Institution: University of Bristol		
Unit of Assessment: 7 Earth Systems and Environmental Sciences		
Title of case study: Microseismic research improves safety of shale gas extraction and efficiency of construction		
Period when the underpinning research was undertaken: 2010 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed:**
James Verdon	Lecturer	2011 – Present
Michael Kendall	Professor	2005 – 2019
Antony Butcher	Research Associate	2018 – Present
Max Werner	Senior Lecturer	2013 – Present
Period when the claimed impact occurred: 2014 – 2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact

The University of Bristol's (UoB) research into small earthquakes generated by industrial activities in the subsurface, known as microseismicity, provides the scientific foundation for the current debate regarding shale gas extraction in the UK and is shaping regulatory and industry practices. Since 2014, the researchers have:

- Advised and trained UK regulators on mitigating the environmental risks of fracking, and provided the scientific basis for the UK government's moratorium on fracking in 2019.
- Designed seismological monitoring arrays for shale gas operators that have reduced the projected costs of drilling by several million GBP.
- Designed and implemented induced earthquake magnitude scales and forecasting systems used by operators and regulators to guide real-time decisions which promote safety and reduce disruption during fracking.
- Formed a profitable spin-out consultancy with international scope.

UoB used the same microseismic methods to measure rock stability during construction of Hinkley Point C. This provided an immediate saving of over GBP200,000 to EDF and shortened the construction programme by 4 weeks, with an estimated energy production value of approximately GBP100 million.

2. Underpinning research

Many human activities in the subsurface create 'microseismicity' – earthquakes that are too small to feel (magnitude (M) < 2). However, occasionally they create larger seismic events that can be felt, and which could potentially cause damage. It is these larger 'induced' seismic events that have raised safety concerns for the shale gas industry. Established in 2004, the Bristol University's Microseismicity ProjectS (BUMPS) research consortium draws funding from industry, regulators and UKRI **[References i-iv]** and leads the way in measuring and analysing patterns of microseismicity to image mechanical processes caused by human activities in the subsurface. Earlier BUMPS research (2009–2012) had focused on the use of microseismicity for oil reservoir analysis to optimise economic production. However, as concerns around induced seismicity have grown, BUMPS research (2013–present) has responded by generating the scientific basis needed to guide safety decisions with respect to induced seismicity. This underpinning research has enabled new monitoring and analysis tools which reduce the chances of induced earthquakes.

Monitoring Techniques. BUMPS researchers were the first in the UK to adapt the latest innovations in seismology, including full-waveform methods (using the entire seismic trace rather than picking phases), Fiber-Optic Distributed Acoustic Sensing (DAS), and machine learning, to detect and locate microseismic events generated by subsurface activities. For example, in 2013, BUMPS developed a method using full-waveform simulation to evaluate and optimise the expected performance of borehole seismometer arrays prior to deployment **[1]**. The combination of these methods has produced order-of-magnitude scale improvements in our ability to detect small-magnitude microseismic events.

Magnitude Scales. Accurate calculation of event magnitudes is critical for assessing induced seismicity hazard. However, prior to 2015, the UK local magnitude scale (designed for natural earthquakes) had been calibrated using only larger earthquakes recorded on distant stations and it therefore produced significant systematic errors when applied to induced events recorded on local networks in close proximity to the source. BUMPS were the first to identify this issue and, in 2017, provided the necessary corrections to the scale **[2]**. In 2018, they collaborated with the British Geological Survey to create a 'unified' scale that provides accurate magnitude values at all distances, encompassing both natural earthquakes and local-scale microseismicity **[3]**.

Forecasting. Operational decision-making to mitigate induced seismicity during hydraulic fracturing requires accurate forecasts of event magnitudes, i.e. what event magnitudes might be reached if operations continue as planned? BUMPS researchers have pioneered statistical methods based on the parameterisation of seismic event populations to forecast event magnitudes as a function of injection volume **[4]**.

