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An improved framework for discriminating seismicity induced by industrial activities from natural earthquakes

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ABSTRACT

Heightened concerns regarding induced seismicity necessitate robust methods to assess whether detected earthquakes near to industrial sites are natural, or induced by the industrial activity. These assessments are required rapidly, which often precludes detailed modeling of fluid pressures and the geomechanical response of the reservoir and nearby faults. Simple question-based assessment schemes in current use are a useful tool but suffer from several shortcomings: they do not specifically address questions regarding whether available evidence supports the case for natural seismicity; they give all questions equal weighting regardless of the relative influence of different factors; they are not formulated to account for ambiguous or uncertain evidence; and the final outcomes can be difficult to interpret. We propose a new framework that addresses these shortcomings by assigning numerical scores to each question, with positive values for answers that support induced seismicity and negative values for responses favoring natural seismicity. The score values available for each question reflect the relative importance of the different questions, and for each question the absolute value of the score is modulated according to the degree of uncertainty. The final outcome is a score, the Induced Assessment Ratio (IAR), either positive or negative (or zero), that reflects whether events were induced or natural. A second score, the Evidence Strength Ratio (ESR), is assigned that characterizes the strength of the available evidence, expressed as the ratio of the maximum score possible with the available evidence relative to the maximum score that could be obtained if all desired data were available at a site. We demonstrate this approach by application to two case studies in the UK, one widely regarded as a case of induced seismicity, the other more likely to be a series of tectonic earthquakes.

1. INTRODUCTION

Many industrial activities, such as hydrocarbon extraction, wastewater disposal, geothermal energy, and carbon sequestration involve injection of fluids into, and/or fluid withdrawal from the subsurface. Seismicity associated with such activities has been recognized for a long time: see Grigoli et al. (2017), and Keranen and Weingarten (2018) for recent reviews. In many cases, this association is clear and obvious, meaning that the connection between human activity and the seismicity is not controversial. However, in other cases the links between industrial activity and seismicity are more ambiguous.

As the number of cases of induced seismicity has grown in recent years, and as public controversy associated with processes such as hydraulic fracturing has increased, there has been heightened attention on this issue from decision-makers, industry, the public and the media. Operators and regulators therefore require an accessible, robust and objective procedure to assess whether seismic activity is or is not causally associated with industrial activities.

Several schemes have been proposed for this purpose, which can be broadly grouped into two categories. Some are essentially qualitative, based on a series of binary questions regarding aspects of the observed seismicity and the anthropogenic activity. While we acknowledge the valuable contribution of such proposals, we also identify many shortcomings in their application, which will often render the interpretations from their application as ambiguous or even misleading. The other group of approaches involve very detailed analyses to estimate probabilities of a causal link between the observed seismicity and the industrial activity. While such approaches can provide robust answers, they invariably require a great deal of data and significant effort, which means that they are not appropriate for providing the swift assessments that both operators and regulators require when there are claims or accusations of seismic activity having been induced, and public clamor for immediate regulatory actions.

In this paper, we propose a new framework for making assessments that can be applied rapidly, but also be updated as more information becomes available, avoiding the vagueness and ambiguity that can result with existing approaches. We begin with a critical review of the existing approaches and then present the proposed new framework, explaining how it meets the requirements for such a scheme to be useful for practical application. As well as proposing an improved general framework, we also put forward numerical values for this quantitative approach based on our current judgement and apply these to some case histories. However, we stress that the specific details of the framework are only a suggestion and others may wish to adapt and adjust these features. Moreover, we only present illustrative applications for activities related to fluid injection and extraction, but we believe that the framework could be adapted to other potential causes of induced seismicity such as mining and reservoir impoundment.

