault, with the increased pore pressure resulting in its failure. The report argued that the seismic events at Preese Hall were induced by the improbable coincidence of many factors, representing a "worst case scenario" because of the well's proximity to a large, critically stressed fault. Second, laboratory analysis of core samples from the PH1 well were used to determine rock properties for the shale gas reservoir and generate a geomechanical model. The model estimated that the maximum magnitude for induced seismicity in a similar situation is 3.0 ML.

Thirdly, De Pater and Baisch (2011) used the measured ground velocities and frequencies from the Preese Hall earthquakes to determine the critical Richter-magnitude above which slight material damage to structures could occur. To do this, the analysis adopted the German standard by which vibration damage to buildings are regulated. Known as DIN4150-3, this standard specifies the minimum velocity of movement that would inflict damage upon different classes of building as they transmit seismic waves within different frequency ranges. The maximum magnitude that would ensure ground movement remained below the DIN4150-3 threshold was determined to be 2.6 ML. However, the analysis also took account of a complicating factor in that the largest magnitudes were 'trailing' or delayed events, occurring a period after the hydraulic injections. On the basis that the maximum post-injection magnitude increase was an estimated 0.9 ML, a limit of 1.7 ML was proposed in order to prevent the occurrence of an earthquake with a potentially damaging magnitude in excess of 2.6 ML.

The threshold of 1.7 ML damage was the basis for De Pater and Baisch's (2011) proposal of a Traffic Light System (TLS), adapted from a protocol used with EGS projects in Germany and Switzerland, to control operational activity in line with seismic activity. During operations, seismic data is monitored in real time so that action can be taken to mitigate induced earthquakes on the basis of specified local magnitude thresholds at three levels: green—injection proceeds as planned; amber—injection proceeds with caution, possibly at reduced rates, and monitoring is intensified; red—injection is suspended immediately. The report specified that: magnitudes smaller than 0.0 ML should constitute a green-light; magnitudes between 0.0 ML and 1.7 ML trigger an amber-light, with monitoring for at least 2 days until the seismicity rate falls below one event per day; and magnitudes greater than 1.7 ML signify a red-light event, where operations are suspended with continued monitoring (de Pater and Baisch 2011).

The DECC subsequently convened a scientific committee to review Cuadrilla's Preese Hall investigation. The aim of the review was to make "appropriate recommendations for the mitigation of seismic risks in the conduct of future hydraulic fracture operations for shale gas" (Green *et al.* 2012: ii). The DECC report concurred with Cuadrilla's conclusions about the nature and mechanism of the seismic activity in the Preese Hall area. However, given that no specific geologic fault had been definitively identified as the hypocentre of the earthquakes, it argued that there was insufficient data to state that there is a low probability of encountering a similar scenario in any future wells. Moreover, taking account of the magnified 'trailing events' observed at Preese Hall, the proposed 'red-light' TLS threshold at 1.7 ML would not have prevented the 2.3 ML earthquake. Consequently, the report recommended a more "conservative" upper threshold of 0.5 ML, arguing that this would "reduce the likelihood of events perceptible to local residents, and offer a higher margin of safety against any possibility of damage to property" (Green *et al.* 2012: 12)

The rationale provided in Green *et al.*'s (2012) report for the DECC reflected a concern for conservatism, "public perception" and "margin of safety" that had emerged following the Preese Hall events. However, the 0.5 ML limit was not an arbitrarily precautionary figure. Nor was it simply arrived at through an approximate subtraction of the observed magnitude increase (0.9 ML) from the smaller (1.5 ML) trailing seismic event detected on 27th May. Rather, the traffic light system proposed by Green *et al*. (2012) was the product of a detailed understanding of the tectonic history and regional stress regime of the British Isles, as well as the mechanisms that lead to tensile and shear failure of rocks. As detailed in a briefing note by Styles and Baptie (2012), co-authors of the DECC report, in comparison to the Appalachian Basin of the United States, which has been the basis for assumptions of the regional stress regime in the Bowland Basin, the continental crust of the UK has a longer and more complex tectonic history. As they state:

> *A more recent phase of loading and unloading superimposed upon the British Isles from the advance and retreat of ice sheets during the last 10,000 years. It is crisscrossed by networks of faults, some of which move on a reasonably frequent basis with observable and often felt seismicity [and] may be in a quasi-critical state, in which the rocks store energy which can be released by changes in stress or hydrogeological conditions (Styles and Baptie 2012: 1).*