Mechanical Processes and Interpretation. BUMPS developed new methods which use microseismic observations to understand mechanical processes in the subsurface. These include imaging and understanding interactions between hydraulic fractures and faults **[4]** and using velocity observations to image fracturing during rock excavation **[5]**. Following earthquakes near oil-drilling activities in Newdigate in 2018, BUMPS developed a novel decision-making framework to discriminate between human-induced and natural earthquakes **[6]**, and this was the first to incorporate, quantify and characterise observational uncertainties.

3. References to the research

[1] Usher P., D.A. Angus, J.P. **Verdon**, 2013. Influence of velocity model and source frequency on microseismic waveforms: some implications for microseismic locations. Geophysical Prospecting. 61, 334-345. DOI: 10.1111/j.1365-2478.2012.01120.x
[2] Butcher A., R. Luckett, J.P. **Verdon**, J.-M. **Kendall**, B. Baptie, J. Wookey 2017. Local Magnitude Discrepancies for Near-Event Receivers: Implications for the U.K. Traffic-Light Scheme. Bulletin of the Seismological Society of America. 107, 532-541. DOI: 10.1785/0120160225.
[3] Luckett R., L. Ottemoller, A. **Butcher**, B. Baptie 2019. Extending local magnitude M_L to short distances. Geophysical Journal International. 216, 1145-1156. DOI: 10.1093/gji/ggy484.
[4] Verdon J.P., J. Budge, 2018. Examining the capability of statistical models to mitigate induced seismicity during hydraulic fracturing of shale gas reservoirs. Bulletin of the Seismological Society of America. 108, 690-701. DOI: 10.1785/0120170207.
[5] Foord, G., J.P. **Verdon** and J.-M. **Kendall**, 2015. Seismic characterization of fracture compliance in the field using P- and S-wave sources, Geophysical Journal International. 203, 1726-1737. DOI: 10.1093/gji/ggv395.
[6] Verdon J.P., B.J. Baptie, J.J. Bommer, 2019. An improved framework for discriminating seismicity induced by industrial activities from natural earthquakes. Seismological Research Letters. 90, 1592-1611. DOI: 10.1785/0220190030.
[i] Kendall (2010-2019). Bristol University Microseismicity Projects (BUMPS): Joint industry project Funders during this REF period include: BP (2014-2016), Total (2014-2019), the Oil and Gas Authority (2015-2016), Chevron (2014-2019), Cuadrilla (2014-2017), Environment Agency (2017), Exxon (2014-2017), Magnitude-CGG (2014-2017), Microseismic Inc. (2014-2017), Schlumberger (2014-2019), Tesla (2014-2017) and Wintershall (2014-2019). Total funding c. GBP1,250,000
[ii] Verdon (2018-2022). An integrated assessment of UK shale resource distribution based on fundamental analyses of shale mechanical and fluid properties. NERC R018162/1, GBP224,000
[iii] Kendall (2018-2022). Impact of hydraulic fracturing in the overburden of shale resource plays: Process-based evaluation (SHAPE-UK). NERC R018006/1, GBP449,000
[iv] Kendall (2018-2019). Fibre-optic distributed Acoustic Sensor Technology for seismic Monitoring During shale gas Extraction (FAST-MoDE). NERC R014531/1. GBP225,000

4. Details of the impact (indicative 750 words)

1. The UK Shale Gas Industry: Impacts on regulators and operators

The shale gas ('fracking') industry is valued globally at over USD40 billion per year. The British

Geological Survey estimates the UK has a resource of 1,200 trillion cubic feet of shale gas, with an economic value of approximately GBP1 trillion, could it be extracted safely. However, fracking remains controversial as a method of resource extraction with high levels of public concern surrounding induced seismicity in particular. BUMPS researchers have worked closely with the regulators of the shale gas industry, the Oil and Gas Authority (OGA) and the Environment Agency (EA), to reach significant safety decisions on shale gas development in the UK. The OGA's Head of Onshore Exploration and Development states UoB's research *"has provided us with significant insight into understanding the risk of induced seismicity and supported our evidence base for the operational and policy decisions"* **[Evidence a]** and the EA's Principal Scientist notes that the research "*is being used in helping to inform day to day operational and regulatory decisions*" **[b].** All three major hydraulic fracturing companies in the UK (Third Energy, IGas and Cuadrilla) approached BUMPS to help ensure safe conduct with respect to induced seismicity and the potential for shallow groundwater contamination. IGas state "*The contribution made by BUMPS to the debate was extremely valuable as it took a rigorous and analytical approach*" **[c]**.