In closing this introduction, we should explain that the motivation behind this proposal has not arisen from academic curiosity. In October 2018, a panel comprised of industry, academics, and regulators was convened by the UK's Oil and Gas Authority (OGA) (the regulator for seismicity associated with oil and gas activities) to assess a sequence of seismicity in southeast England that had been linked by some nearby residents, local politicians, and academics to nearby oil extraction (Oil and Gas Authority, 2018). This panel ultimately concluded that the events were unlikely to have been induced by oil and gas activities and were probably of natural origin. However, the main proponent of the case for the swarm being induced by hydrocarbon production invoked one of the most widely-used existing schemes – that of Davis and Frohlich (1993) – to support the claim, while others invoked the same framework to make the counter case. The assembled panel agreed that while the Davis and Frohlich framework provided a useful starting point for discussions, it was not fully fit for purpose, especially in a situation where (i) the evidence base was seen by some to be ambiguous, leading to different interpretations of the available data and different answers; (ii) there was significant and ongoing public interest in the case; and (iii) the regulator might be expected to make regulatory decisions of financial significance, such as imposing limits or a moratorium on production, on the basis of the assessment outcome.

2. CRITIQUE OF EXISTING INDUCED SEISMICITY ASSESSMENT FRAMEWORKS

The pioneering work of Davis and Frohlich (1993) provided the first such set of criteria for assessing induced seismicity. This approach, and derivatives thereof (e.g. Davis et al., 1995; Frohlich et al., 2016a), remain widely used today (e.g., Montalvo-Arrieta et al., 2018; Grigoli et al., 2018). Hereafter we refer to Davis and Frohlich (1993) and the various frameworks derived from it as "Frohlich-based" (in honor of the common author among all of these papers).

Davis and Frohlich (1993) ask a series of questions in order to assess the relationship between observed seismicity and a fluid injection project:

1. Background Seismicity: Are these events the first known earthquakes of this character in the region?

2. Temporal Correlation: Is there a clear correlation between the time of injection and the times of seismic activity?

3a. Spatial Correlation: Are epicenters near the wells?

3b. Spatial Correlation: Do some earthquakes occur at depths comparable to the depth of injection?

3c. Local Geology: If some earthquakes occur away from wells, are there known geologic structures that may channel fluid flow to the sites of the earthquakes?

4a. Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the bottom of the well?

4b. Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or aseismic failure at the hypocentral locations?

Each of these questions is answered “yes” or “no”. Five or more “yes” answers would provide strong evidence that the earthquake sequence is induced. Four “yes” answers suggest that although there is a link between the seismicity and injection, incomplete or conflicting evidence makes the relationship ambiguous. Three or fewer “yes” answers suggest that a sequence is unlikely to be induced.

Recognizing that seismicity may also be caused by fluid withdrawal, Davis et al. (1995) adapted these questions for extraction scenarios, where in this case seven or more “yes” answers provide strong evidence that the earthquakes are induced:

1a. Are these the first known earthquakes of this character in the region?

1b. Did the events only begin after fluid withdrawal had commenced?

1c. Is there a clear correlation between withdrawal and seismicity?

2a. Are epicenters within 5 km of wells?

2b. Do some earthquakes occur at production depths?

2c. Do epicenters appear spatially related to the production region?

3a. Did production cause a significant change in fluid pressures?

3b. Did seismicity begin only after fluid pressures had dropped significantly?

3c. Is the observed seismicity explainable in terms of current models relating to fault activity?

While investigating historic cases of potential induced seismicity in Texas, Frohlich et al. (2016a) recognized that robust evidence regarding pressure changes would not be available. Therefore, they reduce the number of questions to five, with scores of 1.0, 0.5 and 0.0 for answers of “yes”, “possibly” and “no”, to obtain a scheme specifically designed to address historical cases of seismicity, rather than recent, modern cases where more information is likely to be available:

> QT: Do the earthquakes occur only after potentially influential human activities begin?
>
> QS: Are the earthquakes and human activities close enough so that a causal relationship is plausible?
>
> QD: Is there evidence from the pattern of felt reports, surficial features, or credible hypocentral locations that is consistent with a relatively shallow depth and a possible causal relationship?
>
> QF: Near the epicenter, are there known faults, either as mapped or as inferred from linear groupings of epicenters, that might support an earthquake, or enhance movement of fluids?
>
> QP: Have credible scientists investigated these events and concluded a human cause is plausible?

The answers are then summed to give an overall score. Frohlich et al. (2016a) suggest scores of 4 – 5 indicate events are almost certainly induced; 2.5 – 3.5 indicate probably induced; 1.5 – 2 indicate possibly induced; and 0 - 1 indicate that events have a natural cause.

