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Fracking bad language – hydraulic fracturing and earthquake risks

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Abstract. Hydraulic fracturing, or fracking, is a borehole stimulation technique used to enhance permeability in geological resource management, including the extraction of shale gas. The process of hydraulic fracturing can induce seismicity. The potential to induce seismicity is a topic of widespread interest and public concern, particularly in the UK where seismicity induced by hydraulic fracturing has halted shale gas operations and triggered moratoria. Prior to 2018, there seemed to be a disconnect between the conclusions of expert groups about the risk of adverse impacts from hydraulic-fracturing-induced seismicity and the reported level of public concern about hydraulic fracturing induced seismicity. Furthermore, a range of terminology was used to describe the induced seismicity (including tremors, earthquakes, seismic events, and micro-earthquakes) which could indicate the level of perceived risk. Using the UK as a case study, we examine the conclusions of expert-led public-facing reports on the risk (likelihood and impact) of seismicity induced by hydraulic fracturing for shale gas published between 2012 and 2018 and the terminology used in these reports. We compare these to results from studies conducted in the same time period that explored views of the UK public on hydraulic fracturing and seismicity. Furthermore, we surveyed participants at professional and public events on shale gas held throughout 2014 asking the same question that was used in a series of surveys of the UK public in the period 2012–2016, i.e. "do you associate shale gas with earthquakes?". We asked our participants to provide the reasoning for the answer they gave. By examining the rationale provided for their answers, we find that an apparent polarisation of views amongst experts was actually the result of different interpretations of the language used to describe seismicity. Responses are confounded by the ambiguity of the language around earthquake risk, magnitude, and scale. We find that different terms are used in the survey responses to describe earthquakes, often in an attempt to express the risk (magnitude, shaking, and potential for adverse impact) presented by the earthquake, but that these terms are poorly defined and ambiguous and do not translate into everyday language usage. Such "bad language" around fracking has led to challenges in understanding, perceiving, and communicating risks around hydraulic-fracturing-induced seismicity. We call for multi-method approaches to understand the perceived risks around geoenergy resources and suggest that developing and adopting a shared language framework to describe earthquakes would alleviate miscommunication and misperceptions. Our findings are relevant to any applications that present – or are perceived to present – the risk of induced seismicity. More broadly, our work is relevant to any topics of public interest where language ambiguities muddle risk communication.

1 Introduction

Shared decision-making on complex sociotechnical issues such as climate change requires effective dialogue between stakeholders, including academics, regulators, industry, policy makers, civil society, and the public. However, clear communication to support effective dialogue presents challenges. Geoscience topics can face particular communication challenges for several reasons. First, geoscience underpins many issues of environmental and societal importance, such as resource development (water, mineral, and energy resources) and understanding and mitigating climate change. These issues are not only important for future generations but also associated activities (e.g. resource extraction and the development of low-carbon energy projects) have direct and indirect socioeconomic and environmental impacts at a range of scales (Leach, 1992; Vergara et al., 2013; Adgate et al., 2014; Stephenson et al., 2019). Second, many geoscience concepts and technologies, as well as the geological resources that modern lives depend on, are uncertain or unfamiliar to the wider public. This is complicated by the fact that the Earth's subsurface is by nature both heterogenous and largely inaccessible. Amongst geoscientists, uncertainties around, for example, geological heterogeneity, affect the confidence of predicted geological properties or structure (Lark et al., 2014; Bond, 2015) and can lead to differing interpretations of the subsurface (Bond et al., 2007; Alcalde et al., 2019; Shipton et al., 2019) – even scientific dispute; compare the interpretations of the North Sea Silverpit Crater (Stewart and Allen, 2002, 2004; Underhill, 2004) or causes of the Lusi mud volcano (Mazzini, 2018; Tingay et al., 2018). Third, the inaccessibility of and general unfamiliarity with the subsurface can make it challenging for laypeople to conceptualise it (Gibson et al., 2016) and, particularly, to conceptualise geological processes or climate and engineering risks (Taylor et al., 2014). Finally, geoscience terminology is often ambiguous, incomprehensible for many outside – and within – the discipline, or has multiple meanings. As an example, it is common to use ambiguous phrases or descriptors such as "deep" in the Earth, "low levels" of contaminants, a "large" fault, or "geological timescales". Even the technical language used to describe geological observations can imply a specific conceptual model or processes, or have slightly misleading meanings relating to the outdated origins of the word, both of which can lead to miscommunication amongst geoscience experts (Shipton et al., 2019; Bond et al., 2007). A key finding of this paper is that language ambiguity around earthquakes presents challenges for geoenergy communication and decision-making.

Stakeholder perspectives have diverged on issues such as the risk or of the geological disposal of radioactive waste (Vander Becken et al., 2010; Lowry, 2007), shale gas (Graham et al., 2015), and urban planning (Marker, 2016). Hydraulic fracturing (often referred to as "fracking", sometimes spelt "fraccing" or "fracing") for shale gas presents one such high-profile example. Here, we explore the perception of, and terminology around, the risks (likelihood and impact) of induced seismicity presented by hydraulic fracturing for shale gas in the UK context. This work is timely – how we use the subsurface is changing as we transition to a low-carbon economy, new technologies and new ways of using the subsurface are anticipated in coming decades (Stephenson et al., 2019), and there is a clear need for further social scientific insights to inform risk management and communication around geoenergy-induced seismicity (Trutnevyte and Ejderyan, 2018).

To frame our work, we consider the importance of communication, including language and framing amongst stakeholders, and provide an overview of shale gas exploration and development and induced seismicity, with a particular focus on the UK as a case study. We then present our research in two parts. In Sect. 2, we examine how the risk of induced seismicity is described in expert-led technical reports and in public perception studies of hydraulic fracturing. In Sect. 3, we present our survey approach and results to investigate the perceived risk of seismicity induced by hydraulic fracturing for shale gas and explore how understanding of perceived risk is complicated by language ambiguity around seismicity[1]. We discuss our findings and their implications in Sect. 4.

Our findings are applicable to a range of geological applications which could induce seismicity (including hydropower dam construction, carbon capture and storage, geothermal energy extraction, energy storage, etc.), many of which are considered fundamental to delivering a sustainable future (Trutnevyte and Ejderyan, 2018; Stephenson et al., 2019). Furthermore, the findings around language and communication and understanding perceived risk are applicable to issues beyond geological engineering and are key for supporting stakeholder dialogue for shared decision-making.

1.1 Language and communication in geosciences

There have been growing moves to increase public involvement in scientific issues – from funding priorities and data collection, to policy decisions – particularly on topics with social and environmental importance such as climate change, flooding, energy policy, and genetically modified crops (e.g. Rowe et al., 2005; Parkins and Mitchell, 2005; Horlick-Jones et al., 2007; Nisbet, 2009). This progression brings a new communication challenge, i.e. for scientists, policy makers, and the public to be able to share information, concepts, and ideas, and to make shared decisions, they must be able to understand each other. The truth is that within languages there are subsections that are only accessible to those with technical expertise on the matter at hand. Specific language frameworks and jargon are prevalent within specific disciplines and underpin the explanation of concepts between experts (Montgomery, 1989; Collins, 2011). However, such language can be incomprehensible to those outside the

[1] We use the term seismicity in the body of this paper as a catch-all term to describe the phenomena of rapidly radiated seismic energy that has been described by terms that include earthquakes, tremors, and so on. Second, although we focus on seismicity in this paper, in doing so we do not construe any specific importance to this or other issues associated with shale gas extraction. We merely use it as a pertinent example of the importance of language use in scientific communication.

subject area (Leggett and Finlay, 2001; Sharon and Baram-Tsabari, 2014). This creates an “unequal communicative relationship,” whereby laypeople struggle to comprehend the technical language and goals set by experts (Fischer, 2000, p. 18), particularly as many experts are ill-equipped in communicating with members of the public (Simis et al., 2016).

This unequal communicative relationship is likely enhanced in the geosciences where seemingly nontechnical, uncertain, or ambiguous terms are used routinely but assume tacit understanding. As an example, geoscientists may refer to the dip and strike of faults, joints, or cleavage; these are all terms which have specific meanings in geology but also have other meanings in the English language. But tacit understanding is not reliable; loose use of language, ambiguity, and poorly defined technical terms can lead to misunderstanding even amongst experts (van Loon, 2000; Doust, 2010) and between subdisciplines (Collins, 2011).

It is well established that how individuals perceive new information is influenced by factors such as expertise, context, prior knowledge, and the language used (McMahon et al., 2015; Venhuizen et al., 2019). Values and motivation, including affiliations and world view, have particular influence on perceptions of risk and the assessment of any new information (NASEM, 2017; Roberts et al., 2020) and how the information is framed (Pigeon, 2020). Consider the original work on framing by Tverskey and Kahneman (1981). In their example, when disease treatment options were framed positively (lives saved) rather than negatively (lives lost) people chose more risky treatment options. Similar work has found that how geoscience data and information are framed affects decision-making (Taylor et al., 1997; Barclay et al., 2011; Alcalde et al., 2017).

There was a notable shift in the framing of positive and negative arguments around shale gas extraction in the UK. Early arguments adopted local frames, such as concerns about local effects like induced seismicity, traffic, and noise. These arguments were replaced by global frames such as concerns about the climate change implications of developing onshore gas resources (Hilson, 2015) or the changing role of natural gas in the energy transition (Partridge et al., 2017). But, as we show in the remainder of this section, induced seismicity kept a high public and political profile in the UK.

1.2 Hydraulic fracturing, induced seismicity, and shale gas development

Hydraulic fracturing (often referred to as “fracking”) is the process of fracturing rocks at depth by injecting pressurised fluids. The process locally increases the permeability of the rock formation, which is useful for a range of applications from improving water extraction (Cobbing and Ó Dochartaigh, 2007) and enhancing deep geothermal energy production (Breede et al., 2013) to enabling the recovery of natural gas trapped in rocks with a low permeability, such as “tight gas” or shale gas (Mair et al., 2012). Hydraulic fracturing also occurs in nature, usually where geological processes cause geofluids to become overpressured enough to overcome the rock strength and cause the rock to fracture (e.g. Engelder and Lacazette, 1990; Fall et al., 2015).

For shale gas extraction, hydraulic fracturing is one of several processes that allows the hydrocarbons to be recovered from the low-permeability rocks in which they are trapped (King, 2012). A borehole might be hydraulically fractured as part of shale gas exploration or development, where exploration refers to activities that investigate the commercial viability of a potential shale gas resource and development refers to activities that support the commercial production of the resource.

As a rock fractures, seismic energy is released (e.g. Tang and Kaiser, 1998) as a seismic event or seismicity. For shale gas hydraulic fracturing, because the fracturing process is caused by human activity, the seismicity is categorised as being human-induced seismicity or, simply, induced seismicity. Many processes induce seismicity, from mining and quarrying and filling and dewatering reservoirs to disposing of wastewaters by injection into rock formations (Westaway and Younger, 2014; Pollyea et al., 2019). However, not all seismic events have any detectable effect in terms of being felt at the surface or even recorded (Kendall et al., 2019).

There are a number of approaches to quantifying, and reporting on, the size of a seismic event. The moment magnitude (M_w) relates to the seismic moment, which is the energy released by the event. The local magnitude (M_l) measures the ground displacement. The two scales of M_l and M_w are fundamentally different, and so the M_w and M_l of a seismic event can diverge, particularly for large ($> M$ 6.0) and small ($< M$ 2.0) events (Clarke et al., 2019; Kendall et al., 2019). Seismologists prefer M_w because it relates to the properties of the fracture (the seismic moment) and because M_l breaks down for events below M_l 2.0 (Kendall et al., 2019). However, M_l is easier to use for real-time reporting, and so it is used to report seismic events and to regulate induced seismicity (Butcher et al., 2017). A variety of terms are used by both experts and laypeople to describe a seismic event, including earthquakes, tremors, and micro-earthquakes. Seismologists have proposed particular terminology based on the property of a seismic event, such as the frequency content or the magnitude (for example, see Bohnhoff et al., 2010; Eaton et al., 2016), but there is no common classification framework. This poses questions such as “How big is a small earthquake?” (Kendall et al., 2019).

Hydraulic fracturing will be accompanied by the release of seismic energy as the rock is fractured by the fluid pressure (Kendall et al., 2019). The energy released by an individual fracture is small, typically representing M_l −1.5 (Mair et al., 2012), but if hydraulic fracturing fluids reach a prestressed fault then larger events can occur (Clarke et al., 2019). Induced seismicity is, thus, inherent in hydraulic fracturing. But there are uncertainties regarding the measurement, forecasting of, and magnitude of these events (Kendall et al., 2019). The nominal detection level for the UK seismic monitoring network (seismograph stations operated by the British Geological Survey) is M_l 2.0 (i.e. events above M_l 2 might be measured at the surface; Kendall et al., 2019), or M_l 2.5 in urban areas due to background noise. Acoustic monitoring systems away from background noise, such as in mines, can record very small seismic events down to magnitude M_w −4 (Kwiatek et al., 2011; Jalali et al., 2018). Whether or not an event is felt at the surface depends on several factors, including the seismic moment, the hypocentral depth and the attenuating properties, the structure of the rocks through which the energy travels, and other local conditions, such as the stiffness of the ground, the background noise, and the time of day (Butcher et al., 2017; Kendall et al., 2019). Furthermore, recorded M_l is dependent on the seismic detection network, including the array density and location distance between the source and the detector (Butcher et al., 2017).