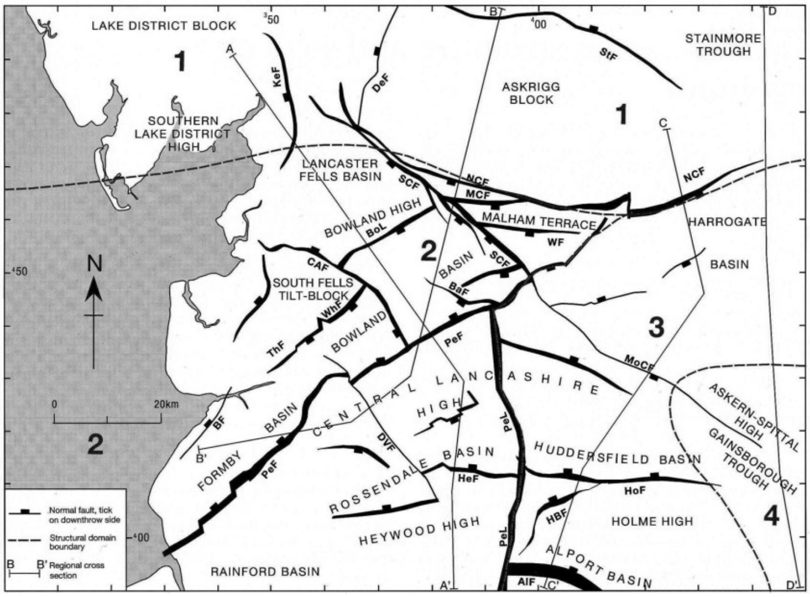

Figure 1: Principal early Carboniferous structures of the Bowland-Hodder region of northwest England (Source: Prof. P. Styles).

Induced seismicity is produced via two main mechanisms. Firstly, the injection of fluids under high pressure generates new cracks and fractures, and brittle (tensile) failure of this rock generates seismicity. Secondly, increased pore-space pressure resulting from the fluid injection causes slippage along pre-existing faults with critical shear stresses. Importantly, while the magnitude of the first type of seismic event is constrained by the energy of the injection process, the size of the ground movement in the latter case depends largely on the amount of latent elastic strain energy in the rocks (Baptie 2017). Just as with estimates of UK shale reserves, the fixing of 0.5 ML as the 'red light' threshold for seismicity induced by hydraulic fracturing in the DECC report was based on research conducted on the analogue of the Barnett Shale basin in the United States (see also Kama and Kuchler 2019, Kuchler 2017). This indicated that the change in magnitude from 0.5 ML to 1.0 ML marked the transition from hydrofracture driven seismicity (i.e., due to tensile failure) to seismicity driven by fault movement (i.e., due to shear failure). Reflecting this geological complexity, Styles, Green and Baptie prescribed a detailed set of procedures (see Figure 2) to be followed in conjuction with the TLS seismic thresholds specified in their DECC report .

Following a public consultation on the Green *et al*. (2012) report, a further review of hydraulic fracturing was subsequently commissioned by the DECC with the Royal Society (RS) and the Royal Academy of Engineering (RAE), focussing on the major risks including seismicity and mitigation (Mair *et al.* 2012). The report pointed to an "emerging consensus" that the magnitude of seismicity induced by hydraulic fracturing in the UK would be no greater than 3.0ML, which would be "felt by few people and resulting in negligible, if any, surface impacts" (Engineering 2012: 4). While also recommending a TLS monitoring system, the RS/RAE report cautioned that TLS systems rely on the extrapolation of statistical relationships observed in natural seismicity that may not necessarily apply to induced seismicity. They also pointed to the incidence of delayed or 'trailing' seismic responses to fluid

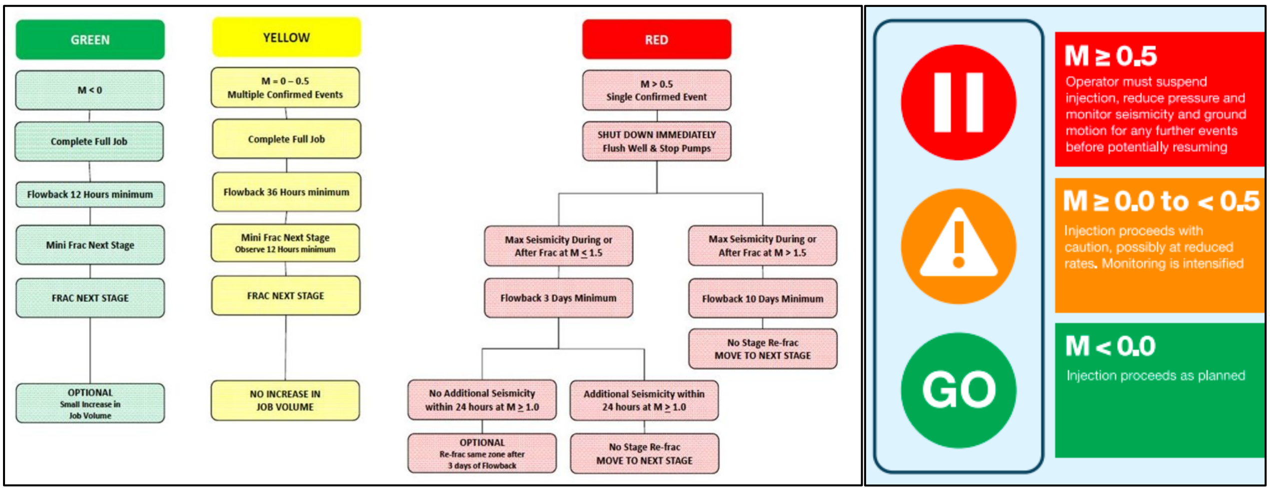

Figure 2: Traffic Light Systems recommended by Styles, Green and Baptie (left) and implemented by OGA (right).

injections, such as were experienced at Preese Hall, which complicate the real-time monitoring and mitigation of earthquakes. Highlighting that the thresholds used in EGS are based on peak ground acceleration, velocity and frequency, the report suggested that the traffic light monitoring system need not be magnitude-based. However, the RS/RAE report concluded that earthquake risk was minimal, and recommended fracking be given nationwide clearance.