In the following paragraphs we detail the limitations to the Frohlich-based frameworks, while we acknowledge that they have been an important contribution by virtue of providing schemes that have been applied and also facilitating consideration of how the framework can be made more effective. The limitations of the existing frameworks can be summarized as: results that are not easily interpreted by a wider audience; equal weighting between all questions that may not be justified; the lack of a formal system within which uncertainty can be addressed; a requirement that all questions be answered; and a failure to ask “are the events not induced?”.

Given present public interest in cases of induced seismicity, a framework to assess induced seismicity should be easily understood by all stakeholders including the public, industry and regulators as well as the academic community. The Frohlich-based frameworks do not achieve this. While experts in the field may know what is meant by “a score of 3 on the Davis and Frohlich (1993) scale”, in our experience both the wider public and interested stakeholders will struggle to make sense of such a statement.

Indeed, the same “score” means very different things for the different versions of the Frohlich-based frameworks. This is confusing to a non-expert audience: a score of 3 is “ambiguous” on the Davis and Frohlich (1993) scale (3 out of 7); probably not induced on the Davis et al. (1995) scale [3 out of 9, although Davis et al. (1995) never explicitly state how lower values should be classified]; but “probably induced” (3 out of 5) on the Frohlich et al. (2016a) scale. Hence communication with stakeholders requires the full framework to be described in detail first.

The Frohlich-based frameworks assign equal weight to each question. We do not believe that this is appropriate. Some pieces of evidence may provide a very strong indication that seismicity is or is not induced – for example the observation of similar events before industrial activity starts would count as strong evidence for events being natural – while other pieces of evidence, such as estimated pressure changes at the hypocentral locations, may be more circumstantial.

The Frohlich-based frameworks are not formulated to account for uncertain or ambiguous evidence. For example, Davis and Frohlich (1993) answer some questions as “yes?” or “no?”, implying that these assignments are not certain, but in the final summation, these “yes?” and “no?” scores count as much as their unqualified counterparts, i.e. +1 for “yes?” and 0 for “no?”. Any uncertainty in the answering of the initial question is ultimately ignored in the final assessment, with the consequence that a conclusion that has been inferred from few or even no unambiguous answers may appear far more compelling than is really the case.

For some of their case studies, Davis et al. (1995) are not able to answer some of the criteria, so satisfy the question with a “?”. In the final summation, these questions contribute a score of 0. In other words, inability to answer a question provides the same 0 score as an unambiguous piece of evidence suggesting that events are not induced. The scheme does not distinguish between a case where the outcome of the assessment is neutral because of lack of reliable evidence (data) and another for which ample data are available but nonetheless the conclusion is ambiguous. The two cases are quite distinct from operational and regulatory perspectives, especially since the conclusion in former case may change as data become available.

This issue compelled Frohlich et al. (2016a) to derive a new scale to address historic cases of induced seismicity in Texas since many of the original Davis and Frohlich (1993) questions would have been unanswerable given the limited data quality. Otherwise the cases studied may have come out with few “yes” answers but lots of “?” responses, and therefore low overall scores.

This re-drafting of the framework produced an inconsistency between the Davis and Frohlich (1993) and Frohlich et al. (2016a) scales, as identified by Everley (2016). Davis and Frohlich (1993) argue against mere proximity being used to assign an induced cause: "*in many of these cases the only strong evidence favoring an injection-induced cause is that earthquakes occurred near injection wells. Thus the presently available data do not encourage us to conclude that these sequences are induced by injection*". However, the updated Frohlich et al. (2016a) criteria include two questions (QS and QF as defined above) that are based on proximity. Therefore any earthquakes within a reasonable distance from the industrial activity must score at least two "yes" answers, putting them into the "possibly induced" category as defined by Frohlich et al. (2016a), regardless of any other evidence that might suggest the events are not induced. Frohlich et al. (2016b) argue that "*when assessing evidence that an earthquake is or is not induced, proximity is fundamentally important […] correlation is not causation but it sure is a hint.*" We would contend that this change of position is in fact symptomatic of the inability of these frameworks to incorporate and quantify the relative significance and robustness of the available evidence for given case studies.