Incidences of felt seismicity associated with hydraulic fracturing for shale gas in the UK, US, Canada, and China are well documented (Warpinski et al., 2012; Verdon and Bommer, 2021; Schultz et al., 2020), but when shale gas exploration began in the UK circa 2009, this was not the case. Despite many thousands of hydraulic fracturing treatments, there were no recorded or reported incidences of felt seismicity associated with fracking in the shale gas basins first developed in the USA (Verdon and Bommer, 2021). Seismic events that had been felt were due to the geological disposal of hydraulic fracturing wastewater rather than the fracking process itself (e.g. Elsworth, 2013). However, in 2011, a series of seismic events with maximum magnitude (M_l) 2.3 (Clarke et al., 2014) occurred at the Preese Hall shale gas exploration site in Lancashire (northwestern England, UK), suspending operations. These seismic events led shale gas activities to have a high public and political profile (Green et al., 2012; Selley, 2012; Clarke et al., 2014), receiving widespread media coverage and stimulating a wave of public protests against shale gas activities (Matthews and Hansen, 2018; Jaspal and Nerlich, 2014). The UK government introduced a moratorium on hydraulic fracturing for 6 months following the 2011 events. In December 2012, the UK government lifted the moratorium in England and Wales (Alessi and Kuhn, 2012), but in Scotland, moratoria have been applied by Scottish Government. The UK government introduced new regulatory requirements intended to effectively mitigate seismic risks (DECC, 2013a, b), including a traffic light system (Fig. 1) based on the local magnitude (M_l) of induced events. In November 2019, the moratorium was reapplied following publication of the Oil and Gas Authority (OGA)'s report (BEIS, 2019a; OGA, 2019) on a series of seismic events of up to 2.9 M_l that occurred at the Preston New Road shale gas site, also in Lancashire, in August 2019. Since the 2011 events at Preese Hall, many more incidences of felt seismicity related to hydraulic fracturing have been documented in the UK and internationally (Schultz et al., 2020; Verdon and Bommer, 2021). It is now understood that the occurrence of felt seismicity from hydraulic fracturing is highly site specific and depends on the geological and geomechanical conditions of the reservoir and the hydraulic fracturing operation design (Schultz et al., 2020; Verdon and Bommer, 2021), as well as local characteristics (Butcher at al., 2017).

Figure 1. The UK's traffic light system for regulating induced seismicity from hydraulic fracturing activities for shale gas extraction, figure from the Department of Energy and Climate Change (DECC, 2013b), made by the OGA. The traffic light system is based on a risk mitigation technique originally developed for geothermal energy production (Cremonese et al., 2015). It requires operators to monitor seismic activity in real time and, if seismic events are detected, to proceed or stop, depending on the magnitude (M_l) of these events. Under this regulation, activities at Preston New Road were suspended several times during hydraulic fracturing in December 2018 (OGA, 2019).

It is with this backdrop that we examine the available evidence of expert and nonexpert perspectives on the risk of hydraulic-fracturing-induced seismicity and the terminology used to describe these risks.

2 Induced seismicity and hydraulic fracturing – a review of perspectives and language used

In order to investigate expert and nonexpert views and language preferences around induced seismicity and hydraulic fracturing in the UK, we must first define what is meant by the terms "expert" and "nonexpert" in this context. Expert is a flexible term but is usually applied to a person considered to be particularly knowledgeable or skilled in a certain field (Lightbody and Roberts, 2019). Here, we consider expertise to refer to in-depth knowledge about an aspect of the hydrocarbon industry, be it technical (environmental regulation, oil field services, including geoscience, and petroleum engineering) or topical (energy policy and politics, energy or gas markets, regulation, environmental impact assessment, financing projects, and investments). The wider public or lay audiences are not expected to have in-depth technical or topical expertise, and so we refer to them as "nonexpert" or "lay" audiences in this paper. However, we understand that such categorisations are simplistic; the public can hold valuable experiential and contextual knowledge rather than (but not excluding) technical or topical knowledge.

To examine expert and nonexpert perspectives on induced seismicity, we review publicly available resources published before November 2019. For expert views, we look to reports from expert groups, such as learned societies, expert panels, and scientific enquiries. These reports draw on a range of sources, including peer-reviewed publications in scientific journals, and so represent the state of expert knowledge that is articulated for nonexpert audiences, including the public. We do not consider peer-reviewed publications in scientific journals; the outcomes of such studies will be captured within the expert reports, and peer-reviewed publications are not intended for public readership. For lay perspectives, we examine social science studies examining public opinions on hydraulic fracturing, looking for evidence of public views on induced seismicity in particular.

We restrict our study to the risk of induced seismicity from hydraulic fracturing reported by expert and lay audiences and the associated language used. We do not seek to determine whether the risk is considered to be acceptable and to whom or the variables that influence this.

A summary of the conclusions on the risk of shale-gas-induced seismicity from expert-led publications are shown in Table 1 and from studies of public perceptions around shale gas topics in Table 2. It should be noted that in the review period (2012 to 2019) the state of knowledge about hydraulic fracturing induced seismicity was evolving, as outlined in Sect. 1.2.

2.1 Expert and lay perspectives on the risk of induced seismicity for hydraulic fracturing

All expert reports that we reviewed, and which examined seismicity risk, concluded that the risks of induced seismicity from hydraulic fracturing in the UK are very low, and that any induced events will be below the threshold of felt seismicity (Table 1). It is, therefore, fair to surmise that there is general agreement amongst expert bodies that the risks of hydraulic-fracturing-induced seismicity are lower than or no different to other types of seismicity caused by human activity. To be clear, agreement on low risks associated with induced seismicity does not reflect agreement on or support for other aspects of shale gas exploration and development, such as the business case for, or environmental ethics of, fracking (Howell, 2018; Van de Graaf et al., 2018).

All studies of public perceptions (nonexpert) around shale gas topics in the UK find that the public associate the risk of induced seismicity with hydraulic fracturing. However, risk of contamination of drinking water is more often of larger concern than induced seismicity. These studies and their findings are summarised in Table 2. Table 2 also illustrates the similarities and differences in the phrases used in these studies to refer to induced seismicity. These differences are typically introduced by researchers either in the research design or the analysis, rather than reflecting the phrasing used by participants. To examine insights from these studies in more detail, we first summarise findings from cross-public surveys before we look to the results of dialogic and deliberative research. In each case, mindful that public views may have been evolving, the studies are presented chronologically in the order in which they were conducted (not the order in which they were published). As before, we are interested in the perceived risks of, and language around, induced seismicity and not the public opinion around fracking for shale gas, though the latter is the primary motivation for many of the studies that we examined.

A number of closed-response surveys have been undertaken to assess UK-wide public attitudes towards shale gas and related topics. The most comprehensive of these in terms of a longitudinal data set is the YouGov survey organised by University of Nottingham. The survey was administered 12 times in the period March 2012–October 2016 (Andersson-Hudson et al., 2016; O'Hara et al., 2016). Following a knowledge question which filtered out participants who did not know what hydraulic fracturing or shale gas was, respondents were then asked questions about multiple aspects of shale gas development. A question asked regarding whether they do or do not associate earthquakes with shale gas, with the option to answer "do not know". In the period 2012–2014, there is a steady decline in the number of participants who associate shale gas extraction with earthquakes and a corresponding increase in those that do not (Fig. 2). In the three surveys conducted in 2014, the responses appear to have stabilised.

The Energy and Climate Change Public Attitudes Tracker is a quarterly UK-wide survey conducted by the Department of Business, Energy and Industrial Strategy (BEIS, previously the Department of Energy and Climate Change, DECC), to capture changing public attitudes towards energy and climate change issues. Questions about shale gas were included in the survey from June 2012, and since 2015, the reasons for support, opposition, or no view have been enquired about (Howell, 2018). Of the reasons for opposition to shale gas, one that is consistent across the BEIS surveys is the "risk of earthquakes", which is ranked fourth out of five common concerns (Bradshaw and Waite, 2017). Opinium Research led two online surveys to explore public attitudes to fracking in 2014 and 2015 (reported in Howell, 2018). The survey did not ask participants about perceived risks. However, questions from Opinium Research were adapted

Table 1. A compilation of publicly available expert reports on hydraulic fracturing for shale gas which address induced seismicity, the key conclusion regarding risks of induced seismicity, and the phrasing used in the reports to refer to seismicity. While we primarily examine policy-facing reports from the UK, we include examples from EU policy, Australia, and the US.

Year	Report (purpose)	Conclusion on (risk of) induced seismicity	Terminology used to describe seismicity
2012	Mair et al. (2012) Royal Society and Royal Academy of Engineering (2012) – "Shale gas extraction in the UK: a review of hydraulic fracturing". (Report commissioned by UK Government Chief Scientific Adviser.)	"Seismic events induced by hydraulic fracturing … do not produce ground shaking that will damage buildings. The number of people who feel small seismic events is dependent on the background noise" (pp. 16). "Magnitude 3 M_l may be a realistic upper limit for seismicity induced by hydraulic fracturing (Green et al., 2012)" (pp. 41). The report recommends a traffic light system to be put in place (transferred learning from geothermal energy developments).	Varied terminology, including the terms "induced seismicity", "seismic event", "vibrations", "felt/not felt", "magnitude", and "intensity".
	Forster and Perks (2012) Report prepared by AEA Technology, plc for the European Commission Directorate-General for Environment – "Identification of Potential Risks for the Environment and Human Health arising from Hydrocarbons Operations involving Hydraulic Fracturing in Europe". (Report commissioned by the European Commission Directorate-General for Environment to inform policy.)	The risk of "significant" induced seismic activity was considered to be low, the frequency of significant seismic events is judged to be "rare", and the potential significance of this impact is "slight" (pp. 60).	Tend to refer to "very small magnitude", "seismic activity", and "Earth tremors".
	Green et al. (2012) Preese Hall shale gas fracturing review and recommendations for induced seismic mitigation. (Report commissioned by the Department of Energy and Climate Change (DECC) to examine the possible causes of seismicity at Preese Hall in April–May 2011.)	The report concludes that the observed seismicity in April–May 2011 was induced by the hydraulic fracture treatments at Preese Hall. The authors also conclude that the risk of induced seismicity should not prevent further hydraulic fracture operations in this area, provided that proposed best practice operational guidelines are implemented and followed.	The authors primarily refer to "earthquakes" or "seismic events" and sometimes refer to "small" events or earthquakes.
	Kavalov and Pelletier (2012) European Commission Joint Research Centre (2012) – "Shale Gas for Europe: Main Environmental and Social Considerations". (Undertaken by the European Commission's in-house science service to provide evidence-based scientific support to the European policy-making process.)	"Drilling and hydraulic fracturing activities may lead to low-magnitude earthquakes" (pp. 26). The authors make no conclusions on risk but recommend that "the severity and probability of this hazard should be carefully assessed on a site-by-site basis".	Refer to "low-magnitude earthquakes".
2013	DECC (2013c) DECC report "About shale gas and hydraulic fracturing (fracking)". (Government response to common questions raised in the UK-wide consultation on shale gas and fracking.)	Regulations are designed to "ensure that seismic risks are effectively mitigated".	A mix of terms are used, including "seismicity", "events", "activity", and "tremors". The most frequent term is "earthquake", which is used in some cases with qualifiers such as "perceptible", "large", "small", and "very small".
	National Research Council (2013) US National Research Council – "Induced Seismicity Potential in Energy Technologies".	"The process of hydraulic fracturing a well as presently implemented for shale gas recovery does not pose a high risk for inducing felt seismic events" (pp. 18).	Refer to "earthquakes" and "seismicity".
	Cook et al. (2013) Australian Council of Learned Academies (ACOLA) unconventional gas production – a study of shale gas in Australia. (Report to the Prime Minister's Science, Engineering, and Innovation Council.)	Induced seismicity from hydraulic fracturing itself does not pose a high safety risk (pp. 137). Risks can be managed by adopting a range of mitigation steps.	"Earthquakes" or "seismicity" are used most often but with qualifiers such as "minor", "low magnitude", and "felt".

Table 1. Continued.

Year	Report (purpose)	Conclusion on (risk of) induced seismicity	Terminology used to describe seismicity
2014	European Commission (2014) European Commission recommendation on minimum principles for the exploration and production of hydrocarbons using high-volume hydraulic fracturing. (EU regulation and legislation.)	The recommendations refer only to risk assessment protocols for induced seismicity and not the risk of seismicity.	Refers only to "seismicity".
	Scottish Government (2014) Expert scientific panel on unconventional oil and gas development. (Report from an expert panel set up by the Scottish Government.)	The "seismic effects are expected to be small in magnitude" (pp. 39); there is a "very low likelihood of felt seismicity" from fracking (pp. 48).	A number of phrases are used. "Seismicity" is often preceded by "micro-", "trigger", "induce", or "felt". Also refers to "tremors" and ("natural") "earthquake".
2015	TFSG (2015) Task Force on Shale Gas – "Assessing the Impact of Shale Gas on the Local Environment and Health". (Second report by the industry-funded expert panel Task Force on Shale Gas.)	"Shale gas operations have the potential to cause tremors, albeit not at a level higher than … other comparable industries in the UK nor at a frequency or magnitude significantly higher than natural UK earthquakes" (pp. 9).	Refer mostly to "earthquakes" and "tremors" (and, to a lesser extent, "events"), but these terms are often preceded with words such as "small", "tiny", "minor", and "micro-".
	Cremonese et al. (2015) Institute for Advanced Sustainability Studies (IASS) – Potsdam Policy Brief on Shale Gas and Fracking in Europe. (Policy brief to inform European Policy.)	"The rock fracturing process generates small seismic events of a very low magnitude (micro-seismicity), which are not generally felt by humans." Site-specific stress investigations will significantly lower risk of triggering major events. (pp. 3).	Refer to "small" induced "seismic events" and "micro-seismicity".
2016	Baptie et al. (2016) Unconventional Oil and Gas Development – Understanding and Monitoring Induced Seismic Activity. (Report commissioned by the Scottish Government.)	Hydraulic fracturing to recover hydrocarbons is generally accompanied by earthquakes with magnitudes of less than 2 M_l that are too small to be felt. (pp. 2).	Only refer to "earthquakes" and "seismicity" or "seismic activity" but often specify that these events are induced. Sometimes refers to "felt".
2018	Scottish Government (2018) Report for the Scottish Government's Strategic Environmental Assessment (SEA) on unconventional gas. (Report commissioned by the Scottish Government.)	The risk of fracking-induced felt seismicity causing damage to properties or people at the surface is considered to be very low (para 13.9). Risk table (14.1) reports that felt seismic activity would have minor negative or negligible effect on activities.	A number of terms are used, including "felt seismicity", "earthquakes", and "trigger".
	Delebarre et al. (2018) House of Lords Briefing paper CBP 6073 – "Shale gas and fracking". (Briefing paper to inform the House of Lords debate.)	No position indicated but quotes several expert reports that state that the risk of induced seismicity can be managed.	"Seismicity" is used most frequently. "Earthquakes" and "events" are also commonly used. "Tremor" and "trigger" are used infrequently.
2019	Department for Business, Energy, and Industrial Strategy (BEIS, 2019b) Guidance on fracking – developing shale gas in the UK (updated 12 March 2019). (UK Government Department for Business, Energy, and Industrial Strategy.)	"Measures are in place to mitigate seismic activity" (Sect. 1, par 4).	"Seismicity" or "seismic activity" are most often used. Does not refer to "earthquakes".
	Oil and Gas Authority (OGA, 2019) OGA – "Interim report of the scientific analysis of data gathered from Cuadrilla's operations at Preston New Road". (Summary outcomes from four reports commissioned by OGA in response to induced seismicity at Preston New Road.)	It is currently not possible to "reliably eliminate or mitigate induced seismicity" (pp. 13).	"Seismicity" is most often used, with some reference to "events" and "activity".