Nevertheless, when the DECC released their Traffic Light Monitoring System infographic to accompany their regulatory guidance (DECC 2013b), the prescriptive recommendations of Green *et al*. (2012) and the reservations in the RS/RAE review were largely elided. Instead, a 'green light' for "go" simply instructed operators to proceed "as planned" with seismicity up to 0.0 ML. An 'amber light' triggered by tremors between 0.0 ML and 0.5 ML advised that injections should "proceed with caution, possible at reduced rates [and] monitoring is intensified." A 'red light', meanwhile, directed injection operations to be "suspended immediately" with fluid pressure reduced, but no guidance as to time periods or further steps. A later version, which remains effective, advises that a 'red light' should be followed by an indeterminate period during which seismicity and ground motions are monitored "before potentially resuming."

A November 2012 letter from the Cuadrilla Chief Executive, Francis Egan to the then Energy Secretary, John Hayes suggests that this TLS was mutually developed and agreed between company, experts and the government. Referring to a recent meeting, the letter said:

> *In conjunction with industry experts and your team at DECC we have developed a "traffic light" seismic monitoring and mitigation system [...] (Cuadrilla 2012).*

Cuadrilla did not dispute the 0.5 ML threshold recommended by Green *et al*. (2012). To the contrary, it put forward the adoption of this regime as further evidence of the relative safety of hydraulic fracturing in the UK in respect to other countries – an argument that has frequently been made in support of the development of the industry – stating:

> *The traffic light levels set for our potential forthcoming fracturing operation in Lancashire have [...] been set well below levels commonly used worldwide to ensure that we maintain a much larger factor of safety at this exploratory stage (Cuadrilla 2012).*

In December 2012 the government announced that it was "in principle prepared to consent to new fracking proposals for shale gas" on the basis that "appropriate controls are available to mitigate the risks of undesirable seismic activity" – effectively lifting the 19-month moratorium in place since the Preese Hall earthquakes (DECC/Davey 2012).

One year later, in 2013, the DECC published its regulatory roadmap for onshore oil and gas in the UK. The roadmap set out requirements for operators to develop a Hydraulic Fracturing Plan (HFP) based on an environmental risk assessment, describing the control and mitigation measures for potential induced seismicity. This required the evaluation of historical and background seismicity and the delineation of faults in the area that may be activated by hydraulic fracturing. The guidance stated that the HFP should also include an array of sensors to detect seismic activity before, during and after operations. These sensors were to be linked to a live TLS, with 0.5 ML specified as the 'red light' threshold, at which point the operator must "suspend injection, reduce pressure and monitor seismicity and ground motion for any further events before potentially resuming". The prescriptive TLS recommendations of Green, Styles and Baptie were again omitted, with the regulations requiring operators to devise their own decision-tree for responding to a seismic event to be submitted with the HFP (DECC 2013a).

Further regulatory problems emerged over the proceeding four years. Amidst much public controversy and resistance from local anti-fracking groups and environmental groups, Cuadrilla were unable to obtain planning consent for key sites in Lancashire. Citing road safety, noise and landscape concerns, Lancashire County Council's (LCC) 2015 refusal for the company's Preston New Road site prompted an appeal and a high-profile public inquiry led by the Planning Inspectorate. Nevertheless, during the inquiry the Department for Communities and Local Government (DCLG) announced that the Secretary of State would make the final decision on the appeal due to the national importance of the scheme (Weaver 2015), effectively circumventing local planning control. In October 2016, following the recommendations of the Planning Inspectorate, the DCLG Secretary allowed Cuadrilla's appeal on the grounds that the PNR proposal was "of major importance having more than local significance" (DCLG 2016).

With permits secured, on 18 August 2017 Cuadrilla began drilling two horizontal wells, PNR-1z and PNR-2, at the PNR site some 2.5 miles from Preese Hall. The HFP for the first well to be fractured, PNR1z, indicated that it was located some distance from known large faults and provided for seismic monitoring in line with the TLS. Fracturing of the well ran from 15 October to 17 December 2018 and induced 38,000 anomalous seismic events. Six of these exceeded the 0.5 ML threshold and the largest, a 1.5 ML event, occurred after pumping had ceased and was felt by a small number of residents near to the well site (OGA 2019). Cuadrilla, concerned about their ability to operate within the 0.5ML threshold, ceased hydraulic fracturing having attempted only 17 of their planned 41 injection stages. In February 2019, the OGA announced plans to carry out an analysis of the extensive data gathered during the fracturing operations on PNR-1z.