To quantify uncertainties, Davis and Frohlich (1993) put final numbers in parentheses for cases where 3 or more questions were unanswered ("?"), and where 5 or more questions were answered in an uncertain way ("yes?" or "no?"). A more effective framework should be capable of incorporating the different levels of uncertainty that may be associated with different pieces of evidence, and it should provide a quantification of the overall strength of the evidence used to make the assessment.

An alternative family of schemes, based on recommendations made by Dahm et al. (2013), has recently been developed. Dahm et al. (2013) suggest three mechanisms by which anthropogenic and natural seismicity might be discriminated. The first mechanism involves physics-based probabilistic modeling, whereby a physical model of the causative mechanism is used to compute the expected change in Mohr-Coulomb stress at the hypocenter location(s) (e.g., Passarelli et al., 2012; Dahm et al., 2015). The simulated anthropogenic seismicity is compared against the probability of a natural event occurring at this location, as estimated from background seismicity rates.

Physics-based probabilistic modeling such as presented by Dahm et al. (2015) is potentially a very powerful method to discriminate induced seismicity. However, physics-based models require detailed information about subsurface fluid-flow and geomechanical properties, so this approach may be precluded by a lack of data (Grigoli et al., 2017). The development of physics-based models can be time-consuming, meaning that results are not available in a time-frame that is relevant to operators, regulators or the concerned public.

Moreover, the results of geomechanical models can be very dependent on a selection of model input parameters which may not be well constrained. As a result, user-defined choices of input parameters may introduce biases into the physics-based modelling approach that are difficult to quantify. Indeed, given that it is common practice to "tune" the input parameters of geomechanical models such that they reproduce geophysical observations including induced seismicity (e.g., Verdon et al., 2011; Verdon et al., 2015), it is arguable whether a geomechanical model can ever be entirely free from biases introduced by user-input choices.

The second mechanism proposed by Dahm et al. (2013) is based on establishing statistical correlation between rates of seismicity and industrial activities (such as injection or production rate). The observed population of seismic events is characterized statistically, primarily with respect to the rate of seismicity (e.g., Oprsal and Eisner, 2014; Goebel et al., 2015), but potentially also the magnitude distribution, spatial distribution and inter-event times (e.g., Schoenball et al., 2015). Changes in these statistics are then correlated to the onset of an industrial activity and/or changes in the rate of activity (such as changes in injection rate), with strong correlation implying that the events are likely to be induced. Much like the physics-based methods, observations of statistical correlation between seismicity and industrial activities can be a powerful indication of induced seismicity. However, it need not be a necessary condition: Keranen et al. (2013) show that for the 2011 $M_W = 5.7$ earthquake near Prague, Oklahoma, which is generally considered to have been induced by wastewater injection, there was no obvious correlation between injection rates and the observed seismicity. This approach also suffers from the same issues as described above for the physics-based models described above with the requirement of well-characterized records of historical seismicity, and for detailed records of operational data. Moreover, the statistical characterization of event populations requires a statistically significant number of events, which may not be available at the early stages of a seismic sequence, which is when an assessment of induced seismicity may be most critical in terms of mitigation.

The final mechanism proposed by Dahm et al. (2013) is based on an analysis of source mechanisms (e.g., Cesca et al., 2012). Seismicity induced by industrial activities may have source mechanisms that reflect the deformational mechanism causing the events. One might expect thrust faulting to occur above a subsiding oilfield (e.g. Segall, 1989), implosion-type sources above a collapsing mine (e.g., Dreger et al., 2008), and tensile failure associated with fluid injection (e.g., Ross et al., 1996; Zhao et al., 2014). The first problem with this approach is that well-constrained source mechanisms require good quality monitoring data, which is often not available. Secondly, many induced events have source mechanisms that are consistent with regional tectonic stress conditions (e.g., Clarke et al., 2014; Eaton and

Mahani, 2015; McNamara et al., 2015). In such cases this approach would not be successful in distinguishing induced and naturally occurring seismicity.