Table 2. A compilation of published studies which report on public perceptions of induced seismicity in the UK. These are divided into surveys (many of them UK-wide) and more qualitative approaches, such as focus groups, and each group is ordered chronologically in terms of when the data were gathered (not in terms of when the papers were published). We identified whether the phrasing used to describe seismic events was dictated by the language of the survey questions, the researcher undertaking the analyses, or the participants themselves.

	Source	Year data collected (method or approach; sample size)	Findings on public perception of induced seismicity	Phrases used (by whom)
Surveys	Andersson-Hudson et al. (2016)	2014 (University of Nottingham YouGov survey – closed questions; sample size – 3822)	Whether or not "earthquakes" are associated with hydraulic fracturing is an indicator of opposition or support for shale gas.	"Earthquake" (researcher's phrasing in the closed survey question).
	Craig et al. (2019)	2014 (face-to-face surveys in four locations – open questions; total sample size – 120)	Risk of "increased seismicity" was ranked eighth out of 10 identified risks associated with fracking.	"Increased seismic activity" (researcher's phrasing in their analysis of open-question response).
	Evensen (2017)	2014 (University of Nottingham YouGov survey – closed questions; sample size – 3823 for the US survey; sample size – 1625 for the UK survey)	UK public associated "earthquakes" with shale gas more than US public.	"Earthquake" (researcher's phrasing in the closed survey question).
	Whitmarsh et al. (2015)	2014 (local and regional online survey – closed questions; sample size – 1457)	When asked if they were concerned about the risks of "earthquakes" from shale gas fracking, 40.4 % agreed and 20.8 % disagreed.	"Earthquake" (researcher's phrasing in the closed survey question).
	Howell (2018)	2015 (YouGov online omnibus survey – closed question; sample size – 1745)	Fracking could cause "earthquakes and tremors" (43.2 % agree; 18.8 % disagree).	"Earthquake" or "tremor" (researcher's phrasing in the closed survey question).
	Andersson-Hudson et al. (2019)	2016 (University of Nottingham YouGov survey – closed question; sample size – 4992)	Whether or not "earthquakes" are associated with hydraulic fracturing is an indicator of opposition or support for shale gas.	"Earthquake" (researcher's phrasing in the closed survey question).
	McNally et al. (2018)	2017 (face-to-face surveys in one location – open and closed questions; sample size – 200)	"Seismicity" was raised as a common concern when the survey used a "fracking" frame but was not when survey used a "hydraulic pressure" frame.	"Seismicity" (researcher's phrasing in their analysis of the open-question response).
	Evensen et al. (2019)	2019 (YouGov online survey – closed question; sample size – 2777)	Some level of concern around the risks of "seismic activity" is implicit in the public attitudes towards the traffic light system (which is perceived not to be stringent enough).	"Seismic activity" (researcher's phrasing in the closed survey question).
Deliberative approaches	Whitmarsh et al. (2014)	2013–2014 (deliberative interviews – sorting risk cards; sample size – 30)	Minor earthquakes were ranked 13th out of 19 predefined risks.	"Minor earthquake" (researcher's phrasing in risk cards which interviewees ranked).
	Williams et al. (2017)	2013 (six deliberative focus groups; total sample size – 48)	Explicit concern about induced seismicity was not expressed.	"Seismicity" (researcher's phrasing in their analysis).
	Thomas et al. (2017a)	2014 (series of four 1 d deliberative workshops, with two in UK and two in the US; total sample size – 55)	Some concerns were raised regarding earthquake risk, but these were not particularly important in the context of the deliberations. However, all four groups felt that if shale development were to cause earthquakes, no matter how small, then shale gas should not be pursued at all.	"Earthquake" (researcher's phrasing in their analysis).
	Bradshaw and Waite (2017)	2016 (qualitative analysis of a public enquiry into shale gas in Lancashire, UK; sample size – not applicable)	Concerns about seismic activity were voiced by the public during the inquiry proceedings.	"Seismic activity" (researchers' phrasing in the paper).
	Bryant (2016)	2016 (Citizens' Jury in Lancashire; sample size – 15)	Questions about seismic activity were asked, but concerns about induced seismicity was not explicitly mentioned in the deliberation outcomes.	The terms "real" or "genuine" earthquake and "natural tremor", as referred to by participants.

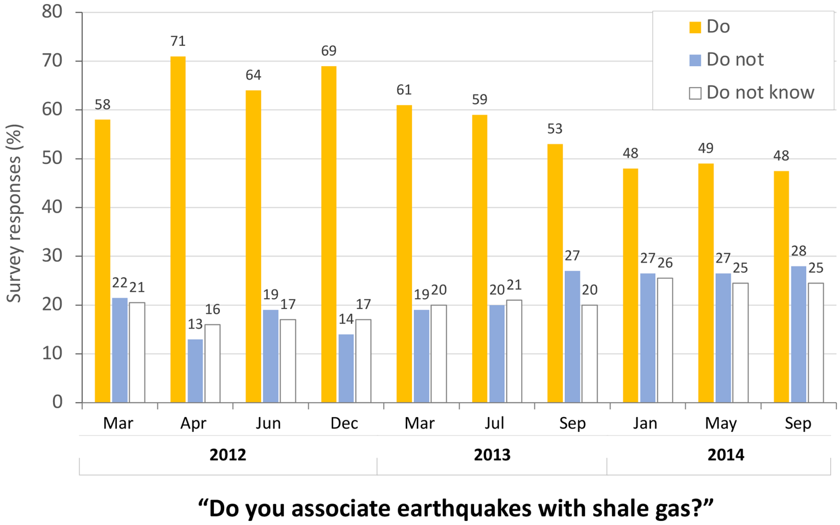

Figure 2. Responses to the 10 University of Nottingham surveys administered between 2012–2014 via YouGov to assess public perspectives on shale gas development (O'Hara et al., 2016). During the period 2012–2014, the number of participants that associate shale gas with earthquakes decreases, while the number of participants that do not associate shale gas with earthquakes or do not know increases. Results from the additional two surveys administered between 2014–2016 are not publicly available.

for a different online omnibus survey fielded by YouGov, also in 2015 (Howell, 2018). Howell (2018) found the majority (43.2 %) of respondents who answered a knowledge question about shale gas correctly agreed that "fracking could cause earthquakes and tremors", whereas 18.8 % disagreed (the remainder answered "do not know"). However, the level of positive response for earthquakes and tremors ranked towards the lowest in the range of negative environmental and social risks (including damage to the local environment, water contamination, negative affect on climate change, and health risks). A one-off online survey in 2014 (Whitmarsh et al., 2015) finds that 40.4 % of participants agreed that they are "concerned about the risks of earthquakes from shale gas fracking", with 20.8 % reporting that they disagreed, and the remainder undecided. In this survey, the public were marginally less concerned about earthquakes than they were about water contamination.

The UK National Survey of Public Attitudes Towards Shale Gas conducted in April 2019 is the first to seek to understand what the public knows or thinks about specific regulations for shale gas, including the "traffic light system" for monitoring and regulating induced seismicity (Evensen et al., 2019). The majority of participants felt that the traffic light guidance is not stringent enough, and would oppose any changes to raise the threshold to 1.5 M_l, suggesting that concerns around risks of induced seismicity from hydraulic fracturing remain (Evensen et al., 2019).

Overall, these surveys indicate that seismicity induced by hydraulic fracturing is an important issue for the public. However, as is the nature of surveys, to some degree the topics of concern are pre-identified during the survey design and are shaped by the phrasing question (a problem that is well-documented in research methods and risk research; see, for example, Gaskell et al., 2017). For example, the Whitmarsh et al. (2015) survey asked questions in the style "I am concerned about [environmental risk]"; other questions in the same survey were focused on risks around energy security or energy prices, and did not use the words "concern" or "risk", both of which have negative associations. Similarly, Howell (2018) found the question, "fracking could cause earthquakes and tremors", is interpreted to be a negative statement about fracking, rather than, say, a factual statement. Furthermore, we note that statements regarding earthquake risk were conditional ("could cause"), whereas all other provided risks except for water contamination were unconditional ("will cause").

A total of two studies adopted open survey questions. Craig et al. (2019) studied public views towards fracking and how these changed with distance from a region of County Fermanagh with potential shale gas resources and a granted petroleum exploration license. Survey results, which were gathered in 2014, indicated that risk of "increased seismicity" ranked eighth amongst the 10 risks considered to be a concern by survey respondents. All of the identified risks increased with proximity of residence to the licensing area, including the perceived risk of increased seismicity due to hydraulic fracturing. McNally et al. (2018) found seismicity ranked third out of four common disadvantages identified from an open question about advantages and disadvantages of fracking. When the same question was asked about "using hydraulic pressure to extract natural gas", seismicity was not raised as a disadvantage.

Analysis of qualitative data presented in the public inquiry on planning permission for shale gas development in Lancashire (held in 2016) found that "seismic activity was raised regularly in the public sessions. Several of those who spoke had first-hand experience of seismic activity, having felt the tremors from Cuadrilla's hydraulic fracturing at Preese Hall in 2011" (Bradshaw and Waite, 2017).

Williams et al. (2017) report on deliberative focus group discussions on shale gas development. The groups were held in northern England in 2013, and Williams et al. (2017) reported that explicit concern about induced seismicity was not expressed, although some groups did express "worst-case scenario" thinking around a number of potential risk and impact pathways (Williams et al., 2017). Similarly, a series of 1 d deliberations in the UK and the US, held in 2014, found that participants did not express particular concern about induced seismicity (Thomas et al., 2017a). In deliberative interviews held in Wales in 2013–2014 the risk of earthquakes or tremors was ranked 13th out of 19 pre-identified risks in a card-sorting exercise (Whitmarsh et al., 2014). In 2016, a Citizens' Jury (a format for public deliberation) was held in Preston, Lancashire (northwestern England) approximately 15 km from the Preese Hall shale gas development. Transcriptions from the proceedings show that while participants raise questions around earthquake risks from shale gas extraction (and geological CO_2 storage), concerns about induced seismicity are not reported to be a dominant issue (Bryant, 2016).

2.2 Language used by expert and lay audiences on the risk of induced seismicity

As Jaspal and Nerlich (2014) reflect, terms such as "earthquakes" evoke imagery of destruction and disaster, whereas phrases like "seismic activity" or "tremors" are less threatening. Since language is not a neutral tool, the choice of words used by experts, social researchers, and public participants might be carefully chosen to communicate particular meaning.

Experts use a range of terms to describe induced seismicity (Table 1). The seismic events themselves might be referred to as "micro-seismic events", "seismicity", and "earthquakes". A distinction is made between natural and induced earthquakes and the events that may occur from hydraulic fracturing or other human-caused activities are described as being "induced" by or "triggered" by these activities, where induced can mean solely due to fracking and triggered can mean that the occurrence was accelerated by fracking but might have occurred naturally. The authors use qualifiers such as "minor", "low", and "small" to indicate the magnitude of seismicity associated with fracking. Finally, while the consequences of seismicity are sometimes referred to in terms of "vibrations" or "tremors" and more often there is a distinction between "felt" and "not felt" events.

In some cases, the language around seismicity in policy reports is inconsistent and confusing. For example, a DECC (2013c) report lays out regulatory requirements designed "to ensure that seismic risks are effectively mitigated" (p. 6) and "to prevent any more earthquakes being triggered by fracking" (p. 19). But the regulations allowed induced seismic events of magnitude (M_l) < 0.5 ("green light"), implying that these events are not considered to be earthquakes, although no definition of the term is provided. On the next page (p. 20), an additional qualifier is added which works around this contradiction; the regulations are "designed to prevent any more *perceptible* earthquakes being triggered by fracturing". The 2019 OGA report (which summarised a series of studies commissioned by the OGA to understand and learn from the induced seismicity observed at the Preston New Road development in 2018) concluded that rules based on the current understanding of induced seismicity cannot be "reliably applied to eliminate or mitigate induced seismicity" (OGA, 2019). The authors of this OGA report do not define what is meant by induced seismicity (i.e. what magnitude will not be reliably mitigated). As outlined in Sect. 2.1, it is not possible to eliminate risks of all magnitudes of induced seismicity from the hydraulic fracturing process.

In comparison, the terminology to describe the induced seismicity reported in public perception studies is much less varied (Table 2). However, in many cases, the phrases are selected by the researchers, either when designing the survey question or when reporting on the research outcomes. For example, four of the five closed-question surveys about induced seismicity refer to risk of "earthquakes". The researchers designing closed-question surveys might have opted to use the term "earthquake", since it is commonplace and widely understood, whereas "seismic activity" might be considered to be jargon. Results from the only survey to add a size qualifier, asking about "earthquakes or tremors" (Howell, 2018), are very similar to the results of surveys which simply asked about "earthquakes".

In contrast, of the phrasing chosen by researchers to communicate outcomes from qualitative methods, only one study refers to "earthquakes" (Thomas et al., 2017a). Instead, researchers reporting qualitative methods use terms such as "seismic activity", "seismicity", or "minor earthquakes". These terms might have been selected to reflect the level of risk perceived by participants. The phrases that the public themselves adopted are not reported in these studies, except for in the report on the Citizens' Jury on fracking where, in their questions, participants wanted to come to grips with whether the 2011 Preese Hall seismic events had been "real" or "genuine" (i.e. caused by hydraulic fracturing) or a "natural tremor" (i.e. background seismicity) (Bryant, 2016, pp. 14).

While dialogic or deliberative studies in the UK find that risks of induced seismicity tend not to take precedence in the public discussions, that is not to say that the risks are acceptable. Thomas et al. (2017a) report that deliberative groups in the UK and the US felt that, if shale gas development were to cause earthquakes, however small, then development should not be pursued. Similarly, Williams et al. (2017) reports how one deliberative group reflected that public tolerances to industrial activities which induce seismicity may have changed such that activities that were acceptable in the past are no longer acceptable to the public. Finally, early results from a recent investigation into public attitudes to the UK government's traffic light system to regulate induced seismicity suggest that participants support stringent monitoring of induced seismicity (Evensen et al., 2019). These insights imply that the public's risk tolerance to induced seismicity from shale gas production is low.