Meanwhile, Cuadrilla submitted a revised hydraulic fracturing plan (HFP) for the PNR-2 well in June 2019, introducing options to use either slick water, gel or a hybrid frac fluid as a mitigation against induced seismicity. However, 11 days after fracking resumed on 15th August, BGS recorded a 2.9ML earthquake, and operations on the PNR site were again suspended. The 26th August event was the latest, and most alarming to the public, in a string of more than 90 tremors detected following the resumption of operations on the site. In response, around 3000 members of the public reported experiencing ground shaking to BGS, with reports to regulators and the operator indicating potential superficial damage to buildings. It was the largest quake known to have been caused by fracking in the UK, registering at more than 250 times the red-light threshold of 0.5ML permitted by the OGA, and close to the upper limit projected by scientific reports following the Preece Hall quakes. Shortly afterward, the OGA announced that operations at the PNR-2 well were suspended while the agency gathered data and considered whether the operations, mitigations and assumptions set out in Cuadrilla's Hydraulic Fracture Plan were appropriate to manage the risk of induced seismicity.

A month later, the OGA published the its report on the PNR-1z seismic data. It emphasised the necessity for further research in order to adequately assess the probability and impact of seismic events. However, the report stated that current models are unable to anticipate the variable seismic responses to hydraulic fracturing. In a public statement, Andrea Leadsom, the Secretary of State for BEIS conceded: "it is clear that we cannot rule out future unacceptable impacts on the local community". Leadsom declared, "[f]or this reason, I have concluded that we should put a moratorium on fracking in England with immediate effect". At first sight, this announcement appeared to signal the end of fracking in the UK, following previous moratoriums in Scotland and Wales. However, the government's accompanying press release equivocated in its interpretation of the term 'moratorium'. Proclaiming an immediate 'pause' in operations, it added that this would remain effective unless further evidence proves that extraction can be carried out "safely" within regulatory limits. Indeed, while some media coverage and anti-fracking groups hailed the decision as an inevitable and permanent 'fracking ban', Leadsom clarified that an ultimate prohibition was not in fact being imposed:

> *because this is a huge opportunity for the United Kingdom, but we will follow the science [...] What we're looking to see now is the exploration that Cuadrilla have carried out at Preston New Road, there will be some reports of what the potential is from those wells. So we will have better information in the future once that data has been assessed (Busby 2019).*

Nevertheless, in February 2020 private equity firm Riverstone sold its 45% stake in Cuadrilla, leaving Australian mining firm AJ Lucas, already Cuadrilla's largest shareholder, with a 93% stake. In October, Ineos Upstream Limited - the second-most prominent UK shale gas operator - cut the value of its UK exploration assets to zero, suffering a loss of £63 million. Added to a significant shift towards low-carbon energy sources following the government's 2019 commitment to net-zero carbon emissions by 2050, the industry's UK prospects appear to have faded to improbable.

3. SEISMO-POLITICS: HOW EARTH TREMORS BECAME POLITICAL EVENTS

Rather than being a period of inactivity, the ongoing enforced hiatus for UK shale gas has manifested as a 'productive pause' in extractive operations (Weszkalnys 2015). During this period, a range of experts—with varying degrees of specialisation, engaged through commercial, governmental, quasi non-governmental and non-governmental organisations—were recruited to undertake (or intervened with) analyses of the seismic hazard posed by hydraulic fracturing. However, rather than being a simple case of policy being informed by objective scientific knowledge production, this period was one characterised by seismo-politics through which the discursive basis for government policy relating to fracking and induced seismicity (alongside parallel concerns for environmental protections such as water, air and traffic) was iteratively shaped (see Table 1). This process entailed the envisioning, abstraction and transposition of subsurface materials, structures and phenomena into symbols, rules and action. Lithology, regional stress orientations, injection pressures and seismic events in Lancashire and other locations were variously and partially incorporated into magnitudes, geomechanical models, seismic hazard and corresponding operational thresholds. These knowledges were represented in written reports, briefings and mediated through parliamentary debates, committees and policy statements, legislation and regulatory guidance for fracking operations.

However, in framing the mitigation of unacceptable seismic hazard in terms of a simple cut-off at 0.5 ML, and a suspension of operations for monitoring over an unspecified period, the DECC's TLS permitted the focus to shift from the technical to the political immediately following a seismic event. In this shift, rather than adhering to a set of procedures designed to mitigate seismicity and allow operations to continue where criteria are met, the definitive red light allowed operations to resume only once sufficient public consent and political legitimacy had been re-established. Thus, Cuadrilla and DECC anticipated (at least tacitly) two things: (1) that such legitimacy could be re-attained within undefined yet economically feasible time-scales; and (2) that any instance of seismicity above 0.5 ML would be anomalous. However, while the former thesis would prove true up to a point, the latter proposition presumed a subterranean homogeneity at odds with the complex tectonic history of the Bowland basin.