3. THE PROPOSED FRAMEWORK

A framework for assessing induced seismicity should meet a number of requirements. Many extractive industries have attracted considerable controversy, with the very existence of some industries becoming the subject of significant public debate. When seismicity is linked to such industries, the judgement as to whether events are induced is of great interest to the public, to the industry, to objectors, and to governments who may be expected to introduce regulation to mitigate induced seismicity. As such, any assessment framework must provide results that are easily comprehendible not just by experts in the field, but by stakeholders with variable levels of expertise. It must also be unbiased, and be seen to be so, such that it has buy-in from all stakeholders.

An assessment framework should weight different pieces of evidence according to their significance. For example, an observation of strong temporal correlation between injection and seismicity may count as stronger evidence for events being induced than does a reservoir model indicating that any induced pore pressure changes could not have reached the hypocenter location count against events being induced.

The availability and quality of evidence with which to assess induced seismicity may vary significantly between cases. At some sites, precisely located earthquakes with detection thresholds down to very low magnitudes, extensive data about the industrial activity (e.g., fluid injection/extraction rates and pressures), and geological information (e.g., reservoir porosities and permeabilities, the locations of faults), may all be available. If so, an assessment of induced seismicity may be very well evidenced. However, at other sites earthquakes may only be detected by regional or national networks, meaning that catalogs have poor detection thresholds and hypocenter locations have large uncertainties, while information about both industrial activities and the local geology may be very limited. In such cases, an assessment of induced seismicity may have a more limited evidential basis. Therefore, an assessment framework should be capable of incorporating different pieces of evidence that have different degrees of uncertainty, and should allow some questions to remain unanswered without distorting the overall scale. Moreover, the result should include a characterization of the quality and robustness of the available evidence base.

Finally, we note that the science around induced seismicity is currently a highly active one. It would not be surprising if our understanding of the causes and mechanisms of induced seismicity change or improve in the coming years. Therefore, ideally an assessment framework should be adaptable such that new knowledge can be readily incorporated.

In summary, an induced seismicity assessment framework must:

- provide results that are comprehensible to a wide audience, and it must be unbiased towards either conclusion (induced or not induced), and be seen to be so.
- weight different sources and types of evidence appropriately according to their significance.
- be capable of incorporating evidence that has different levels of uncertainty, should characterize the quality of evidence available, and should allow some questions to remain unanswered without distorting the overall scale.
- be flexible enough such that new questions, and/or new types of evidence, can be easily incorporated without having to make significant adjustments to the framework.

We recognize that the question-based framework is a useful starting point for an induced seismicity assessment framework, and we retain this aspect of the Frohlich-based schemes. However, because we recognize that any individual piece of evidence could point towards an induced cause, or towards a natural cause, each question is assessed as such, with evidence scoring positive “points” if it indicates an induced cause, and negative “points” if it indicates a natural cause. If a question cannot be answered, zero points are scored. When applying the framework and assigning points, cognizance should be taken of how much information is actually available for the assessment, so that the answers can be judged for their degree of reliability. We therefore propose that the framework yield two numerical values, the Induced Assessment Ratio (IAR) which categorizes the conclusion regarding the origin of the earthquake inferred from the available data, and the evidence Strength Ratio (ESR) describing quality and quantity of information used in the assessment.