Presented here is a timeline of key actions and decisions underpinned by BUMPS research, starting with the development of Hydraulic Fracture Plans (HFPs) and culminating in the Department for Business, Energy & Industrial Strategy's (BEIS) decision to impose a moratorium on fracking in 2019.

Hydraulic Fracture Plans (HFPs) (2017-2019). Hydraulic Fracture Plans (HFPs) describe the actions that an operator will take to minimise the risks of induced seismicity and to ensure that hydraulic fractures do not propagate beyond the target zone where they could potentially pose a risk of groundwater contamination by fluids used in fracking. Produced by operators, HFPs must be approved by both the OGA and EA before operations can commence.

BUMPS researchers worked with both operators and regulators to develop and assess HFPs. For operators, the researchers designed geophysical monitoring arrays using full waveform analysis methods **[1]**, and developed safety protocols that in 2017 formed the basis of Third Energy's HFP **[d]**, and of operational plans for IGas in 2019 **[c]**. IGas' Senior Geophysicist states that IGas "*incorporated the designs developed by the* [UoB] *group*" into their planned microseismic deployment **[c]**, and BUMPS' "*capability assessments have been factored into* [IGas'] *well designs*" **[c]**. In particular, BUMPS demonstrated that an existing well would provide sufficient monitoring to meet regulatory requirements, thereby removing the need to drill an additional well **[c],** which typically costs several million GBP. For Third Energy, one of the first shale gas developers in the UK, BUMPS researchers designed surface and downhole microseismic monitoring arrays for their planned hydraulic fracturing at the KM-8 well in North Yorkshire **[d]**. These arrays were installed and calibrated in November 2017. BUMPS researchers further designed the decision-making protocols and risk mitigation measures that Third Energy agreed to apply if a larger seismic event were to occur. Third Energy's HFP for the KM-8 well is lead-authored by a BUMPS researcher, James Verdon, reflecting BUMPS' involvement in Third Energy's planning **[d]**. This was the first HFP to receive regulatory approval from the OGA and EA.

In terms of regulatory assessment of HFPs, the EA had little experience with microseismic monitoring or induced seismicity prior to 2017. Thus, in 2017-18, a BUMPS researcher, Anna Stork, spent 6 months embedded at the EA where she trained over 70 EA staff in geophysical monitoring and provided expertise to ensure appropriate regulation of hydraulic fracturing **[b]**. The EA's Principal Scientist states that, as a consequence, EA staff are now *"better able to specify information required for regulatory purposes, from industry about their proposals"* and *"better equipped to deal with questions from the public and freedom of information requests"* **[b].** Webinar and workshop materials produced by BUMPS are retained in EA's library of training resources **[b].**

Implementing the Traffic Light Scheme (October 2018-2019). In 2012, the OGA proposed a Traffic Light Scheme to regulate induced seismicity based on the magnitude of microseismic events; operators must pause and assess activities if a 'red' event (over M 0.5) occurs. Since the UK magnitude scale at the time produced systematic errors when applied to microseismicity **[3]**, the British Geological Survey responded by adopting BUMPS' newly-revised local magnitude scale for all magnitude calculations in the UK in 2018 **[3]**. This was done in preparation for Cuadrilla's Preston New Road site - the first hydraulic fracturing operations in 7 years and the first

use of the scheme **[a]**.

Distinguishing Natural and Induced Seismicity (2018). In 2018, a sequence of earthquakes with magnitudes up to 3.2 occurred near Newdigate in southeast England. Media reports[1] (and some academics) attributed this earthquake sequence to nearby oil drilling activities (by UKOG and Angus Energy). BUMPS researchers were invited by the OGA to join a panel of experts convened to assess the events in October 2018 **[e]**. This panel judged that the events were natural and, therefore, the OGA took no further regulatory action, allowing operators to continue their activities **[a]**. The panel also concluded that existing methods for distinguishing between natural and induced seismicity were not fit for purpose. BUMPS researchers therefore created a scheme capable of handling observational uncertainties **[5]** that the OGA states "*is a significant improvement and the OGA will use this scheme to assess future cases of potential induced seismicity*" **[a]**, i.e. where earthquakes occur near an oilfield and it is unclear whether they are induced or natural.