Yet such anticipatory politics (Kama 2020, Szolucha 2018)were reflected in a subsequent report commissioned by DECC on the resource prospects of the UK's shale gas basins. A July 2012 report, authored by the BGS, estimated that—by analogy with shale gas production in United States—UK shale gas reserve potential could be as large as 150 billion cubic metres, or almost 2 years of UK gas consumption (DECC 2013c). The following December, the government announced that it would establish an Office for Unconventional Gas, with the express aim of realising this potential (Kama and Kuchler 2019). At the same time, a new National

	De Pater and Baisch (2010)		Styles *et al*. (2012)		Green *et al*. (2012)		Royal Society / RAE (2012)		UKOOG (2013)		DECC (2013)		OGA (2018)	
	Magnitude (ML)	Action	**Magnitude (ML)**	Action	**Magnitude (ML)**	Action	**Magnitude (ML)**	Action	**Magnitude (ML)**	Action	**Magnitude (ML)**	Action	**Magnitude (ML)**	Action
GREEN	**<0.0**	Proceed	**<0.0**	Minimum well 'flowback' period for 12 hours after completing each stage, and a test injection ('mini-frac') before commencing the next stage, with an optional increase in injection volume.	**<0.0**	Initially, smaller volumes should be injected, with immediate flowback, and the results monitored for a reasonable length of time. Meanwhile, the fracture diagnostics (microseismic and prefrac injection data) should be analysed to identify any unusual behaviour post-treatment, prior to pumping the job proper. [...] A reasonable period of time (12-24 hours) should also be allowed to elapse after the injection, to be sure that no seismic activity occurs as the fluid diffuses away from the wellbore. The monitored results should be fully considered, to allow determination of not only reservoir parameters, but also the in-situ stress, before the design of the main injection operation is finalised. We consider that this should be standard practice, at least until more data are collected and a more thorough analysis undertaken.	**Not specified**	Injection proceeds as planned.	**Not specified**	Injection proceeds as planned.	**<0.0**	Injection proceeds as planned.	**<0.0**	Injection proceeds as planned.
AMBER	**0.0<1.7**	Monitoring for at least 2 days until the seismicity rate falls below one event per day.	**0.0<0.5**	Increased 36-hour flowback period after completing the stage, and a further 12-hour pause following the mini-frac, with no increase in injection volume for the next stage.	**0.0<0.5**	Not specified	**Not specified**	Injection proceeds with caution, possibly at reduced rates. Monitoring is intensified.	**Not specified**	Injection could proceed after analysis, but with more caution, possibly at reduced rates and with a longer monitoring period and analysis between injections.	**0.0<0.5**	Injection proceeds with caution, possibly at reduced rates. Monitoring is intensified.	**0.0<0.5**	Injection proceeds with caution, possibly at reduced rates. Monitoring is intensified.
RED	**>1.7**	Operations are suspended with continued monitoring.	**>0.5**	Immediate cessation of injection and flushing of the well. In the event that the maximum seismicity detected during or after the injection was less than 1.5 ML, a longer 3-day flowback period is mandated. If no further seismicity greater than 1.0 ML is subsequently detected, the operator has the option of re-fracking the stage. However, if additional tremors above 1.0 ML occurred, no further injections on this stage are to be permitted, and the operator is required to move to the next stage. Finally, if the maximum seismicity during or after the initial frack exceeds 1.5 ML, a minimum 10-day flowback period is required, after which the operator must move to the next stage before fracking again.	**>0.5**	Operations should be halted and remedial action instituted. Immediate flow back should be implemented.	**Not specified**	Injection is suspended immediately.	**Not specified**	Injection is suspended immediately.	**>0.5**	Injection is suspended immediately. Pressure of the fluid reduced.	**>0.5**	Operator must suspend injection, reduce pressure and monitor seismicity and ground motion for any further events before potentially resuming.

Table 1: Traffic Light Systems: genealogy of key scientific report recommendations for regulation of induced seismicity.

Planning Policy Framework required local authorities to, "give great weight to the benefits of the mineral extraction, including to the economy" when determining planning applications (DCLG 2012). A later revision addressed shale gas directly, asserting the "pressing need to establish – through exploratory drilling – whether or not there are sufficient recoverable quantities of unconventional hydrocarbons […] to facilitate economically viable full scale production" (DCLG 2014). The UK Government Spending Round of 2013 thus announced a series of significant proposals to bring about "economic incentivisation at different scales of governance (for onshore oil and gas exploration companies, councils and affected site communities)." These included industry tax breaks, reduced business rates for local councils, proposed community benefits packages, and the introduction of a new regulatory framework. In 2014, Prime Minister David Cameron further announced that Britain was going "all out for shale" (Watt 2014).

Thus, economic and spatial planning policies more conducive to fracking were coupled to a re-stablised techno-political consensus for the regulation of seismic hazard. Speculative claims for the prospectivity of UK on-shore shale gas resources were represented by politicians as an opportunity for jobs, lower bills, local revenues, energy security and carbon emissions, with Prime Minister David Cameron arguing that the UK "cannot afford to miss out on shale gas" (Cameron 2013). At the same time, the framework that would regulate the nascent industry was moulded through a series of scientific commissions, reports and reviews, which constructed the Bowland Basin – and, in fact, all shale gas reservoir formations in England – as a concrete three-dimensional space of rationality and temporal order, in which minimal seismic hazards could be retroactively mitigated.

A key issue has been the means of measuring and quantifying relative levels of risk posed by seismic events. Since the 1930s, earthquakes have been classified according to the 'local magnitude' (ML) scale (more commonly known as the 'Richter Scale'). The measurements on this scale refer to the maximum recorded amplitude – or measured displacement distance – of seismic waves, corrected for the horizontal distance from the seismometer to the epicentre of the earthquake. However, amplitude is a poor measure of the size of an earthquake because its effect is influenced by factors such as the orientation of the fault that slipped and surface geology. Because of these and other factors, different recordings of the same earthquake at different stations may yield different magnitudes (Foulger *et al.* 2018).

