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. Further, 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 publics on hydraulic fracturing and seismicity. Further, 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 publics in the period 2012 – 2016; "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 ambiguity of 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, 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 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 - 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 and the publics. However, clear communication to support effective dialogue presents challenges. Geoscience topics can

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face particular communication challenges for several reasons. First, geoscience underpins many issues of environmental and societal importance, such as resource development (water, energy resources) and understanding and mitigation of climate change. These issues are not only important for future generations, but associated activities (e.g. resource extraction, development of low-carbon energy projects) have direct and indirect socio-economic and environmental impacts at a range of scales (Leach, 1992; Vergara et al., 2013; Adgate et al., 2014; Stephenson et al., 2019). Secondly, 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 interpretations of the N. Sea Silver Pit Crater (Stewart and Allen, 2002; Stewart and Allen, 2004; Underhill, 2004) or causes of the Lusi Mud Volcano (Mazzini, 2018; Tingay et al., 2018)). Thirdly, the inaccessibility of and general unfamiliarity with the subsurface can make it challenging for lay publics 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., 2006; Bond et al., 2007). One of the key findings of this paper is that language ambiguity around earthquakes presents challenges for geoenergy decision-making.

Stakeholder perspectives have diverged on technical issues such as geological risk or environmental impact of 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 & Ejderyan, 2018).

To frame our work, we consider the importance 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 Section 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 Section 3 we present our survey approach and results to investigate 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 in Section 4.

[1] We use the term seismicity in the body of this paper as a catchall term to describe the phenomena of rapidly radiated seismic energy that has been described by terms that include: earthquakes, tremors, and so on. Secondly, although we focus on seismicity in this paper, in doing so we do not

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Our findings are applicable to a range of geological applications which could induced 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 & Ejderyan, 2018; Stephenson et al., 2019). Further, the learnings around language, 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 the 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: for scientists, policy makers and the publics 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 sub-sections 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 subject area (Leggett and Finlay, 2001; Sharon and Baram-Tsabari, 2014). This creates an 'unequal communicative relationship' whereby lay publics struggle to comprehend the technical language and goals set by experts (Fischer, 2000, p. 18), particularly as many experts are ill-equipped to communicate with members of the public (Simis et al., 2016).

This unequal communicative relationship is likely enhanced in the geosciences where seemingly non-technical, uncertain, or ambiguous terms are used routinely but assume tacit understanding. As an example, geoscientists may refer to *dip* and *strike* of *faults*, *joints*, or *cleavage*, which have specific meanings in geology, but 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 sub-disciplines (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 & Lightbody, 2020), as well as 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 is 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, 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.

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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.

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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 ranging from improving water extraction (Cobbing & Dochartaigh, 2007), to enhancing deep geothermal energy production (Breed 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 & Lacazette, 1990; Fall et al., 2015).

For shale gas extraction, hydraulic fracturing is one of several processes that allow 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 to investigate the commercial viability of a potential shale gas resource, and development refers to activities to support 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 human-made, the seismicity is categorised as 'human-induced seismicity' or, simply, 'induced seismicity'. Many processes induce seismicity, from mining and quarrying, filling and dewatering reservoirs, to disposing of wastewaters by injection into rock formations (Westaway & Younger et al., 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 quantify, and so report 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 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 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, 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 Bonhoff et al., 2009; 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 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 pre-stressed fault 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). Further,

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recorded M_L is dependent on the seismic detection network, including the array density and location distance between source and 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, 2020; 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 incidences of felt seismicity associated with fracking in the shale gas basins first developed in the USA (Verdon and Bommer, 2020). Seismic events that had been felt were due to geological disposal of hydraulic fracturing waste water rather than the fracking process itself (e.g. Elsworth et al., 2015). 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 (NW 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 (Jaspal & 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, 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; DECC 2013b), including a traffic light system (Figure 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'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 (Schultz et al., 2020; Verdon and Bommer, 2020). It's now understood that the occurrence of felt seismicity from hydraulic fracturing is highly site-specific, and depends on geological and geomechanical conditions of the reservoir and the hydraulic fracturing operation design (Schultz et al., 2020; Verdon and Bommer, 2020), as well as characteristics of the local site (Butcher at al., 2017).