2.3 Knowledge, language, and risks of induced seismicity

The physical process of hydraulic fracturing will, by definition, release seismic energy – whether the release of this energy is detectable as an event or not. Accordingly, the expert reports that we reviewed conclude that there is risk of induced seismicity from hydraulic fracturing, albeit low. Depending on how the term earthquake is defined (e.g. "How big is a small earthquake?"; Kendall et al., 2019), it could be argued that assertions used to gauge public views such as "shale gas development is associated with earthquakes" are factual. Might the questions indicate level of knowledge of the association, rather than indicate the level of perceived risk? Howell (2018) finds that respondents who correctly answer a knowledge question about shale gas are more likely to agree with the statement "fracking could cause earthquakes and tremors" (43.2 %) than to answer that they do not know (38.0 %) or to disagree (18.8 %). Furthermore, Andersson-Hudson et al. (2019) find that laypeople who are more knowledgeable about shale gas have more unified views. Indeed, all cross-public surveys studied here find that motivations determine public responses: associating fracking with earthquakes negatively correlates with support for the technology and relates to demographic variables, including political views and gender (Andersson-Hudson et al., 2016, 2019; Howell, 2018; O'Hara et al., 2016; Evensen, 2017). These findings align with similar studies in Europe (Lis et al., 2015; Evensen, 2018), the US (Boudet et al., 2014; Graham et al., 2015), and Canada (Thomas et al., 2017b).

In summary, through our review and analysis of previous surveys, reports, and papers, we have revealed uncertainties in the perceived risk of seismicity induced by hydraulic fracturing for shale gas. There is broad agreement amongst experts that, while induced seismicity is associated with hydraulic fracturing, the likelihood of felt seismicity is dependent on context-specific technical factors. All the expert reviews concluded that the risk presented by such seismicity is low. Generally, these reports distinguish between felt and not felt seismic events, but there is no systematic use of terminology to describe seismicity or the risk it presents. We find that associations between induced seismicity and shale gas are common across nearly all public studies that we reviewed. Perceived risk is not ubiquitous amongst all members of the public, and often, other reported environment or social risks take prevalence. However, the level of perceived risk of induced seismicity and understanding around the topic is difficult to compare due to differences in research approaches and the language used to elicit and report on public views. Given the ambiguities in terminology around hydraulic-fracturing-induced seismicity, it is interesting to consider whether questions around the risk of earthquakes might be understood or interpreted differently according to, say, the participants' views about shale gas or understanding of the hydraulic fracturing process. And are ambiguous terms, such as earthquake or tremor, potentially loaded or leading?

In the next section, we explore whether or not knowledge levels affect whether seismicity is associated with shale gas, and how the language used in the questions asked affects the answers provided.

3 A survey to examine the rationale and language use behind perspectives on induced seismicity and hydraulic fracturing

3.1 Methodology

3.1.1 Data collection

We recruited 387 participants from a series of geoscience events on shale gas that were held in 2014, including conferences and public talks (see Table 3). We invited attendees to voluntarily complete and return the surveys, which were anonymous. Our sample includes 204 participants from shale-gas-specific conferences, 85 participants from geoscience conferences (that were not shale gas specific), and 98 participants from science outreach events[2] on shale gas. Since a number of individuals attended several of the conferences and events, we requested that people only complete the survey once.

3.1.2 Survey design

We adapted a subset of questions from the University of Nottingham surveys (O'Hara et al., 2014; Andersson-Hudson et al., 2016). The questions were intended to gather information on the perceived risks and level of support for shale gas development and asked for closed answers to a series of statements about shale gas. Crucially, in our modified survey, participants were asked to provide reasoning for the answers they gave.

[2]These events lasted between 1–2 h and consisted of an interactive talk (by one or more of the authors of this paper) followed by a discussion session. All three talks were part of small local events held in Scotland.

Table 3. The events where attendees were invited to anonymously complete surveys. Public events were generally small local events.

Acronym	Event name (location; date)	Description	No. (surveys)
Shale-gas-specific events			
ESGOS	European Shale Gas and Oil Summit (London; September 2014)	An industry-led conference on shale gas.	40
UGA	Unconventional Gas (Aberdeen; March 2014)	An industry-led conference on shale gas.	28
SGUK	Shale Gas UK (London; March 2014)	An industry-led conference on shale gas.	98
Geoscience events			
TSG	Tectonic Studies Group Annual Conference (Cardiff; January 2014)	The annual conference of the Geological Society of London specialist group covers a range of topics relevant to tectonic studies. The event included a technical session on hydraulic fracturing and induced seismicity, followed by an open discussion.	57
CCG	Communicating Contested Geoscience (London; June 2014)	A Geological Society of London conference about issues facing controversial geoscience topics, including shale gas.	66
Public events			
TFA	TechFest (Aberdeen; September 2014)	Talk and discussion at a local science festival.	30
CSA	Café Science (Aberdeen; February 2014)	Talk and discussion at a Café Science, a popular science communication series organised across the UK.	59
CHL	Coffee House Lectures (Glasgow; November 2014)	Talk and discussion at a local research communication series.	9

Conference participants were asked to report which sector they worked in, and all participants were asked to report their sources of information about or experience of shale gas.

Full survey data (raw and analysed) are available; see the data availability statement at the end of the paper.

3.1.3 Data analysis

In this work, we consider only the responses to the closed question, "Please state whether you do or do not associate earthquakes with shale gas", to which respondent could select either "do", "do not", or "do not know", and a subsequent open question seeking the reasoning behind the selected answer to the closed question. In total, 385 participants completed the closed question (99 % of survey respondents), and 292 participants provided informative responses to the open question (67.5 % of survey respondents).

Closed answers were coded numerically. Open answers were categorised through thematic coding to enable analysis. The codes for thematic analysis were derived iteratively as follows: first, the three authors of this paper worked separately on open coding (i.e. inducing themes from the qualitative answers to all questions). The three authors then had a series of workshops to share identified codes, determine similarities or differences in our codes, and then discuss and reconcile the identified themes, and both the themes and their definition or scope agreed. The authors then worked separately again to apply the codes across all qualitative answers (in several cases, a single answer was double or triple coded). The lead author then co-ordinated the codes, seeking consensus in the few cases of disagreement between the applied codes.

Thematic analysis of all qualitative data derived a total of 26 themes, of which 15 apply to answers about induced seismicity. These are shown in Table 4. Qualitative answers were coded as null if the content was irrelevant, i.e. did not explain the rationale for the answer provided (the most common example being a knowledge statement about the topic; for example, "I've analysed this issue"or "I work on this topic"), or the meaning of the response was ambiguous and could not be deciphered. Overall, 80 % of respondents provided qualitative responses that were thematically coded.

We examine how these themes vary with job sector and knowledge level. Job sector responses were grouped into academia, industry, civil service, and other. Most of the 289 conference participants who completed the survey were from industry (52 %) and academia (30 %), with only 12 % from the civil service (3 % did not answer this question). Level of knowledge about shale gas was inferred from a ques-

Table 4. Codes identified for thematic analysis of participant responses to an open question asking them to provide reasoning for the answer they gave to the closed question "Do you associate shale gas with earthquakes?" The codes are often directional, i.e. they are used to reason why earthquakes may be associated with shale gas (positive – ↑) or why earthquakes may not be associated with shale gas (negative – ↓). If the code is not directional, it is considered to be neutral (↔).

Code	The reasoning provided to explain the participant's response to the closed question "Do you associate shale gas with earthquakes?" indicates that...	Dir.
Evidence	There is evidence that shale gas extraction [causes, induces, or is associated with] earthquakes. (Includes references to events in the USA; references to UK events are coded as below.)	↑
Blackpool	Any reference to the seismic sequences at Preese Hall in 2011 as evidence of the risk of earthquakes. (Includes references to Lancashire, Blackpool, Cuadrilla, or, more broadly, to UK events.)	↑
Inconclusive	There is currently not enough evidence to (conclusively) say whether or not shale gas extraction [causes, induces, or is associated with] earthquakes. (Includes reference to a need for further research or data to understand the positive and negative impacts, to improve technology, and so on.)	↔
No evidence	Shale gas extraction is not associated with (does not cause or induce or is not associated with) earthquakes.	↓
Knowledge	Respondent does not feel that they know enough about shale gas extraction to say, or they are on the fence.	↔
Media	Reference to the media coverage of shale gas extraction. Phrases include "press", "news", "high profile", "reporting", "public concern", "miscommunication", "scaremongering", "hype", "anti-fracking activist", and "anti-lobby".	↑
Fracturing rock	Shale gas extraction requires the reservoir rock to be hydraulically fractured. This process will release seismic energy. Phrases include "inherent" or "obvious", "fracturing rock", "high-pressure fluids", "stress change", and "trigger".	↑
Wastewater	Shale gas extraction may not induce earthquakes, but the geological disposal of wastewater (associated with fracking) does. Phrases include "wastewater", "waste disposal" or "injection", and "USA events".	↑
Reactivation	There is a risk that shale gas extraction may cause earthquakes because the process may reactivate existing fractures and faults which could cause seismicity.	↑
Magnitude	The magnitude of any seismic events related to fracking will be very small. Phrases include "micro-" ("seismic" or "earthquake"), "tremor", "low intensity" or "energy", "tiny", "cannot feel them", "insignificant", and "low consequence or impact".	↓
Low risk	The risk that shale gas extraction [causes, induces or is linked with] earthquakes is very low. Phrases include "is possible", "rare", "unlikely", "low risk", "minor", "little impact", and "not a significant risk".	↓
Definition	Comments or questions how earthquake is defined.	↔
Regulation	The risk that shale gas extraction activities may cause earthquakes can be managed by appropriate regulation and monitoring. Includes references to regulation, appropriate regulation, enforcing regulation, and best practice. Phrases include "monitoring", "controllable", and "manageable".	↓
Normal	Any seismic activity that may be induced by shale gas extraction is no different to everyday background or other activities or industries, i.e. not unique to fracking.	↓
Site	Any risk posed by shale gas extraction is location or place specific. Expressions include "determined by the geology of the region", "the depth of the resource", "the population", etc.	↔

tion about the primary sources of information about shale gas, which 95 % of survey respondents answered. Responses were grouped into no prior information, information from media reports, expert reports, and academic research. We consider respondents whose information sources include reports and academic papers to be the most knowledgeable. The majority (81 %) of the conference attendees were in this knowledge category, with 40 % obtaining information from academic papers and 41 % from reports. In contrast, most (60 %) public talk attendees sourced information about shale gas from the media.

The public cohort were not intended to represent the perspectives of the general public. The surveys were completed at the end of a public talk and discussion on the topic of shale gas, in which induced seismicity was raised, and so these members of the public are both interested and informed, and, therefore, cannot be a proxy for UK-wide attitudes and responses. Instead, the public cohort allow us to examine answers for those who obtain the majority of prior information, if any, through media sources (most conference attendees do not fit this category). Public respondents were not asked about their employment sector.

We compare results from our survey with those from the 10 University of Nottingham YouGov surveys (O'Hara et al., 2016). While the Nottingham YouGov surveys document a broad decline in the number of respondents that associate shale gas with earthquakes (see Fig. 2), the results for the three surveys undertaken in 2014, the period in which we undertook our surveys, do not show any decline. We use average values from 2014 surveys (48 % do, 27 % do not, and 25 % do not know) to represent UK-wide views, against which we compare our results. For simplicity, we refer to these as the UoN 2014 surveys and results.

3.2 Survey results and analysis

3.2.1 Closed-question responses

In total, 55 % of survey respondents who answered the closed question, "Do you associate shale gas with earthquakes?", with "do" associate shale gas with earthquakes, 37 % "do not", and 7 % "do not know" (Fig. 3a). Compared to public attitude surveys asking the same question throughout 2014, our survey finds that more respondents "do" (+7 %) and "do not" (+10 %) associate shale gas with earthquakes and far fewer "do not know" (−18 %). Overall, our respondents are much more decided than the general public (see Fig. 2; O'Hara et al., 2016). Of our cohort, we find more participants from professional conferences and events that are about, or have sessions about, shale gas "do" associate shale gas with earthquakes (58 %) than participants attending public talks (48 %; Fig. 3b).

We observe no systematic trend between the closed-answer responses and the level of participant knowledge about shale gas, except that the higher the knowledge levels, the fewer "do not know" responses were recorded. Yet there are differences in responses (Fig. 3c); those who obtain their information from the media and reports are more likely to answer that they "do" associate shale gas with earthquakes, a higher proportion of those with no knowledge of the topic "do not", and the most knowledgeable groups have equal proportion of respondents "do" and "do not" associate shale gas with earthquakes. When grouped into experts and nonexpert groups (those who source information from research and reports, and those who had no prior information or obtained information from the media, respectively), 56 % of experts ($n = 276$) associate shale gas with earthquakes and 39 % do not. These proportions are very similar to nonexperts ($n = 109$), where 53 % do and 33 % do not, and are in fact very similar to the views of UK-wide public in 2013 (see Fig. 2). However, grouping in this way masks a difference in responses between those who obtain information from research articles and those who use reports. For the latter, shale gas is predominantly associated with earthquakes, (64 % do; 31 % do not) whereas, for the former, there is a fairly even split (49 % do; 47 % do not; Fig. 3c). Respondents who source information from research articles are not undecided, and their views are apparently polarised.

The only group that predominantly do not associate shale gas with earthquakes are those with no prior knowledge of shale gas, although this sample is very small ($n = 16$). Our results present a more nuanced view than the results of Andersson-Hudson et al. (2016), who find that those with more knowledge about shale gas are more likely not to associate shale gas with earthquakes.

It would be fair to presume that most academics would source their information from research papers, and so it is interesting that the results for this job sector present quite different results (Fig. 3d). Two response profiles emerge from job sector results: the majority of academics and civil service workers (65 % and 68 % respectively) "do" associate earthquakes with shale gas, and a much smaller proportion "do not" (28 %, 21 %, respectively). In contrast industry respondents present an even mix of views (51 % do; 46 % do not), similar to those that obtain information from research articles.

3.2.2 Open-question responses

Thematic analysis of the open responses that provided reasoning for participants' closed answer to the question, "Do you associate shale gas with earthquakes?", identified 15 codes, which are shown in Table 5; a thematic code definition is listed in Table 4. Often multiple codes apply to a given answer, and so, in total, there are 443 codes for the 292 qualifying responses. Codes are ranked for frequency in Table 5. The six most frequently used codes are identified over 30 times in participant responses, and these themes are examined in more detail in Table 6.