As part of its regulatory guidance, the OGA also makes a distinction between 'magnitude' and the resultant 'ground motion' or intensity (measured in *g-force*, a function of ground *acceleration* – m/sec^2 – against time). It required that assessments of ML must be calibrated against stochastic models that predict ground motion, with knowledge of the regional and local geology also taken into account, allowing modifications made to the TLS thresholds as a result. As the OGA state:

> *While ML is useful for operational decisions because it can be computed very rapidly and defines a unique value for each seismic event, it may not fully reflect any resultant ground motion, which is dependent on such things as depth, distance and surface geology. Accordingly, the HFP should assess potential associated ground motion to identify the potential for damage to buildings (OGA 2018).*

Nevertheless, the primary metric by which the potential risk of adverse effects arising from an induced earthquakes is measured has remained as ML. The OGA's TLS guidance, 'Managing onshore induced seismicity' presents a classic representation of the Richter Scale, with no reference to ground motion intensity.

A number of studies have emphasised that the public evaluates risk communication in a broader context, which includes the historical associations encountered by many through the media between the Richter Scale and large and destructive earthquakes in foreign lands (e.g. Knoblauch *et al.* 2018). There is little empirical evidence for this hypothesis in relation to induced seismicity, however it has been shown that populations of low-seismicity regions are more socially sensitive to seismic events. As highlighted here, however, the arbitrary nature of both the spatial (i.e., magnitude 0.5ML) and temporal delineations in the TLS, and their incommensurability with the spatio-temporal heterogeneity of the Lancashire subsurface, has confounded the political imaginaries of those who seek to exploit shale gas resources in the UK.

4. LESSONS FOR GEOTHERMAL ENERGY IN THE UK'S NET-ZERO TRANSITION

With the fracking moratorium ongoing, a number of major UK Research and Innovation (UKRI) projects have been forced to re-frame their aims and objectives, shifting their focus from shale gas to geo-energy alternatives such as mine water geothermal, hydrogen, carbon capture, utilisation and storage (CCUS) and geothermal. This shift has placed an emphasis on the lessons that can be learned from the failure of shale gas for governance and regulation of these prospective subsurface industries. *Public Engagements with Induced Seismicity: Lessons for Geothermal Energy in the UK's Net-Zero Transition* (PEIS), a NERC/ESRC funded-project, pilots critical inquiry of public engagement with induced seismicity focussing empirically on the UDDGP project.

The approach to the research is informed by a growing body of research within Geography and Science and Technology Studies (STS) concerned with the politics of geoscientific knowledge production (e.g. Whatmore 2006, Barry 2013, Bridge 2013, Bobbette and Donovan 2018, Gormally *et al.* 2018, Kama and Kuchler 2019, Squire and Dodds 2020). This literature emphasises the need to investigate in depth the multiple political agencies and epistemic practices behind disputes over the governance of sub-surface resources.

The UDDGP project is being developed by Geothermal Engineering Limited (GEL), a company specialising in the development of geothermal resources. Sited at the United Downs Industrial Site near Redruth, the aim of the project is to demonstrate the technical and commercial viability of producing power and heat from radiothermal granite beneath Cornwall, exploiting the natural permeability of a significant deep structural fracture zone known as the Porthtowan Fault Zone. In 2009 the company received a £1.5 million grant from the DECC, and Cornwall Council granted planning permission for the project in 2010. The following year, GEL was awarded a further grant of £6m from the European Regional Development Fund.

In light of the contentious debates around induced seismicity in fracking, the UDDGP's two-legged well system was adopted to reduce the possible necessity for hydraulic stimulation of the rock, thereby negating the likelihood of significant tremors (Ledingham *et al.* 2019). However, a requirement both for seismic monitoring and for a monitoring and control protocol was included in the planning consent for the project. The protocol is based on both measured seismicity and surface ground vibration. It aims to minimise vibrations that might result in damage to buildings, or be considered disturbing by the population in the area. Thresholds are defined in terms of the Peak Ground Velocity (PGV), measured at surface and are based on British Standard (BS) 6472-2:2008, which provides a guide to evaluation of human exposure to vibration in buildings due to mine and quarry blasting. GEL has independently implemented a TLS, where different level of ground vibration prompt operational interventions and reporting to Cornwall Council. Site operations enter a 'caution' state if PGVs greater than 0.5mm/s are detected, with further action taken if PGVs of more than 8.5mm/s are detected.

The UDDGP heat production system relies on establishing hydraulic circulation between two wells intersecting the fault zone, an injection well at 2,393 metres deep and a 5,275-metre production well with downhole pump. Drilling began in 2018, and by the August 2019 the first phase of well testing—aimed at characterising the geothermal system, establishing and maintaining circulation and estimating the possible energy extraction—had been completed. Testing confirmed the temperature at 188 degrees Celsius and showed that the target formation has higher flow rates than the surrounding granite.