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

Figure 1: The UK's traffic light system for regulating induced seismicity from hydraulic fracturing activities for shale gas extraction, figure from DECC (2013b), made by the Oil and Gas Authority. The traffic light system is based on a

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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).

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

In order to investigate expert and non-expert views and language preferences around induced seismicity and hydraulic fracturing in the UK, we must first define what is meant by 'expert' and 'non-expert' 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 publics or 'lay' audiences are not expected to have in-depth technical or topical expertise, and so we refer to them as 'non-expert' or 'lay' audiences in this paper. However, we understand that such categorisations are simplistic; the publics can hold valuable experiential and contextual knowledge, rather than (but not excluding) technical or topical knowledge.

To examine expert and non-expert 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 non-expert audiences, including the publics. 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, and 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 1A, 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 Section 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 or no different to other causes of human-made seismicity. 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 (non-expert) around shale gas topics in the UK find that publics 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/differences in the phrases used in these studies to refer

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to induced seismicity. These differences are typically introduced by researchers either in the research design or the analysis, rather than in 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.

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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 dataset 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 didn't know what hydraulic fracturing or shale gas was, respondents were then asked questions about multiple aspects of shale gas development. One question asked whether they do or do not associate earthquakes with shale gas, with the option to answer 'don't 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 (Figure 2). In the three surveys conducted in 2014 the responses appear to have stabilised.

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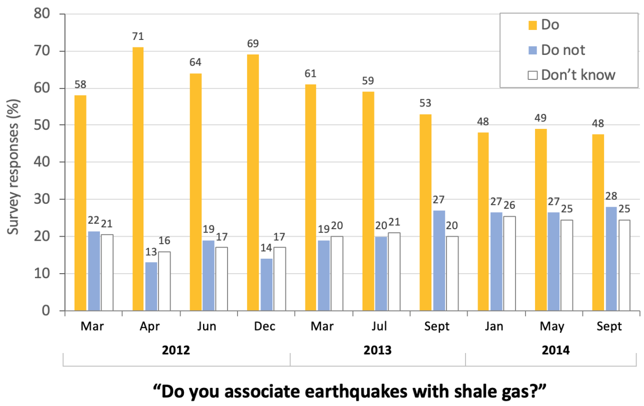

Figure 2: Responses to the ten University of Nottingham surveys administered between 2012-14 via YouGov to assess public perspectives on shale gas development (O'Hara et al., 2016). During the period 2012-14 the number of participants that associate shale gas with earthquakes decreases, while the number of participants that do not associate, or don't know, increases. Results from the additional two surveys administered between 2014-16 are not publicly available.

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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 reasons for support, opposition, or no view have been enquired about (Howell, 2018). One of the reasons for opposition to shale gas that is consistent across the BEIS surveys is 'risk of earthquakes', ranked fourth out of five common concerns (Bradshaw & 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

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participants about perceived risks. However, questions from the Opinium Research were adapted for a different online omnibus survey fielded by YouGov, also 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 'don't know'). However, the level of positive response for earthquakes and tremors ranked towards the lowest of 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 public were marginally less concerned about earthquakes than they were about water contamination.

The most recently published survey, 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 publics. 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. Further, we note that statements regarding earthquake risk were conditional ('could cause'), whereas all other provided risks except for water contamination were unconditional ('will cause').

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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 ten 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.

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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 & Waite, 2017).

Williams et al. (2017) reports on deliberative focus group discussions on shale gas development. The groups were held in Northern England in 2013, and Williams et al., 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-day 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 2013/14 the risk of earthquakes or tremors was ranked 13^{th} out of 19 pre-identified risks in a card sorting exercise

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(Whitmarsh et al., 2014). In 2016 a Citizens' Jury (a format for public deliberation) was held in Preston, Lancashire (NW England) approximately 10 miles 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*, *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*, 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 (2013) report lays out regulatory requirements designed "to ensure that seismic risks are effectively mitigated" (p6) and "to prevent any more earthquakes being triggered by fracking" (p19). 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 (p20) an additional qualifier is added which gets 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 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 won't be reliably mitigated). As outlined in Section 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 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 publics 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 get to grips with whether the 2011 Preese Hall seismic events had been "*real/genuine*" (i.e. caused by hydraulic fracturing) or "*natural tremor*" (i.e. background seismicity) (Bryant et al., 2016, pp 14).