Framework Criteria

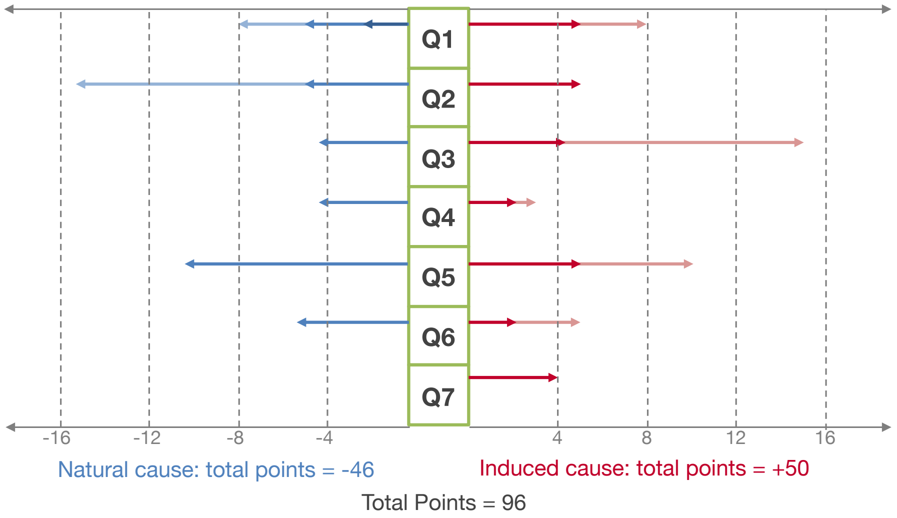


Figure 1. Schematic illustration of the assessment framework. A series of questions are defined, where their scores are assigned for responses that favor natural seismicity (negative, blue) or induced origin (positive, red). The different shading strengths indicate different strengths of responses to the questions, as explained in the text. The weighting of the scores is assigned according to the perceived significance of each piece of evidence. For our proposed questions (see Section 4) 46 negative points, and 50 positive points, are available, a total of 96 points.

Figure 1 shows the schematic structure of an ideal set of questions or criteria. In the framework, each criterion is assigned a negative score for a response that favors natural seismicity and a positive score if the answer supports a conclusion that the earthquake was induced. The relative sizes of the scores are scaled so that factors that provide more compelling evidence are granted greater influence. Moreover, as indicated by the shading, a given criterion may have different scores depending on specific features of the response. For example, question Q1 could be whether or not there has been previous (natural) seismicity in the same area, which would be interpreted as evidence against being induced. A score of -2 (dark blue) may be awarded if the response is that there are epicenters of natural earthquakes in the same regional tectonic setting, -5 (medium blue) if previous natural events occurred relatively nearby to the site in question, but +5 if there have not been previous earthquakes of similar magnitude and/or rate, while an additional +3 or -3 points can be added (light blue and light red) if previous event depths are well constrained (which is rarely the case).

When applying the framework, the first step would be to assess how much information is available. In some cases, particularly when the assessment is being made very soon after the seismicity has occurred, there may be some questions that cannot be answered at all, and others that can only be answered to a degree (such as not having well-constrained depths for past natural seismicity in the example given above). If the judgment of the assessor is that there is ambiguity or uncertainty in the available information (such as poorly-constrained focal depths, for example), then this judgment may be expressed as a percentage and then applied to the available scores (Figure 2). This then defines our first outcome, which we call the Evidence Strength Ratio, which is the ratio of the maximum score that can be assigned with the available data to the maximum score that would be available in an ideal case with all desirable data fully available:

$$\mathrm{ESR} = \frac{(|\text{Maximum} - \text{ve points given available data}| + |\text{Maximum} + \text{ve points given available data}|)}{\text{Total number of} + \text{ve and} - \text{ve points that can be scored in the framework}} \times 100 \qquad (1)$$