However, in late September 2020, following the detection of induced seismicity by the project's monitoring system, the second round of testing on the UDDGP site was suspended after one day. The BGS reported a series of 15 seismic events, one of which registered at ML 1.5. Local news outlets and two national newspapers reported that the tremors were felt by a number of people in the locality, with accounts of "windows rattling" and "houses shaking" (Mirror 2020). During a further phase of testing during the following December, another cluster of earthquakes were triggered. The largest, a ML 1.7 event, was reported to BGS by a at least one local resident, and GEL received a number of direct emails advising that this event had been felt (BGS 2020).

By contrast to fracking, the level of media interest and public controversy in response to the two clusters of seismic events induced by operations at UDDGP project has been minimal. However, notwithstanding GEL's efforts to publicly differentiate the techniques and protocols in place United Downs from those employed in fracking and other forms of EGS using hydraulic stimulation, it is notable that each phase of testing has been interrupted by seismic events of magnitudes that were not anticipated and were comparable to those experienced in Lancashire.

However, prominent in the discourse around UDDGP and its 'sister' project, Cornish Lithium (which aims to extract lithium from the same geothermal waters to supply the burgeoning electric car industry) are representations of Cornish industrial heritage and post-industrial development in the county. Their 'green' credentials are combined with 'UNESCO' imagery, the discourse of 'revival' and local jobs. Perhaps there is a sense that, as well as generating 'opportunities', the resources beneath their feet can make a contribution to solving wider problems. At first glance, there also appears to be a sense of ownership that contrasts starkly with fracking, which somehow was never associated with the equally strong industrial heritage of the northwest, and very much had the sense of a 'foreign' intrusion. We might ask, what difference this all makes to perceptions of seismic risk? Thus other concerns, such as induced seismicity, are eclipsed.

In light of the above, the first objective of the PEIS project is to:

> *Explore the potential consequences of an extension of networked actors, knowledge practices and tensions associated with fracking controversies into EGS.*

This is achieved by examining expert and political discourses around induced seismicity in fracking and EGS through an analysis of official and scientific documents. This analysis will compare the key vectors of controversy and epistemic communities around shale gas and geothermal energy. Building on this documentary research, in-depth interviews are conducted with key informants relating to this objective. These interviews provide a more detailed understanding of the epistemic framings of seismic risk posed by prospective EGS projects.

Secondly, the project will:

Examine how publics engage with scientific and political framings around induced seismicity

through a public workshop conducted in the locality of the UDDGP project. Challenging the top-down transfer of information from experts and policymakers to citizens, this workshop is designed to open institutional rationales to alternative forms of knowledge, experience and affects around the subsurface. Insights from these discussions are then used to co-produce a draft framework for a formal public engagement strategy for seismic monitoring systems aimed at policymakers, industry and regulators.

Finally, a key outcome of the project is a trans-disciplinary network of social and earth scientists, with a view to securing further funding and expanding the scope of the project to address public engagement with seismicity around other forms of geo-energy development. To this end, the project develops a future research agenda towards more meaningful and productive citizen engagement with the geosciences and the governance of geo-energy infrastructure.

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REFERENCES

Baptie, B. 2017. Earthquake Seismology 2015/2016: BGS Seismic Monitoring and Information Service, Twenty-seventh Annual Report. In: Baptie, B. (ed.). Bristish Geological Survey.

Barry, A. 2013. Material politics: Disputes along the pipeline, John Wiley & Sons.

BGS 2020. Induced Seismicity around the British Isles in the last 50 days [Online]. British Geological Survey. Available: http://www.earthquakes.bgs.ac.uk/induced/recent_uk_events.html [Accessed 15 October 2020].

Bobbette, A. & Donovan, A. (eds.) 2018. Political geology: Active stratigraphies and the making of life: Springer.

Bridge, G. 2013. Territory, now in 3D! Political Geography**,** 55-57.

Busby, M. 2019. Jeremy Corbyn decries fracking suspension as election stunt. The Guardian, 2 November 2019.

Cameron, D. 2013. We cannot afford to miss out on shale gas. The Telegraph, 11 August 2013.

Cuadrilla. 1 November 2012 2012. RE: Letter. Type to John Hayes Mp, M. O. S. F. E.

DCLG 2012. National Planning Policy Framework. Department for Communities and Local Government.

DCLG 2014. Guidance on the planning for mineral extraction in plan making and the application process [Online]. Department for Communities and Local Government. Available: https://www.gov.uk/guidance/minerals#planning-for-hydrocarbon-extraction [Accessed 17 April 2020].

DCLG 2016. Recovered appeals: Cuadrilla Bowland Ltd and Cuadrilla Elswick Ltd [Online]. Department for Communities and Local Government. Available: https://www.gov.uk/government/publications/recovered-appeals-cuadrilla-bowland-ltd-and-cuadrilla-elswick-ltd-refs-3134386-3130923-3134385-and-3130924-6-october-2016 [Accessed 17 April 2020].

de Pater, C. J. & Baisch, S. 2011. Geomechanical Study of Bowland Shale Seismicity: Synthesis Report. Geomechanical Study of Bowland Shale Seismicity." Bucknell University.

DECC 2013a. Onshore oil and gas exploration in the UK: Regulation and best practice. Department of Energy and Climate Change.