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While dialogic or deliberative studies in the UK find that risks of induced seismicity tend not to take precedence in the public discussions, that's 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, 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.

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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 'earthquake' is defined (e.g. 'How big is a small earthquake?' Kendall et al., 2019), it could be argued that assertions used to gage 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 don't know (38.0%) or to disagree (18.8%). Further, Andersson-Hudson et al. (2019) find that publics more knowledgeable about shale gas have more unified views. Indeed, all cross-public surveys studied here find motivations determine public responses: associating fracking with earthquakes negatively correlates with support for the technology and relate to demographic variables including political views and gender (Andersson-Hudson et al., 2016; 2019; Howell, 2018; O'Hara et al., 2016; Evensen et al., 2017). These findings align with similar studies in Europe (Lis et al., 2015; Evensen et al., 2018), US (Boudet et al., 2014; Graham et al., 2015) and Canada (Thomas et al., 2017b).

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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, nor 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 publics, 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 'risk of earthquakes' might be understood or interpreted differently according to, say, 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 answer provided.

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 ML 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: *induced seismicity, seismic event, vibrations, felt/not felt, magnitude* and *intensity.*
	AEA (2012) AEA Report for European Commission DG 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 DG 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 only to refer to *very small magnitude, seismic activity, earth tremors.*
	Green, C. A., et al. (2012) Preese Hall shale gas fracturing review and recommendations for induced seismic mitigation. *Report commissioned by DECC to examine the possible causes of seismicity at Preese Hall in April/May 2011.*	The report concludes that the observed seismicity in April and 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/earthquakes.
	Kavalov & 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 site by site basis".	Refer only to *low-magnitude earthquakes*
2013	**DECC (2013c)** DECC Report 'About shale gas and hydraulic fracturing' *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*, *tremors*. The most frequent term is *earthquake*, in some cases with qualifiers such as *perceptible*, *large*, *small*, *very small*.

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	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).	Only 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 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, felt.*
2014	**European Commission (2014)** European Commission Recommendation on minimum principles for the exploration and production of hydrocarbons using high-volume hydraulic fracturing *EU Regulation/legislation*	The recommendations refer only to risk assessment protocols for induced seismicity, 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 Scottish Government*	"seismic effects are expected to be small in magnitude" (pp 39); "very low likelihood of felt seismicity" from fracking (pp 48)	A number of phrases are used. *Seismicity* is often pre- by *micro-, trigger/induce,* or *felt.* Also refer to *tremors*, (*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 often prefacing these terms with words such as *small*, *tiny*, *minor*, *micro*.
	Cremonese et al. (2015) Institute for Advanced Sustainability Studies (IASS) Potsdam Policy Brief 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 (microseismicity), 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 *microseismicity.*
2016	**Baptie et al. (2016)** Unconventional Oil and Gas Development: Understanding and Monitoring Induced Seismic Activity. *Report commissioned by Scottish Government*	Hydraulic fracturing to recover hydrocarbons is generally accompanied by earthquakes with magnitudes of less than 2 ML 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 refer to *felt*.
2018	**Scottish Government (2018)** Report for Scottish Government's SEA on unconventional gas *Report commissioned by 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.	Range of terms including *felt seismicity, earthquakes, trigger.*

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	Delebarre et al. (2018) House of Lords Briefing paper CBP 6073 'Shale gas and fracking' *Briefing paper to inform House of Lords debate.*	No position indicated - but quote several expert reports that state the risk of induced seismicity can be managed.	*Seismicity* is used most frequently. *Earthquakes* and *events* also commonly used. *Tremor* and *trigger* used infrequently.
2019	**BEIS (2019b)** Guidance on fracking: developing shale gas in the UK (updated 12 March 2019) *UK Govt Department for Business, Energy, and Industrial Strategy*	"Measures are in place to mitigate seismic activity." (Section 1, par 4)	*Seismicity* or *seismic activity* are most often referred to. Do not refer to *earthquakes*.
	OGA (2019) Oil and Gas Authority '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 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.