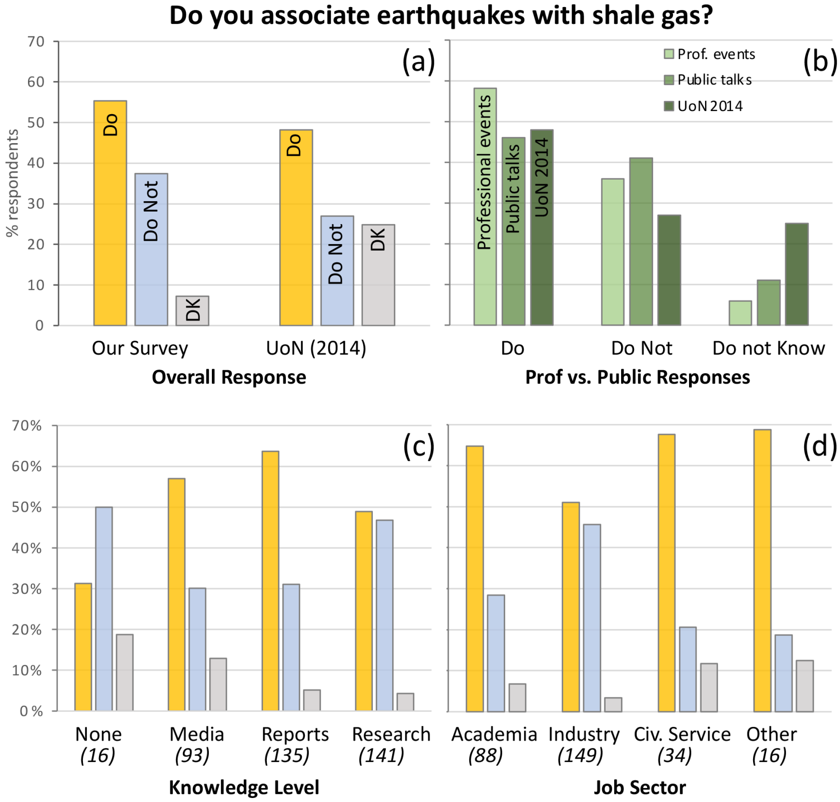

Figure 3. **(a)** Comparing the results of our surveys with UK-wide results from 2014 (UoN 2014; O'Hara et al., 2014), we find that, while results for those who "do" associate shale gas with earthquakes (orange) for both surveys are similar, our survey results have more "do not" (blue) and much fewer "do not know" answers (grey). **(b)** Participants from professional fora (conferences and events – pale green) associate earthquakes with shale gas more than participants from public talks on shale gas (green). Results are compared to UK-wide results from 2014 (UoN 2014; O'Hara et al., 2014; dark green). **(c)** To gauge knowledge levels of our survey participants, we asked respondents to select where they source their information from about shale gas, which we used as a proxy for their level of knowledge, with "research papers" indicating the greatest knowledge and "no previous information" indicating the least prior knowledge. There is no overall trend to the results, suggesting that answers are not simply determined by knowledge level. In fact, those who obtain information from research present an equally polarised response, which is different to information from reports and the media, where the dominant answer is that earthquakes are associated with shale gas. The only group to report that shale gas is not associated with earthquakes is the small sample of respondents that obtained no information about shale gas prior to attending the event where they completed the survey. **(d)** The majority (83 %) of participants recruited at conferences and events ($n = 272$) represent industry and academia (public participants were not asked about their job sector). We observe some differences in closed-question responses between the different sectors; while the majority of participants from academia, the civil service, and other sectors predominantly report that earthquakes are associated with shale gas, industry participants are split almost 50 : 50 between those who do and do not associate shale gas with earthquakes. Very few of those from industry and academia (~ 5 %) answer that they do not know.

Themes relating to magnitude were raised most often, occurring in 40 % of participant responses. Indeed, the magnitude theme accounted for over a quarter of the total number of codes applied across all open responses (Table 5), inclusive of knowledge level or job sector (Table 6). The code is equally prevalent across reasoning to support "do" and "do not" responses but less frequent for "do not know" answers (where, unsurprisingly, inconclusive and knowledge themes become important, even though the sample is very small).

The "magnitude" theme illuminates uncertainty in what is understood to be an earthquake and raises questions around terminology. This is best illustrated using example answers from this theme, as shown in Table 7. Participants who "do" or "do not" associate shale gas with earthquakes explain that the earthquakes will be small. Participants who "do not know" also refer to the size of the earthquake. There are examples in the rationale provided for all three closed-answer responses that indicate that the seismicity that they associate with shale gas are not "earthquakes", but are instead "tremors", "events", "micro-seismic", or some other term. Thus, we find that respondents provide the same reasoning to support different closed answers, i.e. earthquakes are small, and/or the term earthquake is not appropriate. Other common codes include "low risk" and "media". Responses coded

Table 5. The frequency of use of different thematic codes in the reasoning provided for participants' answers, showing total number of times the code was applied and, in parentheses, the percentage relative to the number of responses in that category ("do", "do not", and "do not know"). High-frequency codes are coloured pale yellow (≥ 10 %) and yellow (≥ 20 %), respectively. For each one answer (reasoning) there could be more than one code. In the final row, codes are ranked for frequency, and the six codes that occur over 30 times are coloured in blue. These themes are examined in detail in Table 6.

	Evidence	Blackpool	Inconclusive	No evidence	Knowledge	Media	Fracturing rock	Wastewater	Reactivation	Magnitude	Low risk	Definition	Regulation	Normal	Site
Do	7 (3%)	30 (11%)	1 (0%)	1 (0%)	1 (0%)	32 (12%)	29 (11%)	15 (6%)	9 (3%)	76 (28%)	34 (13%)	7 (3%)	10 (4%)	11 (4%)	7 (3%)
Do Not	2 (1%)	3 (2%)	2 (1%)	5 (4%)	0 (0%)	9 (6%)	6 (4%)	8 (6%)	2 (1%)	38 (27%)	18 (13%)	16 (11%)	6 (4%)	21 (15%)	5 (4%)
Do Not Know	0 (0%)	1 (4%)	5 (20%)	0 (0%)	5 (20%)	3 (12%)	0 (0%)	0 (0%)	0 (0%)	3 (12%)	4 (16%)	3 (12%)	1 (4%)	0 (0%)	0 (0%)
Total	9 (2%)	34 (8%)	8 (2%)	6 (1%)	6 (1%)	44 (10%)	35 (8%)	23 (5%)	11 (3%)	117 (27%)	56 (13%)	26 (6%)	17 (4%)	32 (7%)	12 (3%)
Rank	12	5	13	15	15	3	4	8	11	1	2	7	9	6	10

Table 6. Code frequency and **(a)** different information sources (for all participants) and **(b)** employment sector (for conference attendees) for the six most frequent codes (organised from left to right in order of code frequency). Information sources in panel **(a)** include no source (–), media (M), reports (R), and (A) research (academic) papers. Information in panel **(b)** about the employment sector was asked for conference attendees only and includes academia (A), industry (I), civil service (CS), and other (O). The count for each code is normalised to the total count for that code. These values are then colour coded, as shown in the key, to indicate where codes are used by particular knowledge or employment groups or to support particular answers.

(a)		**Magnitude ↓**				**Low risk ↓**				**Media ↑**				**Frac rock ↑**				**Blackpool ↑**				**Normal ↓**			
		-	*M*	*R*	*A*	-	*M*	*R*	*A*	-	*M*	*R*	*A*	-	*M*	*R*	*A*	-	*M*	*R*	*A*	-	*M*	*R*	*A*
Do	*n*	0	17	32	27	0	6	14	15	3	17	8	5	0	5	15	9	0	5	12	13	0	2	2	7
	%	0%	15%	27%	23%	0%	10%	24%	26%	7%	37%	17%	11%	0%	14%	41%	24%	0%	15%	35%	38%	0%	6%	6%	22%
Do Not	*n*	2	5	16	15	3	0	4	11	0	2	5	3	0	0	0	7	0	1	0	2	0	8	4	9
	%	2%	4%	14%	13%	5%	0%	7%	19%	0%	4%	11%	7%	0%	0%	0%	19%	0%	3%	0%	6%	0%	25%	13%	28%
Do Not Know	*n*	0	1	1	1	0	2	1	2	1	0	1	1	0	0	0	1	0	1	0	0	0	0	0	0
	%	0%	1%	1%	1%	0%	3%	2%	3%	2%	0%	2%	2%	0%	0%	0%	3%	0%	3%	0%	0%	0%	0%	0%	0%
Sum	*n*	2	23	49	43	3	8	19	28	4	19	14	9	0	5	15	17	0	7	12	15	0	10	6	16
	%	2%	20%	42%	37%	5%	14%	33%	48%	9%	41%	30%	20%	0%	14%	41%	46%	0%	21%	35%	44%	0%	31%	19%	50%

(b)		**Magnitude ↓**				**Low risk ↓**				**Media ↑**				**Frac rock ↑**				**Blackpool ↑**				**Normal ↓**			
		A	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*
Do	*n*	25	29	10	2	7	12	6	2	4	13	0	0	10	13	1	2	11	8	2	2	3	2	4	1
	%	26%	30%	10%	2%	16%	28%	14%	5%	15%	50%	0%	0%	29%	38%	3%	6%	44%	32%	8%	8%	12%	8%	16%	4%
Do Not	*n*	7	17	2	1	1	11	1	0	1	5	1	0	2	5	0	0	0	2	0	0	4	10	0	1
	%	7%	18%	2%	1%	2%	26%	2%	0%	4%	19%	4%	0%	6%	15%	0%	0%	0%	8%	0%	0%	16%	40%	0%	4%
Do Not Know	*n*	1	0	1	1	1	0	1	1	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0
	%	1%	0%	1%	1%	2%	0%	2%	2%	0%	4%	4%	0%	0%	0%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Sum	*n*	33	46	13	4	9	23	8	3	5	19	2	0	12	18	2	2	11	10	2	2	7	12	4	2
	%	34%	48%	14%	4%	21%	53%	19%	7%	19%	73%	8%	0%	35%	53%	6%	6%	44%	40%	8%	8%	28%	48%	16%	8%

Key: <10% | 10 - 25% | 25 - 40% | >40%

as low risk refer to low risk, low likelihood, or low consequence (Table 7), and the low risk rationale is provided to explain closed responses for all three categories ("do", "do not", and "do not know"). That is, whether respondents "do" or "do not" associate shale gas with earthquakes or they "do not know", they consider the risk to be "insignificant", "minimal", "unimportant", "very low", and so on. In contrast, the term media is used mostly to describe reasons for answering "do", alongside reference to the Blackpool (Preese Hall) seismic events, and the rationale that fracturing rock inevitably releases seismic energy, and so fracking and earthquakes are associated by definition. Where the media theme is used for "do not" responses, often the respondent is expressing judgement about the accuracy or veracity of media claims.

Moreover, two additional themes are identified in the rationale for "do not" responses. First, the argument that any

Table 7. Example of the open responses to illustrate how the most common codes are used to defend the range of participant responses to whether or not they associate shale gas with earthquakes. "Magnitude" is generally used to defend "do" and "do not" answers, "risks" is used for all responses, whereas "media" most often applies to "do" answers. "Normal" and "definition" codes tend to be applied to "do not" answers.

	Closed response	Example open responses (in quotes) provided to explain the participant's answer to the closed question, "Do you associate shale gas with earthquakes?"
Magnitude	Do	"The earthquakes associated with shale gas are very small" and will be "micro-seismic earthquakes that won't be felt", "small magnitude events", or "minor tremors".
	Do not know	"Major earthquakes [are] probably unlikely"; fracking may cause "seismic activity but not quakes".
	Do not	"There may be possible tremors – not earthquakes", events will be "mostly unfelt, very small events", or there a "very few cases [with] little intensity".
Low risk	Do	Shale gas "can trigger earthquakes but very rarely"; it "has the potential to induce seismic activity, but the risk is not significant", and "any induced seismicity [has] small consequences".
	Do not know	"It is probably unlikely that fracking triggers major earthquakes", there is "probably an association but the risk is relatively trivial", and earthquakes might be associated "with a tiny minority of shale [operations – they are] not an intrinsic by-product".
	Do not	"Seismicity risks are minimal and manageable", "insignificant", "very low", "unimportant", and so people "do not consider it [to be] a significant hazard".
Media	Do	Earthquakes are associated with shale gas due to "publicity", "media reports", and "media portrayal and local campaign group resources". Responses also include judgement statements such as "thanks to the media, I associate fracking with [earthquakes], but I do not agree".
	Do not know	The "media and other bias form of reporting on shale gas give this impression; however, I do not know of any evidence of the link".
	Do not	"Earthquakes" are associated publicly with shale gas thanks to inaccurate media reporting", "while I do not [associate shale gas with earthquakes], from media alone I would".
Normal	Do	"We have a lot of evidence of Earth tremors associated [with shale gas], but these are … comparable to historic mining activity in the UK".
	Do not	"Earthquakes can be induced from many different types of industrial processes", "numerous unfelt earthquakes occur daily, and [there are] only a select few examples of fracking caused felt earthquakes"; "any earthquakes from shale gas will be negligible versus natural seismicity".
Definition	Do	"Fracking causes micro-seismicity; in rare occasions they cause earthquakes. Where is the transition between micro-seismic [events] and earthquakes?" Fracking does "create micro-seismicity … [but] not on the scale you would call an earthquake". The terms "'Earth tremors' or 'seismic events' [are] more appropriate than 'earthquake'."
	Do not know	Fracking might cause "tremors but not specifically earthquakes". "I think of earthquakes as being of natural origin."
	Do not	"I do not think the minor, largely insensible tremors associated with shale gas merit the term 'earthquake'." "Seismicity", "tremors", and "micro-seismicity" "is not an earthquake."

earthquakes associated with shale gas extraction will be no more significant than other everyday background seismicity or industry processes, and so is considered to be "normal". This code is unique in that it is used mostly to support "do not" responses. Furthermore, in their reasoning for "do not" responses, a number of participants raise questions about how the term earthquake is defined. Themes around earthquake definition also arise within rationale for "do not know" responses (Table 7), with the same questions being raised regardless of the answer, i.e. "What is the difference between micro-seismic event and an earthquake?". Some respondents confidently assert that micro-seismic events or tremors are not earthquakes, others indicate that earthquakes refer to "natural" seismic events (similar to comments made by the Citizens' Jury participants reported in Bryant, 2016).