Real-time Forecasting and Mitigation (Q4 2018-Q3 2019). Cuadrilla began operations at the Preston New Road site in 2018, first working on the PNR-1z well in Q4 2018, followed by the PNR-2 well in Q3 2019. The abilities and reputation of the BUMPS group is such that both the regulator (the OGA) and the operator (Cuadrilla) chose to embed BUMPS researchers in their organisations during these activities. Cuadrilla used BUMPS' event magnitude forecasting capabilities to guide their operational controls on induced seismicity. A paper lead-authored by Cuadrilla's Senior Geoscientist **[f]** states that "*this approach was used in real time to make operational decisions during hydraulic fracturing operations*", and that "*this information allowed* [Cuadrilla] *to adjust its injection program, ensuring that levels of seismicity did not exceed the overall objectives set by the regulator*". For the OGA, BUMPS' microseismic analysis and interpretation "*inform*[ed] *decisions made* [by the OGA] *with respect to restarting operations after a "red" event was detected during operations*" **[a]**.

At PNR-1z, BUMPS' forecasting model **[4]** had predicted that magnitudes would not exceed M 2. Hence, even though events had reached the precautionary M 0.5 red light threshold on several occasions, the operator was able "*to proceed with confidence that the hydraulic stimulation was unlikely to cause reactivation of the larger faults that had been identified*" **[f]**, and to be sure that "*the levels of seismicity would not exceed the objectives set by the OGA, and therefore injection could be conducted safely*" **[f]**. As such, Cuadrilla could continue operations without needing to adjust their injection plans, using full injection volumes and pressures for all available stages **[f]**. For the regulator, BUMPS' models and interpretations provided the scientific basis to allow the operations to proceed **[a]**. The largest event magnitude at PNR-1z was M 1.5, a level that can barely be felt at the surface and is far too small to cause damage.

At PNR-2, BUMPS' analysis showed the onset of interaction between hydraulic fractures and a potentially seismogenic fault, and the forecasting model predicted that magnitudes might exceed M 2.5. A paper co-authored by BUMPS researchers and Cuadrilla's geologists shows that "*the operator was able to identify the increased rate of seismicity relative to the PNR-1z well and adjusted the injection program to reduce the likelihood of further fault interaction*" **[f]**, by increasing the injection fluid viscosity and reducing the injected fluid volumes by two-thirds. Despite these adjustments, seismicity continued, and the largest event magnitude reached M 2.9. This event was widely felt in the towns of Preston and Blackpool and some media reports indicated potential minor damage at nearby properties[2]. Evidently, the operator's adjustments failed to prevent larger events from occurring, but this example demonstrated that BUMPS' forecasting model was able to identify that a larger event was likely, and that this information was acted upon by the operator. Following the M 2.9 event, BUMPS' updated forecasts showed that events with magnitudes larger than M 3 might be expected if operations were to continue. On this basis, the OGA halted all hydraulic fracturing activities at the Preston New Road site **[a]**.

Informing the Moratorium (November 2019). Following the seismicity at the PNR site, the OGA commissioned BUMPS researchers in 2019 to write two reports, on the geomechanical interaction between hydraulic fractures and faults, and on forecasting of magnitudes **[g]**. These BUMPS'

[1] https://www.bbc.co.uk/news/uk-england-44727326
[2] https://www.bbc.co.uk/news/uk-england-lancashire-50202033

contributions **[g]** were two of just four reports used in the subsequent OGA report (published November 2019) which analysed induced seismicity at PNR-1z **[h]**. On the day of the OGA report's publication, the UK government announced a moratorium on fracking. BEIS stated that "*Ministers took the decision on the basis of* [the] *report by the Oil and Gas Authority*" **[h]**. This demonstrates BUMPS' prominent role in guiding and influencing this highly significant government decision.