	Source	Year data collected; method/approach; sample size	Findings on public perception of induced seismicity	Phrases adopted (by who)
Surveys	Andersson-Hudson et al. (2016)	2014 (University of Nottingham YouGov survey, closed questions; sample size: 3,822)	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 8 out of 10 identified risks associated with fracking.	Increased seismic activity (researchers phrasing in their analysis of open question response)
	Evensen (2017)	2014 (University of Nottingham YouGov survey, closed questions; sample size: 3,823 + US survey, sample size: 1,625)	UK public associated *earthquakes* with shale gas more than US publics.	Earthquake (researcher's phrasing in the closed survey question)
	Whitmarsh et al. (2015)	2014 (local/regional online survey, closed question; sample size: 1,457)	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: 1,745)	Fracking could cause *earthquakes and tremors* (43.2% agree, 18.8% disagree).	Earthquake or tremor (researcher's phrasing in the

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				closed survey question)
	Andersson-Hudson et al. (2019)	2016 (University of Nottingham YouGov survey, closed question; sample size: 4,992)	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 open question response).
	Evensen et al. (2019)	2019 (YouGov online survey, closed question; sample size: 2,777)	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 pre-defined 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 wasn't expressed.	Seismicity (researcher's phrasing in their analysis)
	Thomas et al. (2017a)	2014 (series of four 1-day deliberative workshops, two in UK, two in the US; total sample size: 55)	Some concerns were raised regarding earthquake risk, but these weren't 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, shale gas should not be pursued at all.	Earthquake (researcher's phrasing in their analysis)
	Bradshaw & Waite (2017)	2016 (qualitative analysis of a public enquiry into shale gas in Lancashire, UK; sample size: N/A)	Concerns about seismic activity were voiced by publics 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 wasn't explicitly mentioned in the deliberation outcomes.	"real" or "genuine" earthquake, "natural tremor", as referred to by participants

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.

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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.

Acronym	Event name (location; date)	Description	N (surveys)
Shale gas specific events			
ESGOS	European Shale Gas and Oil Summit (London; 09/2014)	An industry led conference on shale gas	40
UGA	Unconventional Gas (Aberdeen; 03/2014)	An industry led conference on shale gas	28
SGUK	Shale Gas UK (London; 03/2014)	An industry led conference on shale gas	98
Geoscience events			
TSG	Tectonic Studies Group Annual Conference (Cardiff; 01/2014)	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; 06/2014)	A Geological Society of London conference about issues facing controversial geoscience topics, including shale gas.	66
Public events			
TFA	TechFest (Aberdeen; 09/2014)	Talk and discussion at a local science festival	30
CSA	Café Science (Aberdeen; 02/2014)	Talk and discussion at a Café Science, a popular science communication series organised across the UK.	59
CHL	Coffee House Lectures (Glasgow; 11/2014)	Talk and discussion at a local research communication series	9

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

3.1.2 Survey design

We adapted a subset of questions from the University of Nottingham surveys (O'Hara et al., 2[illegible] Andersson-Hudson et al., 2016). The questions we used were intended to gather information on the perceived risks of and level of support for shale gas development, and asked for closed answers to a series

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[2] These events lasted between 1-2 hrs 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.

of statements about shale gas. Crucially, in our modified survey, participants were asked to provide reasoning for the answers they gave.

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 Data Availability statement.

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"* from which respondent could select either 'do', 'do no 'don't know', and a subsequent open question seeking the reasoning behind the selected answer t 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 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 bot 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 au 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 a induced seismicity. These are shown in Table 4. Qualitative answers were coded as null if the content 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", "I work on this topic") or the meaning of the response was ambiguous and couldn't be deciphered. Overall 80% of respond provided qualitative responses that were thematically coded.

We examine how these themes vary with job sector and knowledge level. Job sector responses 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 question a the primary sources of information about shale gas, which 95% of survey respondents answ Responses were grouped into no prior information, information from media reports, expert reports academic research. We consider respondents whose information sources include reports and acade papers to be the most knowledgeable. The majority (81%) of the conference attendees were in knowledge category, with 40% obtaining information from academic papers and 41% from repor contrast most (60%) public talk attendees sourced information about shale gas from media.

The public cohort were not intended to represent the perspectives of the general public. The surveys completed at the end of a public talk and discussion on the topic of shale gas, in which induced seism was raised, and so these publics are both interested and informed, and therefore cannot be a prox UK-wide attitudes and responses. Instead, the public cohort allow us to examine answers for those 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 employment sector.

We compare results from our survey with those from the 10 University of Nottingham YouGov su (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 Figure 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% don't 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.