Results presented in Table 6 indicate that neither knowledge level nor job sector have any significant influence on the themes raised in open responses. We observe only two small trends; participants from industry tend to appeal to media themes more than other sectors, and academics are more likely to refer to Blackpool events, (i.e. the Preese Hall events), as an indicator that earthquakes are associated with shale gas development.

3.2.3 Language and terminology

A theme that is applied in particular to the rationale for "do not" answers refers to the definitions of earthquakes, indicating that different phrases are more appropriate, depending on the scale, size, or magnitude of the seismic event. We examine the language used within participants' open responses to determine whether there are any language preferences amongst different answers or different survey groups.

Participants used a range of terms to describe or refer to earthquakes. Similar words are used to describe earthquakes in responses for both "do" and "do not" closed answers, though there is some indication that words like "seismic" and "tremor" are used more for "do not" responses. We find that more knowledgeable participants (experts – those who obtain information from reports and peer-reviewed publications) are 4 times more likely to use phrases such as "seismicity" and "minor" than less knowledgeable respondents. In terms of job category (conference participants only), academics use the phrase "earthquake" far more than those employed in other sectors, and civil service employees prefer "tremor" rather than "micro-" or "induced" seismicity, and more often refer to the "energy" of the event.

Moreover, an undercurrent theme to all the open responses was to critique the question that they were asked, which was about the perceived association between shale gas and earthquakes. As noted in the previous section, many participants raised questions about the phrase "earthquake", claiming it was "too strong" and that any seismicity that might arise from shale gas development would not be "earthquakes" but "tremors" or "micro-earthquakes". Others preferred to mention earthquake consequences in terms of felt or not felt or damage inducing or not. Several participants critiqued the use of the phrase "shale gas", mentioning that they did not associate shale gas with seismicity, but they do associate the hydraulic fracturing technique (by which shale gas is extracted) with seismicity. Others note that the question is leading. Finally, most of the respondents that raised themes relating to the code "low risk" were essentially communicating that, whether they "do" or "do not" associate shale gas and earthquakes, it does not concern or worry them (see Table 7). These statements make clear that, for our sample, associating earthquakes with shale gas does not necessarily indicate concern about hydraulic-fracturing-induced seismicity.

4 Discussion

The results from our survey reflect a snapshot of participant views from 2014 about hydraulic-fracturing-induced seismicity. Furthermore, our results show perspectives from the UK only, a country with low background seismic activity, and for English language use. The results were not intended to inform whether or not people associate earthquakes with shale gas but, rather, to explore the underlying rationale for the apparent differences in perspectives on the topic, particularly between experts and nonexperts. It is important to acknowledge that perspectives of both experts and members of the public are likely to have evolved in the time since the surveys were run. Preston New Road is the only shale gas hydraulic fracturing activity in Europe that has been undertaken since our surveys were conducted in 2014; many countries, including Scotland, had moratoria in place during this period, and, once the moratorium in England was lifted in 2012, it took several years to obtain planning permissions to enable activities to commence at the Preston New Road site, followed by repeated suspension of hydraulic fracturing activities (see Sect. 1.2). We cannot postulate whether the rationale for the answers provided by participants might have changed in light of these developments in the UK or internationally, including other incidences of felt seismicity induced by hydraulic fracturing around the world (Verdon and Bommer, 2021) and subsequent advances in our understanding of induced seismicity and remaining knowledge gaps (Schultz et al., 2020). Nonetheless, our study presents, for the first time, how language ambiguity around seismicity complicates understanding of perceived risks and sheds light on the apparent differences in views on the matter in 2014. Furthermore, advances in knowledge and understanding on topics of public interest is common, but presents additional communication challenges, in particular around the communication of uncertainty (NASEM, 2017). Our findings suggest that language ambiguity around hydraulic-fracturing-induced seismicity posed additional difficulties for understanding and communicating stakeholder risk perception and may have confounded risk communication.

Expertise is an ambiguous quality with multiple dimensions that can be difficult to assess (Lightbody and Roberts, 2019). Many of our survey respondents were attending professional fora about shale gas and, therefore, might be considered to have expertise on the topic. Those who attended public lectures on hydraulic fracturing could be said to be informed (and engaged) members of the public. Accordingly, we find that our survey participants are, on the whole, much more decided about shale-as-induced seismicity than the UK general public (based on the University of Nottingham surveys, as reported in O'Hara et al., 2016). Of the relatively few participants in our survey who answered "do not know", their response did not necessarily reflect lack of knowledge; several explained that the evidence was inconclusive or questioned the definition of "earthquake". Survey respondents who attended public events and who answered "do not know" were more likely to express that they lack knowledge on the topic, and so we could conjecture that this is the likely rationale when the UK public answer "do not know". A fourth closed-answer category of "undecided" or "it depends" would capture these differences.

On one hand, fewer "do not know" responses might be expected of those working in shale gas topics or attending public lectures on shale gas, given that they are knowledgeable about the topic, and reports at the time conclude that risk of earthquakes from hydraulic fracturing is low (see Sect. 2.1). On the other hand, fewer "do not know" responses might be somewhat surprising, given that experts are expected to have strong grasp of uncertainty within their field (e.g. Landström et al., 2015), and a range of dependencies are provided in the qualitative responses. Furthermore, it is now understood that the occurrence of felt seismicity from hydraulic fracturing is highly site specific (Butcher at al., 2017; Schultz et al., 2020; Verdon and Bommer, 2021) and that "methods for predicting event maximum and magnitude … cannot be viewed as reliable" (OGA, 2019, p. 3). Perhaps the certainty in expert views on shale gas and earthquakes also reflects their motivations, such as support for the resource. While we cannot test this using our data, we do note that over 90 % of the most knowledgeable participants in our study supported shale gas exploration compared to ∼ 50 % of the UK public in 2014 (O'Hara et al., 2016).

The proportions of those who do associate earthquakes with shale gas vary according to different factors including the fora being attended (professional or public), the sources of information used to obtain information about shale gas (outside of the event they were attending, expert reports vs. academic papers vs. media) and job sector (academic, industry, and civil service); in every case, the closed survey results are bimodal. While this might be interpreted as showing polarisation of views amongst both experts and the public, by examining the underlying rationale for the answers provided by our participants, we find this not to be the case. Language ambiguity leads to differences in understanding of what defines or constitutes an earthquake and what is meant by "associating" earthquakes with shale gas. As a result, participants with similar underlying views or rationale give different responses to the closed question.

Regardless of whether our respondents do or do not associate earthquakes with shale gas, qualitative answers most commonly express uncertainty around what magnitude of seismic event is understood to be an earthquake. In particular, those who do not associate earthquakes and shale gas question the definition of an earthquake. The term earthquake (the phrase used in the survey question) is clearly felt to be ambiguous by our survey respondents. Similar language ambiguities are expressed by experts interviewed by Lampkin (2019), in which one said, "I would call them tremors, not earthquakes; they are very, very small" and another asserted that "people who talk of earthquakes are sort of over-egging [overdoing] it a bit".

So, what constitutes an earthquake? Is it wrong or, indeed, "over-egging it" to describe a $M_l < 2$ event as an earthquake? Technically, it is not (Kendall et al., 2019). In which case, how should earthquakes be described? There are multiple scales with which to describe the size or properties of earthquakes, including different scales of magnitude and energy release. However, there is no common descriptive scale to define whether an event is a tremor, a micro-earthquake, small or large, or felt. "Tremor" has been used to refer to low-frequency earthquake signals (Shelly et al., 2007), and terms such as "micro-" or "nano-seismicity" often refer to the frequencies of the seismic energy. The degree to which an earthquake is felt is captured by the European Macroseismic Scale, which includes classifications such as not felt, scarcely felt, weak, and largely observed. Bohnhoff et al. (2010) summarises terminology based on magnitude, including micro-, small, moderate, and large. Eaton et al. (2016) recognise the need for a terminology framework for induced seismicity, particularly to unify regulations in different jurisdictions, and propose that "earthquakes" and "seismic events" should be distinguished by being felt or not and, therefore, should refer to events $> M_l$ 2 and $M_l < 2$, respectively. The UK OGA traffic light system infographic (Fig. 1) describes seismicity as being not felt, usually not felt, minor, light, moderate, strong, major, and great.

In our study, we have not encountered any consistent use of such language when describing and reporting hydraulic fracturing seismicity, i.e. there is no common descriptive scale and certainly none that translates into common language and understanding, even among experts. We find that, while expert reports commonly refer to "earthquakes", "seismicity" and "events", many use additional qualifiers to communicate the scale of the event by using terms such as "small" or "tiny", distinguishing between "felt" or "perceived" events, or by referring to the consequences of the seismicity using terms such "tremors" or "vibrations" (Table 7). Importantly, none of the reports that we reviewed lay out what is meant by these different phrases, though some specifically refer to felt seismicity and stipulate that felt seismicity is generally considered to be above M_l 2. We recommend that public-facing reports define technical or descriptive terminology.

Similarly, our survey respondents include indicators of size, risk, and impacts in their qualitative answers. They might select that they do associate shale gas with earthquakes but explain that "any induced seismicity would be small or rare", or they may select that they do not associate shale gas with earthquakes because "any induced seismicity would be small or rare" (see Table 7). Thus, whether or not a respondent associates shale gas with earthquakes does not reflect the perceived risk of seismicity. We posit that, had a definition of what was meant by the term earthquake been presented in the survey (e.g. the release of seismic energy or seismic events with magnitude greater than 2 M_l), the answers to the closed question would have been in much greater agreement.

These findings raise crucial questions around what constitutes an earthquake and to whom and how language is used to describe and communicate geological phenomena. A second important aspect that our work highlights is the need to apply caution when using ambiguous terminology such as "earthquake" in reports or surveys without defining the meaning of the phrase. But here, there are interesting tensions or trade-offs. Terms such as "earthquake" or "tremors" might be used to avoid jargon, as they are considered to be widely understood. However, as we show, what exactly constitutes an earthquake or tremor is not well defined, and so the use of these terms could lead to equivocal results. And these ambiguities might vary geographically too; the UK is a country of low natural background seismicity, and so while a M_l 2 event might be considered an earthquake by the UK public, in regions with higher background activity, other terms might be preferred.

But if our study finds that associating shale gas with earthquakes does not necessarily indicate concern about the risk of earthquakes, what might this mean for understanding the public's views on induced seismicity? Do closed surveys with few questions or options capture the level of concern about induced seismicity? Or might the use of the term "earthquake" cause uncertainty in the responses? Might participants be answering the same question differently depending on what they interpret "earthquake" to mean? These issues highlight the limitations of closed questions in surveys; such questions are, by their nature, constrained, which can bring limitations – including susceptibility to framing effects (Schuman and Scott, 1987; Gaskell et a al., 2017) – which are recognised by Howell (2018). This is not to undermine closed survey research nor the results of studies we examined; there are strengths and weaknesses to all research methods, including open survey questions (Schuman and Scott, 1987), which researchers will carefully consider during the research design, execution, and analysis. But, altogether, this raises important questions around the methods used to capture, understand, and communicate stakeholder perspectives. Might it be that, for comprehensive understanding of complex topics we must look to multi- or mixed-method approaches (e.g. Walker and Baxter, 2019)?

Unlike the UK's traffic light system (Fig. 1), public risk tolerances of induced seismicity will not simply relate to event magnitude; as we have outlined, there are other important complicating and competing factors at play (Evensen, 2018; Trutnevyte and Ejderyan, 2018; Szolucha, 2019). Understanding risk perception and tolerances, influencing factors, and values is important for public participation in socio-scientific decisions (Dietz, 2013; Stern and Fineberg, 1996). As such, our findings about language ambiguity around induced seismicity have implications for science communication and understanding of stakeholder preferences and perceptions of risk. These implications are relevant across a range of different geological and energy engineering technologies, many of which play a critical role in delivering a sustainable future (Stephenson et al., 2019). We propose that a shared language to describe earthquakes should be developed and adopted to enhance communication around induced seismicity amongst all stakeholders. Such an approach is common in risk communication and management practice (Fischhoff, 2013) and has recently been called for by a community of UK shale gas researchers and practitioners (Brown et al., 2020). It supports communication and, as put by Trutnevyte and Ejderyan (2018), without such a framework, experts must develop their communication approaches based on intuition and learning by doing[3]. As noted previously, language frameworks for seismicity exist (such as the European Macroseismic Scale; Johnston, 1990; Bohnhoff et al., 2010, and so on), but we find these are not in common use. While a language framework might facilitate risk communication, it would not resolve communication and risk tolerance challenges around induced seismicity. Any risk communication strategy must be individual to project, place, and context, as well as being sensitive to issues of environmental and social equity and justice and heritage in which geoenergy is involved (Trutnevyte and Ejderyan, 2018). The perceived risk may be greater for some technologies over others (Knoblauch et al., 2018) and may evolve with time. However, the framework should establish a common understanding through language, which is critical for dialogue on topics of public and political interest. It is increasingly understood that sustainable development requires shared decision-making pathways for which communication approaches that support stakeholders in speaking – and hearing – the same language are valuable.

5 Conclusions

This work has explored expert and nonexpert perspectives on the risk of induced seismicity from shale gas exploration in the UK. We find that a range of terminologies have been inconsistently used to describe seismic events to communicate the risk of induced seismicity from hydraulic fracturing for shale gas. Such language ambiguity has muddled our ability to understand the perceived risk of induced seismicity and hydraulic fracturing amongst stakeholders, raising questions around what constitutes an earthquake and for whom? Our insights present important implications for research, communication, and decision-making on any uncertain, complex, or sensitive topic. The immediate and long-lasting repercus-

[3] These experiences are often described by practitioners as being "at the coal face" or "on the front line", indicating the challenging pressured environment for learning.

sions of using “fracking bad language” is likely amplified by the political and environmental sensitivities around the shale gas sector, as well as a lack of familiarity of seismicity (natural and induced) to UK stakeholders. At its simplest, this research presents a reminder of the importance of clearly defining technical and descriptive terms, whether in expert reports, policy documents, or surveys. We suggest that a shared language to describe earthquakes should be developed and adopted to improve the understanding of perceived risks and to facilitate risk communication within and between expert and nonexpert stakeholders. Our findings are relevant to numerous geoscience applications, since many subsurface technologies deemed critical to a low carbon future could present risk of induced seismicity.

Ethical statement. This research complied with the Ethics Policy and Procedure of the University of Strathclyde. Ethics approval was granted for the survey research.

Data availability. Full survey data are available at https://doi.org/10.15129/a7a906c5-a77e-4a1c-b495-a2d441458d1d (Roberts et al., 2021).