DECC 2013b. Traffic light monitoring system (shale gas and fracking) [Online]. Department for Energy and Climate Change. Available: https://www.flickr.com/photos/deccgovuk/11435544754/in/%20album-72157635443509437/ [Accessed 24 January 2021].

DECC 2013c. The Unconventional Hydrocarbon Resources of Britain's Onshore Basins: Shale Gas. Department of Energy & Climate Change.

DECC/Davey 2012. Written statement to Parliament Written Ministerial Statement by Edward Davey: Exploration for shale gas. Department of Energy and Climate Change/The Rt Hon Edward Davey MP.

Evensen, D., Devine-Wright, P. & Whitmarsh, L. 2019. UK National Survey of Public Attitudes Towards Shale Gas, 2019: Research Brief UKUH 01. Unconventional Hydrocarbons in the UK Energy System.

Foulger, G. R., Wilson, M. P., Gluyas, J. G., Julian, B. R. & Davies, R. J. 2018. Global review of human-induced earthquakes. Earth-Science Reviews, 178**,** 438-514.

Gluyas, J., Adams, C., Busby, J., Craig, J., Hirst, C., Manning, D., McCay, A., Narayan, N., Robinson, H., Watson, S., Westaway, R. & Younger, P. 2018. Keeping warm: a review of deep geothermal potential of the UK. Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 232, 115-126.

Gormally, A. M., Markusson, N. O. & Bentham, M. 2018. The pore space scramble; challenges and opportunities for subsurface governance. Geoforum, 95, 70-77.

Green, C. A., Styles, P. & Baptie, B. J. 2012. Preese Hall shale gas fracturing review and recommendations for induced seismic mitigation.

Kama, K. 2020. Resource-making controversies: Knowledge, anticipatory politics and economization of unconventional fossil fuels. Progress in Human Geography, 44, 333-356.

Kama, K. & Kuchler, M. 2019. Geo-Metrics and Geo-Politics: Controversies in Estimating European Shale Gas Resources. In: Bobbette, A. & Donovan, A. (eds.) Political Geology: Active Stratigraphies and the Making of Life. Cham: Springer International Publishing.

Knoblauch, T. A. K., Stauffacher, M. & Trutnevyte, E. 2018. Communicating Low-Probability High-Consequence Risk, Uncertainty and Expert Confidence: Induced Seismicity of Deep Geothermal Energy and Shale Gas. Risk Analysis, 38, 694-709.

Kuchler, M. 2017. Post-conventional energy futures: Rendering Europe's shale gas resources governable. Energy Research & Social Science, 31, 32-40.

Ledingham, P., Cotton, L. & Law, R. 2019. The United Downs Deep Geothermal Power project. Proc. 44th Work. Geotherm. Reserv. Eng, 1-11.

Maguire, J. 2020. The temporal politics of anthropogenic earthquakes: Acceleration, anticipation, and energy extraction in Iceland. Time & Society, 29, 704-726.

Mair, R., Bickle, M., Goodman, D., Koppelman, B., Roberts, J., Selley, R., Shipton, Z., Thomas, H., Walker, A., Woods, E. & Younger, P. 2012. Shale gas extraction in the UK: a review of hydraulic fracturing. June 2012.: The Royal Society, The Royal Academy of Engineering.

Mirror. 2020. English county hit by 15 earthquakes in space of 48 hours with houses shaking. Mirror, 1 October 2020.

OGA 2018. Consolidated Onshore Guidance, June 2018. Oil and Gas Authority.

OGA 2019. Interim report of the scientific analysis of data gathered from Cuadrilla's operations at Preston New Road. Oil and Gas Authority.

Squire, R. & Dodds, K. 2020. Introduction to the Special Issue: Subterranean Geopolitics. Geopolitics, 25, 4-16.

Styles, P. & Baptie, B. 2012. Induced seismicity in the UK and its relevance to hydraulic stimulation for exploration for shale gas: Briefing Note. Department for Energy and Climate Change.

Szolucha, A. 2018. Anticipating fracking: Shale gas developments and the politics of time in Lancashire, UK. The Extractive Industries and Society, 5, 348-355.

Szolucha, A. 2019. A social take on unconventional resources: Materiality, alienation and the making of shale gas in Poland and the United Kingdom. Energy Research & Social Science, 57, 101254.

Trutnevyte, E. & Ejderyan, O. 2018. Managing geoenergy-induced seismicity with society. Journal of Risk Research, 21, 1287-1294.

Watt, N. 2014. Fracking in the UK: 'We're going all out for shale,' admits Cameron. The Guardian, 13 January 2014.

Weszkalnys, G. 2015. Geology, potentiality, speculation: on the indeterminacy of first oil. Cultural Anthropology, 30, 611-639.

Whatmore, S. 2006. Materialist returns: practising cultural geography in and for a more-than-human world. cultural geographies, 13, 600-609.

Williams, L. & Sovacool, B. K. 2019. The discursive politics of 'fracking': Frames, storylines, and the anticipatory contestation of shale gas development in the United Kingdom. Global Environmental Change, 58, 101935.

Williams, L. & Sovacool, B. K. 2020. Energy democracy, dissent and discourse in the party politics of shale gas in the United Kingdom. Environmental Politics, 29, 1239-1263.