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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/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 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/is associated with] earthquakes. *Includes reference to a need for further research/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 / is associated with] earthquakes.	↓
Knowledge	Respondent doesn't 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, anti- lobby.*	↑
Fracturing rock	Shale gas extraction requires the reservoir rock to be hydraulically fractured. This process will release seismic energy. Phrases include: *inherent/obvious, fracturing rock, high-pressure fluids, stress change, trigger.*	↑
Waste-water	Shale gas extraction may not induce earthquakes, but the geological disposal of waste-water (associated with fracking) does. Phrases include: *waste water, waste disposal/injection, 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/earthquake), tremor, low intensity/energy, tiny, cannot feel them, insignificant, low consequence/impact*	↓
Low risk	The risk that shale gas extraction [causes/induces/is linked with] earthquakes is very low. Phrases include: *is possible, rare, unlikely, low risk, minor, little impact, 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 reference to regulation, appropriate regulation, enforcing regulation, best practice. Phrases include: *monitoring, controllable, manageable*	↓
Normal	Any seismic activity that may be induced by shale gas extraction is no different to everyday/background/other activities or industries. i.e. not unique to fracking.	↓

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Site	Any risk posed by shale gas extraction is location or place specific. Phrases include: *determined by the geology of the region, the depth of the resource, the population etc.*	↔

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 (↔).

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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* … *earthquakes"* '*do*' associate shale gas with earthquakes, 37% '*do not*' and 7% '*don't know*' (Figure … Compared to public attitude surveys asking the same question throughout 2014, our survey finds … respondents '*do*' (+7%) and '*do not*' (+10%) associate shale gas with earthquakes and far fewer '… *know*' (-18%). Overall our respondents are much more decided than the general public (see Figu… O'Hara et al., 2016). Of our cohort, we find more participants from professional conferences and ev… that are about, or have sessions about, shale gas '*do*' associate shale gas with earthquakes (58%) … participants attending public talks (48%) (Figure 3B).

We observe no systematic trend between the closed answer responses and the level of partic… knowledge about shale gas, except that higher the knowledge levels, the fewer '*don't know*' respo… Yet there are differences in responses (Figure 3C); those who obtain their information from the media… reports are more likely to answer '*do*' associate shale gas with earthquakes, a higher proportion of t… with no knowledge of the topic '*do not*', and the most knowledgeable groups have equal proportio… respondents '*do*' and '*do not*' associate shale gas with earthquakes. When grouped into experts and… expert groups (those who source information from research and reports, and those who had no … information or obtained information from the media, respectively), 56% of experts (n. 276) associate … gas with earthquakes and 39% do not. These proportions are very similar to non-experts (n. 109) w… 53% do and 33% do not, and are in fact very similar to the views of UK-wide publics in 2013, see Figu… However, grouping in this way masks a difference in responses between those who obtain inform… from research articles and those who use reports. For the latter, shale gas is predominantly assoc… with earthquakes, (64% do; 31% do not) whereas for the former, there is a fairly even split (49% do; … do not) (Figure 3C). Respondents who source information from research articles are not undecided, … views are apparently polarised.

The only group that predominantly do not associate shale gas with earthquakes are those with no … knowledge of shale gas, although this sample is very small (n. 16). Our results present a more nua… view than the results of Andersson-Hudson et al. (2016) which find that those with more knowledge a… 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 pa… and so it is interesting that the results for job sector present quite different results (Figure 3D). … response profiles emerge from job sector results: the majority of academics and civil service workers … and 68% respectively) '*do*' associate earthquakes with shale gas, and a much smaller proportion '*do* … (28%, 21%, respectively). In contrast industry respondents present an even mix of views (51% do; 46… 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 … question '*do you associate shale gas with earthquakes*' identify 15 codes, which are shown in Table … thematic code definition is listed in Table 4. Often multiple codes apply to a given answer, and so in t… there are 443 codes for the 292 qualifying responses. Codes are ranked for frequency in Table 5. Th… most frequently used codes are identified over 30 times in participant responses, and these theme… examined in more detail in Table 6.