Author contributions. JJR led the research design, data collection, analysis, and writing of this research, with CEB, in particular, and ZKS contributing to all aspects of the paper.

Competing interests. The authors declare that they have no conflict of interest.

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References

Adgate, J. L., Goldstein, B. D., and McKenzie, L. M.: Potential Public Health Hazards, Exposures and Health Effects from Unconventional Natural Gas Development, Environ. Sci. Technol., 48, 8307–8320, https://doi.org/10.1021/es404621d, 2014.

AEA: Climate impact of potential shale gas production in the EU: Final Report, Report for the European Commission DG CLIMA, Didcot, Oxfordshire, UK, 2012.

Alcalde, J., Bond, C. E., and Randle, C. H.: Framing bias: The effect of figure presentation on seismic interpretation, Interpretation, 5, T591–T605, https://doi.org/10.1190/INT-2017-0083.1, 2017.

Alcalde, J., Bond, C. E., Johnson, G., Kloppenburg, A., Ferrer, O., Bell, R., and Ayarza, P.: Fault interpretation in seismic reflection data: an experiment analysing the impact of conceptual model anchoring and vertical exaggeration, Solid Earth, 10, 1651–1662, https://doi.org/10.5194/se-10-1651-2019, 2019.

Alessi, R. J. and Kuhn, J. D.: British government lifts year-old fracking moratorium, Energy alert, available at: https://www.dlapiper.com/en/uk/insights/publications/2012/12/british-government-lifts-yearold-fracking-morato__/ (last access: November 2019), 2012.

Andersson-Hudson, J., Knight, W., Humphrey, M., and O’Hara, S.: Exploring support for shale gas extraction in the United Kingdom, Energ. Policy, 98, 582–589, https://doi.org/10.1016/j.enpol.2016.09.042, 2016.

Andersson-Hudson, J., Rose, J., Humphrey, M., Knight, W., and O’Hara, S.: The structure of attitudes towards shale gas extraction in the United Kingdom, Energ. Policy, 129, 693–697, https://doi.org/10.1016/j.enpol.2019.02.056, 2019.

Baptie, B., Segou, M., Ellen, R., and Monaghan, A.: Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity, 92, available at: https://www.gov.scot/publications/unconventional-oil-gas-understanding-monitoring-induced-seismic-activity/ (last access: November 2019), 2016.

Barclay, E. J., Renshaw, C. E., Taylor, H. A., and Bilge, A. R.: Improving Decision Making Skill Using an Online Volcanic Crisis Simulation: Impact of Data Presentation Format, Journal of Geoscience Education, 59, 85–92, https://doi.org/10.5408/1.3543933, 2011.

BEIS: Department for Business, Energy & Industrial Strategy Press release: Government ends support for fracking (2 November 2019), available at: https://www.gov.uk/government/news/government-ends-support-for-fracking, last access: November 2019a.

BEIS: Department for Business, Energy & Industrial Strategy Guidance on fracking: developing shale gas in the UK, available at: https://www.gov.uk/government/publications/about-shale-gas-and-hydraulic-fracturing-fracking/developing-shale-oil-and-gas-in-the-uk, last access: September 2019b.

Bohnhoff, M., Dresen, G., Ellsworth, W. L., and Ito, H.: Passive Seismic Monitoring of Natural and Induced Earthquakes: Case Studies, Future Directions and Socio-Economic Relevance, in: New Frontiers in Integrated Solid Earth Sciences, edited by: Cloetingh, S. and Negendank, J., Springer Netherlands, Dordrecht, the Netherlands, 261–285, https://doi.org/10.1007/978-90-481-2737-5_7, 2010.

Bond, C. E.: Uncertainty in Structural Interpretation: Lessons to be learnt, J. Struct. Geol., 74, 185–200, https://doi.org/10.1016/j.jsg.2015.03.003, 2015.

Bond, C. E., Gibbs, A. D., Shipton, Z. K., and Jones, S. What do you think this is? “Conceptual uncertainty” In geoscience interpretation, GSA Today, 17, 4–10, https://doi.org/10.1130/GSAT01711A.1, 2007.

Boudet, H., Clarke, C., Bugden, D., Maibach, E., Roser-Renouf, C., and Leiserowitz, A.: “Fracking” controversy and communication: Using national survey data to understand public perceptions of hydraulic fracturing, Energ. Policy, 65, 57–67, https://doi.org/10.1016/j.enpol.2013.10.017, 2014.

Bradshaw, M. and Waite, C.: Learning from Lancashire: Exploring the contours of the shale gas conflict in England, Global Environ. Chang., 47, 28–36, https://doi.org/10.1016/j.gloenvcha.2017.08.005, 2017.

Breede, K., Dzebisashvili, K., Liu, X., and Falcone, G.: A systematic review of enhanced (or engineered) geothermal systems: past, present and future, Geothermal Energy, 1, 4, https://doi.org/10.1186/2195-9706-1-4, 2013.

Brown, R., Clancy, S., Roberts, J., and Gibson, H.: What are the research gaps around induced seismicity and shale gas? A summary of the findings of the first UKUH Integration Event, 9 May 2019, London, UK, 2020.

Bryant, P.: Fracking: A Citizens Deliberation (Preston, Lancashire), Shared Futures CIC, availale at: https://sharedfuturecic.org.uk/wp-content/uploads/2016/08/FRACKING-CD-FINAL-REPORT.web_.pdf (last access: November 2019), 2016.

Butcher, A., Luckett, R., Verdon, J. P., Kendall, J. M., Baptie, B., and Wookey, J.: Local Magnitude Discrepancies for Near-Event Receivers: Implications for the U.K. Traffic-Light Scheme, B. Seismol. Soc. Am., 107, 532–541, https://doi.org/10.1785/0120160225, 2017.

Clarke, H., Eisner, L., Styles, P., and Turner, P.: Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe, Geophys. Res. Lett., 41, 2014GL062047, https://doi.org/10.1002/2014GL062047, 2014.

Clarke, H., Verdon, J. P., Kettlety, T., Baird, A. F., and Kendall, J. M.: Real-Time Imaging, Forecasting, and Management of Human-Induced Seismicity at Preston New Road, Lancashire, England, Seismol. Res. Lett., 90, 1902–1915, https://doi.org/10.1785/0220190110, 2019.

Cobbing, J., and Ó Dochartaigh, B. É.: Hydrofracturing water boreholes in hard rock aquifers in Scotland, Q. J. Eng. Geol. Hydroge., 40, 181–186, 2007.

Collins, H.: Language and practice, Soc. Stud. Sci., 41, 271–300, https://doi.org/10.1177/0306312711399665, 2011.

Cook, P., Beck, V., Brereton, D., Clark, R., Fisher, B., Kentish, S., Toomey, J., and Williams, J.: Engineering Energy: Unconventional Gas Production: A study of shale gas in Australia, Australian Council of Learned Academies (ACOLA) for PMSEIC, Melbourne, Australia, 2013.

Craig, K., Evensen, D., and Van Der Horst, D.: How distance influences dislike: Responses to proposed fracking in Fermanagh, Northern Ireland, Morav. Geogr. Rep., 27, 92–107, https://doi.org/10.2478/mgr-2019-0008, 2019.

Cremonese, L., Ferrari, M., Flynn, M. P., and Gusev, A.: Shale Gas and Fracking in Europe, Institute for Advanced Sustainability Studies (IASS) Potsdam Fact Sheet 1/2015, Potsdam, Germany, 2015.

DECC: Written Ministerial Statement by Edward Davey: Exploration for shale gas, available at: https://www.gov.uk/government/speeches/written-ministerial-statement-by-edward-davey-exploration-for-shale-gas (last access: November 2019), 2013a.

DECC: Guidance: Traffic light monitoring system (shale gas and fracking), 9 September 2013, available at: https://www.gov.uk/government/publications/traffic-light-monitoring-system-shale-gas-and-fracking (last access: November 2019), 2013b.

DECC: About shale gas and hydraulic fracturing (fracking), available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/268017/About_shale_gas_and_hydraulic_fracturing_Dec_2013.pdf (last access: November 2019), 2013c.

Delebarre, J., Ares, E., Smith, L., and Priestley, S.: Shale gas and fracking: Briefing paper CBP 6073, House of Commons, London, UK, 2018.

Dietz, T.: Bringing values and deliberation to science communication, P. Natl. Acad. Sci. USA, 110, 14081, https://doi.org/10.1073/pnas.1212740110, 2013.

Doust, H.: The exploration play: What do we mean by it?, AAPG Bull., 94, 1657–1672, 2010.

Eaton, D. W., van der Baan, M., and Ingelson, A.: Terminology for fluid-injection induced seismicity in oil and gas operations, CSEG Recorder 41:04, Vancouver, Canada, 2016.

Ellsworth, W. L.: Injection-Induced Earthquakes, Science, 341, 1225942, https://doi.org/10.1126/science.1225942, 2013.

Engelder, T. and Lacazette, A.: Natural hydraulic fracturing, in: Rock Joints, edited by: Barton, N. and Stephansson, O., A.A. Balkema, Rotterdam, the Netherlands, 35–44, 1990.

European Commission: Commission Recommendation of 22 January 2014 on minimum principles for the exploration and production of hydrocarbons (such as shale gas) using high-volume hydraulic fracturing (2014/70/EU), available at: https://op.europa.eu/en/publication-detail/-/publication/85528c58-90a5-11e3-a916-01aa75ed71a1 (last access: November 2019), 2014.

Evensen, D.: If they only knew what i know': Attitude change from education about fracking, Environmental Practice, 19, 68–79, https://doi.org/10.1080/14660466.2017.1309884, 2017.

Evensen, D.: Review of shale gas social science in the United Kingdom, 2013–2018, The Extractive Industries and Society, 5, 691–698, https://doi.org/10.1016/j.exis.2018.09.005, 2018.

Evensen, D., Devine-Wright, P., and Whitmarsh, L.: UK National Survey of Public Attitudes Towards Shale Gas, Unconventional Hydrocarbons in the UK Energy System (UKUH) Research Brief 1, available at: https://www.exeter.ac.uk/news/documents/ASSIST_policy_brief-July-29-2019.pdf, last access: November 2019.

Fall, A., Eichhubl, P., Bodnar, R. J., Laubach, S. E., and Davis, J. S.: Natural hydraulic fracturing of tight-gas sandstone reservoirs, Piceance Basin, Colorado, GSA Bulletin, 127, 61–75, https://doi.org/10.1130/B31021.1, 2015.

Fischer, F.: Citizens, Experts, and the Environment: The Politics of Local Knowledge, Duke University Press, London, UK, 2000.

Fischhoff, B.: The sciences of science communication, P. Natl. Acad. Sci. USA, 110, 14033, https://doi.org/10.1073/pnas.1213273110, 2013.

Forster, D. and Perks, J.: Climate impact of potential shale gas production in the EU, Final Report, AEA Technology Inc. for EC DG Climate Action, Final Report, Review Issue 2, available at: https://ec.europa.eu/clima/sites/clima/files/eccp/docs/120815_final_report_en.pdf (last access: November 2019), 2012.

Gaskell, G., Hohl, K., and Gerber, M. M.: Do closed survey questions overestimate public perceptions of food risks?, J. Risk Res., 20, 1038–1052, https://doi.org/10.1080/13669877.2016.1147492, 2017.

Gibson, H., Stewart, I. S., Pahl, S., and Stokes, A.: A "mental models" approach to the communication of subsurface hydrology and hazards, Hydrol. Earth Syst. Sci., 20, 1737–1749, https://doi.org/10.5194/hess-20-1737-2016, 2016.

Graham, J. D., Rupp, J. A., and Schenk, O.: Unconventional Gas Development in the USA: Exploring the Risk Perception Issues, Risk Anal., 35, 1770–1788, https://doi.org/10.1111/risa.12512, 2015.

Green, C. A., Styles, P., and Baptie, B. J.: Preese Hall shale gas fracturing review and recommendations for induced seismic mitigation, Department of Energy and Climate Change, London, UK, 2012.

Hilson, C.: Framing Fracking: Which Frames Are Heard in English Planning and Environmental Policy and Practice?, J. Environ. Law, 27, 177–202, https://doi.org/10.1093/jel/equ036, 2015.

Howell, R. A.: UK public beliefs about fracking and effects of knowledge on beliefs and support: A problem for shale gas policy, Energ. Policy, 113, 721–730, https://doi.org/10.1016/j.enpol.2017.11.061, 2018.

Horlick-Jones, T., Walls, J., Rowe, G., Pidgeon, N., Poortinga, W., Murdock, G., and O'Riordan, T.: The GM debate: Risk, politics and public engagement, Genetics and Society, Routledge, London, UK, 2007.

Jalali, M., Gischig, V., Doetsch, J., Näf, R., Krietsch, H., Klepikova, M., Amann, F., and Giardini, D.: Transmissivity Changes and Microseismicity Induced by Small-Scale Hydraulic Fracturing Tests in Crystalline Rock, Geophys. Res. Lett., 45, 2265–2273, https://doi.org/10.1002/2017GL076781, 2018.

Jaspal, R. and Nerlich, B.: Fracking in the UK press: Threat dynamics in an unfolding debate, Public Underst. Sci., 23, 348–363, 2014.

Johnston, A. C.: An earthquake strength scale for the media and the public, Earthquakes & Volcanoes (USGS), 22, 214–216, 1990.

Kavalov, B. and Pelletier, N.: Shale Gas for Europe – Main Environmental and Social Considerations A Literature Review European Commission Joint Research Centre Institute for Environment and Sustainability EUR 25498 EN, https://doi.org/10.2788/48370, 2012.

Kendall, J. M., Butcher, A., Stork, A., Verdon, J., Luckett, R., and Baptie, B.: How big is a small earthquake? Challenges in determining microseismic magnitudes, First Break, 37, 51–56, 2019.

King, G. E.: Hydraulic Fracturing 101: What Every Representative, Environmentalist, Regulator, Reporter, Investor, University Researcher, Neighbor and Engineer Should Know About Estimating Frac Risk and Improving Frac Performance in Unconventional Gas and Oil Wells, SPE Hydraulic Fracturing Technology Conference, The Woodlands, Texas, USA, 1 January 2012, https://doi.org/10.2118/152596-MS, 2012.

Knoblauch, T. A. K., Stauffacher, M., and Trutnevyte, E.: Communicating Low-Probability High-Consequence Risk, Uncertainty and Expert Confidence: Induced Seismicity of Deep Geothermal Energy and Shale Gas, Risk Anal., 38, 694–709, https://doi.org/10.1111/risa.12872, 2018.