2. Impacts beyond hydraulic fracturing: Hinkley Point C construction

BUMPS' expertise in microseismicity has also brought economic and efficiency benefits for the construction industry, as evidenced by the case of the Hinkley Point C nuclear power station. Previously, the constructors (Kier BAM) had used engineering judgement to assess disturbance at construction sites, meaning that slopes were over-engineered to ensure a safety margin. In 2017, BUMPS provided quantitative assessment methods for Hinkley Point C's construction which allowed Kier BAM to measure rock disturbance more precisely, thereby reducing the amount of slope-stability engineering used. "[The] *results of* [BUMPS'] *geophysical surveys … culminated in a reduction in the slopes construction programme of circa 4 weeks, saving labour and material costs of approximately £225,000. More significantly, a reduction in the slopes construction programme has the potential to benefit the overall station construction programme."* [Technical Manager, Kier Bam Earthworks Joint Venture] **[i]**. In addition to direct labour and material savings, the impact of the reduction in construction programme by 4 weeks, given a strike price of GBP92.5/MWh and a generation capacity of 1600MWe[3], has a value of over GBP100,000,000.

3. Spin-off company and International Impact: Outer Limits Geophysics LLP

BUMPS has a "*strong, international reputation in the use of microseismic monitoring*" [Chief Technology Officer, Petoro AS] **[j].** Its research, therefore, led to the creation of a profitable consultancy company, Outer Limits Geophysics LLP (OLG), which has global reach and *"an annual turnover of £50,000 - £60,000 per year on average*" since its inception in 2014. OLG have provided seismic monitoring services in Saskatchewan; acted as expert witnesses for hearings on induced seismicity in Alberta, Canada; performed array design, data analysis and interpretation for a hydraulic fracturing operator in Argentina; designed geophysical arrays for monitoring geomechanical deformation in the North Sea; and monitored for induced seismicity for a hydraulic fracturing operator in the Thrace Basin, Turkey **[j]**. The lead geophysicists for OLG state "*As a spin-out company from the BUMPS Project at the University of Bristol, our success as a consultancy service is entirely predicated on the high quality and international reputation of the BUMPS group*." **[j]**.

5. Sources to corroborate the impact

[a] OGA (2020) Supporting statement - Head of Onshore Exploration and Development.
[b] Environment Agency (2018) Supporting statement - Principal Scientist, E&B Research.
[c] IGas (2019) Supporting statement - Senior Geophysicist.
[d] Third Energy (2017) Hydraulic Fracture Plan for Well KM-8. See: *Approval List, p2.*
[e] OGA (2018) OGA Newdigate Seismicity Workshop report. See: *Annex 1: p4.*
[f] Clarke et al., (2019), *Seismological Research Letters*. DOI: 10.1785/0220190110; Kettlety et al. (2020), *Seismological Research Letters.* DOI: 10.1785/0220200187.
[g] Verdon et al., (2019), Geomechanical Interpretation of Microseismicity at the Preston New Road PNR-1z Well, Lancashire, England, Report Commissioned by the OGA | Mancini et al., (2019), Statistical Modelling of the Preston New Road Seismicity: Towards Probabilistic Forecasting Tools: Report Commissioned by the OGA.
[h] BEIS, OGA, K. Kwarteng MP, A. Leadsom MP.(2019) Press release: Government ends support for fracking | OGA (2019) Preston New Road - PNR 1Z - Hydraulic Fracturing Operations Data See references to: 'Induced seismicity and potential subsurface mechanisms - led by Outer Limits Geophysics' and 'Innovations in forecasting the distribution of seismicity - led by the British Geological Survey' (co-authored by University of Bristol).
[i] KierBAM (2018) Supporting statement – Technical Manager | EDF (2019) Supporting statement – Geotechnical SME.
[j] Petoro (2020) Supporting statement – Chief Technology Officer; Outer Limits Geophysics (2020) Supporting statement - Founding Partners

[3] https://www.world-nuclear-news.org/NP-Hinkley-Point-C-contract-terms-08101401.html