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

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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, shown in Table 7. Participants that *'do'* or *'do not'* associate shale gas with earthquakes explain that earthquakes will be small. Participants that *'don't know'* also refer to the size of the earthquake. T are examples in the rationale provided for all three closed answer responses that indicate that seismicity that they associate with shale gas are not 'earthquakes', but are instead 'tremors', 'eve 'microseismic' or some other term. Thus, we find that respondents provide the same reasoning to sup different closed answers; earthquakes are small, and/or the term earthquake isn't appropriate. C common codes include *low risk* and *media*. Responses coded as *low risk* refer to low risk, low likeli or low consequence (Table 7), and the *low risk* rationale is provided to explain closed responses f three categories (*'do', 'do not', 'don't know'*). That is, whether respondents *'do'*, or *'do not'* associate s gas with earthquakes, or they *'don't know'*, they consider the risk to be 'insignificant', 'mini 'unimportant', 'very low' and so on. In contrast, *media* is used mostly to describe reasons for answ *'do'*, alongside reference to the Blackpool (Preese Hall) seismic events, and the rationale that *fract rock* inevitably releases seismic energy and so fracking and earthquakes are associated by defini Where the *media* theme is used for *'do not'* responses, often the respondent is expressing judgem about the accuracy or veracity of media claims.

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Deleted: but refers to risk rather than scale of the event (Table 7), and the reasoning is provided to all perspectives (*'do', 'do not', 'don't know'*). In

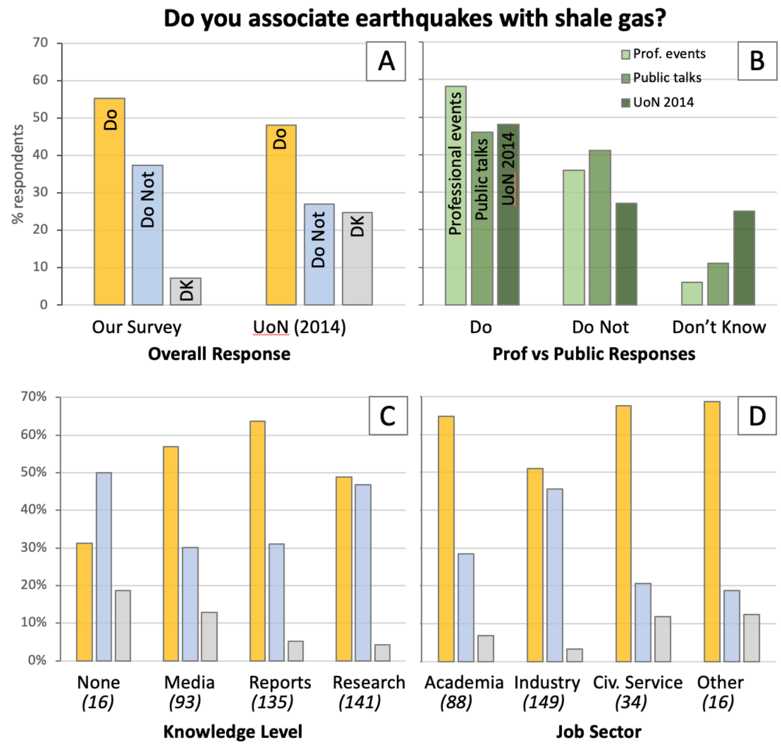

Figure 3 (A) Comparing the results of our surveys with UK-wide results from 2014 (UoN 2014; O'Hara 2015), we find that while results for 'do' associate shale gas with earthquakes (orange) for both surveys are similar our survey results have more 'do not' (blue) and much fewer 'don't know' answers (grey).

(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 2015) (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) source from industry and academia (public participants were not asked 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 almost 50:50 do and do not associate shale gas with earthquakes. Very few of those from industry and academia (~5%) answer don't know.

Two additional themes are identified in the rationale for '*do not'* responses. First, the argument that any 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. Further, 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 '*don't know'* responses (Table 7), with the same questions being raised regardless of the answer: '*what is the difference between microseismic event and an earthquake?*'. Some respondents confidently assert that microseismic 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 or 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.

	Evidence	Blackpool	Inconclusive	No evidence	Knowledge	Media	Fracturing rock	Waste-water	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%)
Don't 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 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 brackets, the percentage relative to the number of responses in that category (do, do not, don't know). High frequency codes are coloured pale yellow (≥10%) and yellow (≥20%). One answer (reasoning) could have more than one code. At the bottom of the table codes are ranked for frequency, and the eight codes that occur over 20 times are coloured in blue. These themes are examined in detail in Table 6.