Kwiatek, G., Plenkers, K., Dresen, G., and Group, J. R.: Source Parameters of Picoseismicity Recorded at Mponeng Deep Gold Mine, South Africa: Implications for Scaling Relations, B. Seismol. Soc. Am., 101, 2592–2608, https://doi.org/10.1785/0120110094, 2011.

Lampkin, J. A.: Will Unconventional, Horizontal, Hydraulic Fracturing for Shale Gas Production Purposes Create Environmental Harm in the United Kingdom? PhD thesis, University of Lincoln, Lincoln, UK, 2019.

Landström, C., Hauxwell-Baldwin, R., Lorenzoni, I., and Rogers-Hayden, T.: The (Mis)understanding of Scientific Uncertainty? How Experts View Policy-Makers, the Media and Publics, Sci. Cult., 24, 276–298, https://doi.org/10.1080/09505431.2014.992333, 2015.

Lark, R. M., Thorpe, S., Kessler, H., and Mathers, S. J.: Interpretative modelling of a geological cross section from boreholes: sources of uncertainty and their quantification, Solid Earth, 5, 1189–1203, https://doi.org/10.5194/se-5-1189-2014, 2014.

Leach, G.: The energy transition, Energ. Policy, 20, 116–123, 1992.

Leggett, M. and Finlay, M.: Science, story, and image: a new approach to crossing the communication barrier posed by scientific jargon, Public Underst. Sci., 10, 157–171, 2001.

Lightbody, R. and Roberts, J. J.: Experts: The Politics of Evidence and Expertise in Democratic Innovation, in: The Handbook of Democratic Innovation and Governance, edited by: Elstub, S. and Escobar, O., Edward Elgar Publishing, Cheltenham, UK, 2019.

Lis, A., Braendle, C., Fleischer, T., Thomas, M., Evensen, D., and Mastop, J.: Existing European Data on Public Perceptions of Shale Gas, available at: http://www.m4shalegas.eu/reportsp4.html (last access: November 2019), 2015.

Lowry, D.: Nuclear waste: The protracted debate in the UK, in: Nuclear or Not?, Palgrave Macmillan, London, UK, 115–131, 2007.

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

Marker, B. R.: Urban planning: the geoscience input. Geological Society, London, Eng. Geol. SP, 27, 35, https://doi.org/10.1144/EGSP27.3, 2016.

Matthews, J. and Hansen, A.: Fracturing Debate? A Review of Research on Media Coverage of "Fracking", Frontiers in Communication, 3, https://doi.org/10.3389/fcomm.2018.00041, 2018.

Mazzini, A.: 10 years of Lusi eruption: Lessons learned from multidisciplinary studies (LUSI LAB), Mar. Petrol. Geol., 90, 1–9, https://doi.org/10.1016/j.marpetgeo.2017.12.025, 2018.

McMahon, R., Stauffacher, M., and Knutti, R. The unseen uncertainties in climate change: reviewing comprehension of an IPCC scenario graph, Climatic Change, 133, 141–154, 2015.

McNally, H., Howley, P., and Cotton, M.: Public perceptions of shale gas in the UK: framing effects and decision heuristics, Energy, Ecology and Environment, 3, 305–316, https://doi.org/10.1007/s40974-018-0102-2, 2018.

Montgomery, S. L.: The cult of jargon: Reflections on language in science, Sci. Cult., 1, 42–77, 1989.

NASEM: Communicating Science Effectively: A Research Agenda. National Academies of Sciences, Engineering, and Medicine (NASEM) National Academies Press, PMID: 28406600, Washington, D.C., USA, 2017.

National Research Council: Induced Seismicity Potential in Energy Technologies, The National Academies Press, Washington, D.C., USA, https://doi.org/10.17226/13355, 2013.

Nisbet, M. C.: Framing science: A new paradigm in public engagement, in: Communicating science, Routledge, New York, UK, 54–81, 2009.

OGA: Interim report of the scientific analysis of data gathered from Cuadrilla's operations at Preston New Road, available at: https://www.ogauthority.co.uk/media/6149/summary-of-pnr1z-interim-reports.pdf, last access: November 2019.

O'Hara, S., Humphrey, M., Andersson, J., Jaspal, R., Nerlich, B., and Knight, W.: Public perception of shale gas extraction in the UK: Is the Balcombe effect taking hold?, University of Nottingham, Nottingham, UK, 2014.

O'Hara, S., Humphrey, M., Andersson-Hudson, J., and Knight, W.: Public Perception of Shale Gas Extraction in the UK: From Positive to Negative, University of Nottingham, Nottingham, UK, 2016.

Parkins, J. R. and Mitchell, R. E.: Public participation as public debate: a deliberative turn in natural resource management, Society and natural resources, 18, 529–540, 2005.

Partridge, T., Thomas, M., Harthorn, B. H., Pidgeon, N., Hasell, A., Stevenson, L., and Enders, C.: Seeing futures now: Emergent US and UK views on shale development, climate change and energy systems, Global Environ. Chang., 42, 1–12, https://doi.org/10.1016/j.gloenvcha.2016.11.002, 2017.

Pidgeon, N.: Engaging publics about environmental and technology risks: frames, values and deliberation, J. Risk Res., 24, 1–19, https://doi.org/10.1080/13669877.2020.1749118, 2020.

Pollyea, R. M., Chapman, M. C., Jayne, R. S., and Wu, H.: High density oilfield wastewater disposal causes deeper, stronger, and more persistent earthquakes, Nat. Commun., 10, 3077, https://doi.org/10.1038/s41467-019-11029-8, 2019.

Roberts, J. J., Lightbody, R., Low, R., and Elstub, S.: Experts and evidence in deliberation: scrutinising the role of witnesses and evidence in mini-publics, a case study, Policy Sci., 53, 3–32, https://doi.org/10.1007/s11077-019-09367-x, 2020.

Roberts, J. J., Bond, C. E., and Shipton, Z. K.: Survey data on the perceptions of shale gas in the UK, [data set], University of Strathclyde, https://doi.org/10.15129/a7a906c5-a77e-4a1c-b495-a2d441458d1d, 2021.

Rowe, G., Horlick-Jones, T., Walls, J., and Pidgeon, N.: Difficulties in evaluating public engagement initiatives: reflections on an evaluation of the UK GM Nation? public debate about transgenic crops, Public Underst. Sci., 14, 331–352, 2005.

Schuman, H. and Scott, J.: Problems in the Use of Survey Questions to Measure Public Opinion, Science, 236, 957–959, https://doi.org/10.1126/science.236.4804.957, 1987.

Schultz, R., Skoumal, R. J., Brudzinski, M. R., Eaton, D., Baptie, B., and Ellsworth, W.: Hydraulic Fracturing-Induced Seismicity, Rev. Geophys., 58, e2019RG000695, https://doi.org/10.1029/2019RG000695, 2020.

Scottish Government: Expert Scientific Panel on Unconventional Oil and Gas report, Edinburgh, UK, ISBN 9781784126834, 2014.

Scottish Government: Unconventional oil and gas policy: SEA, Edinburgh, UK, ISBN 9781787813014, 2018.

Selley, R. C.: UK shale gas: The story so far, Mar. Petrol. Geol., 31, 100–109, https://doi.org/10.1016/j.marpetgeo.2011.08.017, 2012.

Sharon, A. J. and Baram-Tsabari, A.: Measuring mumbo jumbo: A preliminary quantification of the use of jargon in science communication, Public Underst. Sci., 23, 528–546, https://doi.org/10.1177/0963662512469916, 2014.

Shelly, D., Beroza, G., and Ide, S.: Non-volcanic tremor and low-frequency earthquake swarms, Nature, 446, 305–307, https://doi.org/10.1038/nature05666, 2007.

Shipton, Z. K., Roberts, J. J., Comrie, E. L., Kremer, Y., Lunn, R. J., and Caine, J. S.: Fault fictions: systematic biases in the conceptualization of fault-zone architecture, Geol. Soc. SP, 496, SP496-2018-2161, https://doi.org/10.1144/SP496-2018-161, 2019.

Simis, M. J., Madden, H., Cacciatore, M. A., and Yeo, S. K. The lure of rationality: Why does the deficit model persist in science communication? Public Underst. Sci., 25, 400–414, https://doi.org/10.1177/0963662516629749, 2016.

Stephenson, M. H., Ringrose, P., Geiger, S., Bridden, M., and Schofield, D.: Geoscience and decarbonization: current status and future directions, Petrol. Geosci., 25, 501, https://doi.org/10.1144/petgeo2019-084, 2019.

Stern, P. C. and Fineberg, H. C.: US National Research Council Understanding Risk: Informing Decisions in a Democratic Society, edited by: Stern, P. C. and Fineberg, H. C., National Academy Press, Washington, D.C., USA, 1996.

Stewart, S. and Allen, P.: A 20-km-diameter multi-ringed impact structure in the North Sea, Nature, 418, 520–523, https://doi.org/10.1038/nature00914, 2002.

Stewart, S. and Allen, P.: An alternative origin for the "Silverpit crater" (reply), Nature, 428, p. 2, https://doi.org/10.1038/nature02480, 2004.

Szolucha, A.: 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, https://doi.org/10.1016/j.erss.2019.101254, 2019.

Tang, C. A. and Kaiser P. K.: Numerical simulation of cumulative damage and seismic energy release during brittle rock failure – Part I: fundamentals, Int. J. Rock Mech. Min., 35, 113–121, 1998.

Task Force on Shale Gas (TFSG): Assessing the Impact of Shale Gas on the Local Environment and Health, Second Interim Report, London, UK, 2015.

Taylor, H. A., Renshaw, C. E., and Jensen, M. D. Effects of computer-based role-playing on decision-making skills, J. Educ. Comput. Res., 17, 147–164, 1997.

Taylor, A. L., Dessai, S., and Bruine de Bruin, W.: Public perception of climate risk and adaptation in the UK: A review of the literature, Climate Risk Management, 4–5, 1–16, 2014.

Thomas, M., Partridge, T., Harthorn, B. H., and Pidgeon, N.: Deliberating the perceived risks, benefits, and societal implications of shale gas and oil extraction by hydraulic fracturing in the US and UK, Nature Energy, 2, 17054, https://doi.org/10.1038/nenergy.2017.54, 2017a.

Thomas, M., Pidgeon, N., Evensen, D., Partridge, T., Hasell, A., Enders, C., and Bradshaw, M.: Public perceptions of hydraulic fracturing for shale gas and oil in the United States and Canada, Wiley Interdiscip. Rev. Clim. Change, 8, e450, https://doi.org/10.1002/wcc.450, 2017b.

Tingay, M., Manga, M., Rudolph, M. L., and Davies, R.: An alternative review of facts, coincidences and past and future studies of the Lusi eruption, Mar. Petrol. Geol., 95, 345–361, https://doi.org/10.1016/j.marpetgeo.2017.12.031, 2018.

Trutnevyte, E. and Ejderyan, O.: Managing geoenergy-induced seismicity with society, J. Risk Res., 21, 1287–1294, https://doi.org/10.1080/13669877.2017.1304979, 2018.

Tversky, A. and Kahneman, D.: The framing of decisions and the psychology of choice, Science, 211, 453–458, https://doi.org/10.1126/science.7455683, 1981.

Underhill, J. An alternative origin for the "Silverpit crater", Nature, 428, 1–2, https://doi.org/10.1038/nature02476, 2004.

Van de Graaf, T., Haesebrouck, T., and Debaere, P.: Fractured politics? The comparative regulation of shale gas in Europe, J. Eur. Public Policy, 25, 1276–1293, https://doi.org/10.1080/13501763.2017.1301985, 2018.

Vander Beken, T., Dorn, N., and Van Daele, S.: Security risks in nuclear waste management: Exceptionalism, opaqueness and vulnerability, J. Environ. Manage., 91, 940–948, 2010.

van Loon, A. J.: The stolen sequence, Earth-Sci. Rev., 52, 237–244, 2000.

Venhuizen, G. J., Hut, R., Albers, C., Stoof, C. R., and Smeets, I.: Flooded by jargon: how the interpretation of water-related terms differs between hydrology experts and the general audience, Hydrol. Earth Syst. Sci., 23, 393–403, https://doi.org/10.5194/hess-23-393-2019, 2019.

Verdon, J. P. and Bommer, J. J.: Green, yellow, red, or out of the blue? An assessment of Traffic Light Schemes to mitigate the impact of hydraulic fracturing-induced seismicity, J Seismol., 25, 301–326, https://doi.org/10.1007/s10950-020-09966-9, 2021.

Vergara, W., Rios, A. R., Paliza, L. M. G., Gutman, P., Isbell, P., Suding, P. H., and Samaniego, J.: The climate and development challenge for Latin America and the Caribbean: options for climate-resilient, low-carbon development, Inter-American Development Bank, Washington, D.C., USA, 2013.

Walker, C. and Baxter, J.: Method Sequence and Dominance in Mixed Methods Research: A Case Study of the Social Acceptance of Wind Energy Literature, Int. J. Qual. Meth., 18, https://doi.org/10.1177/1609406919834379, 2019.

Warpinski, N. R., Du, J., and Zimmer, U.: Measurements of hydraulic-fracture-induced seismicity in gas shales, SPE Prod. Oper., 27, 240–252, 2012.

Westaway, R. and Younger, P. L.: Quantification of potential macroseismic effects of the induced seismicity that might result from hydraulic fracturing for shale gas exploitation in the UK, Q. J. Eng. Geol. Hydroge., 47, 333–350, https://doi.org/10.1144/qjegh2014-011, 2014.

Whitmarsh, L., Nash, N., Lloyd, A., and Upham, P.: UK Public Perceptions of Shale Gas, Carbon Capture & Storage and Other Energy Sources & Technologies: Summary Findings of a Deliberative Interview Study and Experimental Survey, Cardiff University, Cardiff, UK, 2014.

Whitmarsh, L., Nash, N., Upham, P., Lloyd, A., Verdon, J. P., and Kendall, J. M.: UK public perceptions of shale gas hydraulic fracturing: The role of audience, message and contextual factors on risk perceptions and policy support, Appl. Energ., 160, 419–430, https://doi.org/10.1016/j.apenergy.2015.09.004, 2015.

Williams, L., Macnaghten, P., Davies, R., and Curtis, S.: Framing "fracking": Exploring public perceptions of hydraulic fracturing in the United Kingdom, Public Underst. Sci., 26, 89–104, https://doi.org/10.1177/0963662515595159, 2017.