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%
Don't 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%
Don't 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%

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

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		Magnitude ↓				Low risk ↓			
		-	*M*	*R*	*A*	-	*M*	*R*	*A*
Do	*n*	0	17	32	27	0	6	14	15
	%	0%	15%	27%	23%	0%	10%	24%	26%
Do Not	*n*	2	5	16	15	3	0	4	11
	%	2%	4%	14%	13%	5%	0%	7%	19%
Don't Know	*n*	0	1	1	1	0	2	1	2
	%	0%	1%	1%	1%	0%	3%	2%	3%
Sum	*n*	2	23	49	43	3	8	19	28
	%	2%	20%	42%	37%	5%	14%	33%	48%

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		Magnitude ↓				Low risk ↓			
		A	*I*	*CS*	*O*	*A*	*I*	*CS*	*O*
Do	*n*	25	29	10	2	7	12	6	2
	%	26%	30%	10%	2%	16%	28%	14%	5%
Do Not	*n*	7	17	2	1	1	11	1	0
	%	7%	18%	2%	1%	2%	26%	2%	0%
Don't Know	*n*	1	0	1	1	1	0	1	1
	%	1%	0%	1%	1%	2%	0%	2%	2%
Sum	*n*	33	46	13	4	9	23	8	3
	%	34%	48%	14%	4%	21%	53%	19%	7%

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	Closed response	Example open responses (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", will be "microseismic earthquakes that won't be felt", "small magnitude events" or "minor tremors".
	Don't know	"major earthquakes 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 that there a "very few cases [with] little intensity".
Low risk	*Do*	Shale gas "can trigger earthquakes but very rarely", "has the potential to induce seismic activity, but the risk is not a significant" and "any induced seismicity [has] small consequences".
	Don't 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 "don't consider it [to be] a significant hazard".
Media	*Do*	Earthquakes are associated with shale gas due to "publicity", "media reports" "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 don't agree".
	Don't know	"media and other bias form of reporting on shale gas give this impression however I don't know of any evidence of the link".
	Do not	"'*Earthquakes'* are associated publicly with shale gas thanks to inaccurate media reporting", "while I don't [associate shale gas with earthquakes], from media alone I would do".
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 microseismicity, in rare occasions they cause earthquakes. Where is the transition between microseismic [events] and earthquakes?" Fracking does "create microseismicity… not on the scale you would call an earthquake". "Earth tremors or seismic events is more appropriate than earthquake".
	Don't know	Fracking might cause "tremors but not specifically earthquakes". "I think of earthquakes as being of natural origin"
	Do not	"I don't think the minor, largely insensible tremors associated with shale gas merit the term 'earthquake'." "Seismicity" "tremors" "microseismicity" "is not an earthquake".

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Table 7: Example 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.

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 sub groups.

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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 knowledge participants (experts - those that obtain information from reports and peer-review publications) are four times more likely to use phrases such as '*seismicity*' and '*minor*' than less knowledgeable responden terms of job category (conference participants only), academics use the phrase '*earthquake*' far r than those employed in other sectors, and civil service employees prefer '*tremor*' rather than '*micr* '*induced*' seismicity, and more often refer to '*energy*' of the event.

Finally, an undercurrent theme to all the open responses was to critique the question that they asked, which was about 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 critique 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 earthqu with shale gas does not necessarily indicate concern about shale gas induced seismicity.

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4. Discussion

The results from our survey reflect a snapshot of participant views from 2014 about hydraulic fracturing induced seismicity. Further, 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 in whether or not people associate earthquakes with shale gas, but, rather, to explore the under rationale for the apparent differences in perspectives on the topic, particularly between experts and non-experts. It is important to acknowledge that perspectives of both experts and publics are likely to have 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. 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 & Bommer 2020), 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. Further, advances in knowledge and understanding on topics of public interest is common, but presents additional communication challenges, in particular around the communication of uncertainty (NMAS, 2018). 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.

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Expertise is an ambiguous quality with multiple dimensions that can be difficult to assess (Lightbody 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) publics. Accordingly, we find that our survey participants are, on the whole, much more decided about shale gas induced seismicity than th general public (based on the University of Nottingham surveys as reported in O'Hara et al., 2016). O relatively few participants in our survey who answered '*don't 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 '*don't 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 UK publics' answer '*don't know*'. A fourth closed answer category '*undecided*' or '*it depends*' would capture these differences.

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On one hand, fewer '*don't 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 repo the time conclude that risk of earthquakes from hydraulic fracturing is low, see Section 2.1. On the o hand, fewer '*don't 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. Further, it is now understood that the occurr of felt seismicity from hydraulic fracturing is highly site-specific (Butcher at al., 2017; Schultz et al., 2 Verdon and Bommer, 2020), and that "methods for predicting event maximum and magnitude…cannot be viewed as reliable" (OGA, 2019 p3). Perhaps the certainty in expert views on shale gas and earthquakes reflects also 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).

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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, civil service); in every case the closed survey results are bimodal. While this might be interpreted to show polarisation of views both amongst experts and publics, 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 constitute earthquake, and what is meant by 'associating' earthquakes with shale gas. As a result, participants 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 ex interviewed by Lampkin (2018), in which one said "*I would call them tremors not earthquakes, the very very small*" and another asserts that "*people who talk of earthquakes are sort of over-egging* [over doing] *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, 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 (2009) summarises terminology based on magnitude, including *micro*, *small*, *moderate*, and *large*. The Oil and Gas Authority's traffic light system infographic (Figure 1, made by the Oil and Gas Authority) describes seismicity as *not felt*, *usually not felt*, *minor*, *light*, *moderate, strong, major,* and *great*. Eaton et al. (2016) recognise the need for a terminology framework for ind seismicity in particular to unify regulations in different jurisdictions, and propose that "earthquakes" "seismic events" should be distinguished by being felt or not, and therefore should refer to events > and $M_L < 2$, respectively. The Oil and Gas Authority's traffic light system infographic (Figure 1, mad the Oil and Gas Authority) describes seismicity as *not felt*, *usually not felt*, *minor*, *light*, *moderate, st* *major,* and *great*.

In our study, we have not encountered any consistent use of such language when describing and repo 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 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'

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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 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_L2 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 publics’ views on induced seismicity? Do closed surveys with few questions or options capture the level of concern about ind seismicity? Or might the use of the term ‘earthquake’ cause uncertainty in the responses? M 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 & 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 & 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 & Baxter, 2019)?

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Unlike the UK’s Traffic Light System, public risk tolerances of induced seismicity will not simply rela event magnitude; as we have outlined there are other important complicating and competing factors at play (Evensen, 2018; Trutnevyte & 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 & Fineberg, 1996). As such, our findings about language ambiguity around induced seismicity have implications for science communication and understanding of stakeholder prefere 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 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 & Ejderyan (2018), without such framework experts must develop their communication approaches based on intuition and learning by doing [authors’ note: 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]. As noted previously, language frameworks for seismicity exist (such as the European Macroseismic Scale; Johnston, 1990; Bohnhoff, 2009, 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 sensitive to issues of environmental and social equity and justice and heritage in which geoenergy is involved (Trutnevyte & Ejderyan, 2018). The perceived risk may be greater for some technologies over others (Knoblauch et al., 2017), 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 to support stakeholders to speak – and hear - the same language are valuable.

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5. Conclusions

This work has explored expert and non-expert perspectives on the risk of induced seismicity from shale gas exploration in the UK. We find that range of terminologies have been inconsistently used to describe seismic events to communicate 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 to whom? Our insights present important implications for research, communication, and decision-making on any uncertain, complex or sensitive topic. The immediate and long-lasting repercussions of using "fracking bad language" is likely amplified by the political and environmental sensitivities around the shale gas sector, as well as 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 understanding of perceived risks, and to facilitate risk communication within and between expert and non-expert stakeholders. Our findings are relevant to numerous geoscience applications, since many subsurface technologies deemed critical to a low carbon future present risk of induced seismicity.

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6. Data Availability

Full survey data are available at https://doi.org/10.15129/a7a906c5-a77e-4a1c-b495-a2d441458d1d

7. Funding statement

We thank ClimateXChange and the University of Strathclyde who funded Roberts' position while this research was undertaken.

8. Ethics statement

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

9. Competing interests

We declare no competing interests.

10. Author contributions

JR lead the research design, data collection, analysis, and writing of this research, with CB in particular and ZS contributing to all aspects.

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