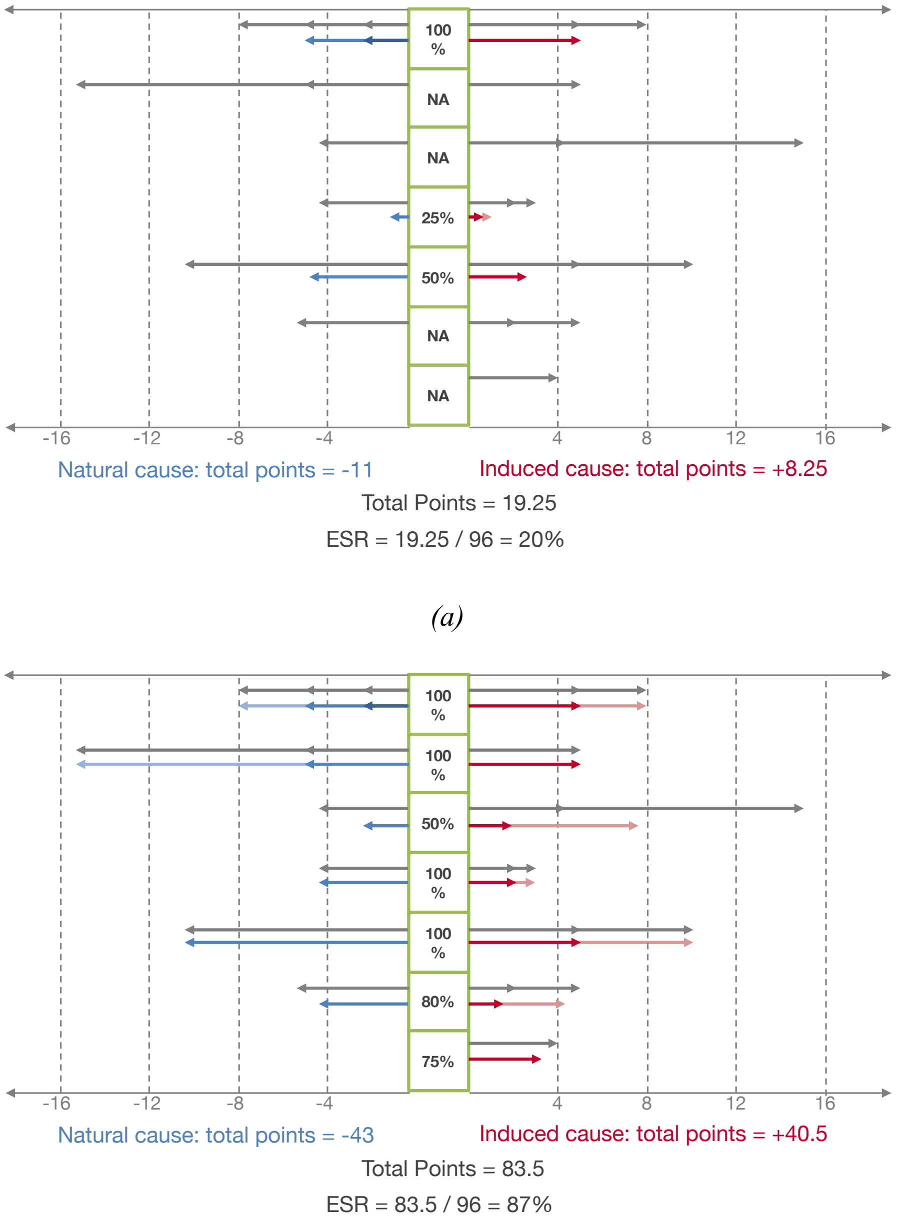
In Figure 2a, the ESR would be equal to 20% [(|-11| + 8.25)/(|-46| + 50)], and in Figure 2b the ESR would be equal to 87% [(|-43| + 40.5)/(|-46| + 50)]. The value of ESR may grows over time as evidence is accumulated. This means that a preliminary assessment could be issued that would be qualified by a low ESR and followed subsequently with a revised and better constrained assessment that would classified as being based on stronger evidence.

Once the ESR has been determined, each criterion is answered as to whether it indicates natural or induced seismicity. This produces our second outcome, the Induced Assessment Ratio (IAR), which quantifies whether the overall assessment indicates a natural or an induced cause. The total number of points scored across each criterion, combining both positive and negative values, is expressed as a ratio of the maximum points that could have been scored if all answers were positive (if the summed score is positive) or negative (if the summed score is negative):

$$IAR = \frac{\text{Summed score}}{|\text{Maximum points given available data}|} \times 100 \qquad (2)$$

Figure 3 illustrates the outcome of the framework in Figures 1 and 2, showing assessments made immediately after the occurrence of an earthquake sequence and the same seismicity subsequently re-evaluated with more complete data. In the early-stage assessment, the scores lean towards supporting an anthropogenic origin of the earthquakes, with an IAR of +15% [(-2 + 3.25) / 8.25]. While the positive IAR value would indicate an induced cause, the low value of the IAR should be interpreted as an ambiguous assessment, based on insufficient data (low ESR). By contrast, Figure 3b shows the same case re-evaluated a few months later at which time the available datasets are greatly improved. The IAR now takes a negative value – indicating that the seismicity was not induced – and moreover a much stronger value: -79% [(-36 + 2) / -43]. This would be interpreted as a compelling case for the earthquakes not being linked to the assumed anthropogenic cause, and this case being robust given the strength of data on which it is based.

Evidence Strength Assessment

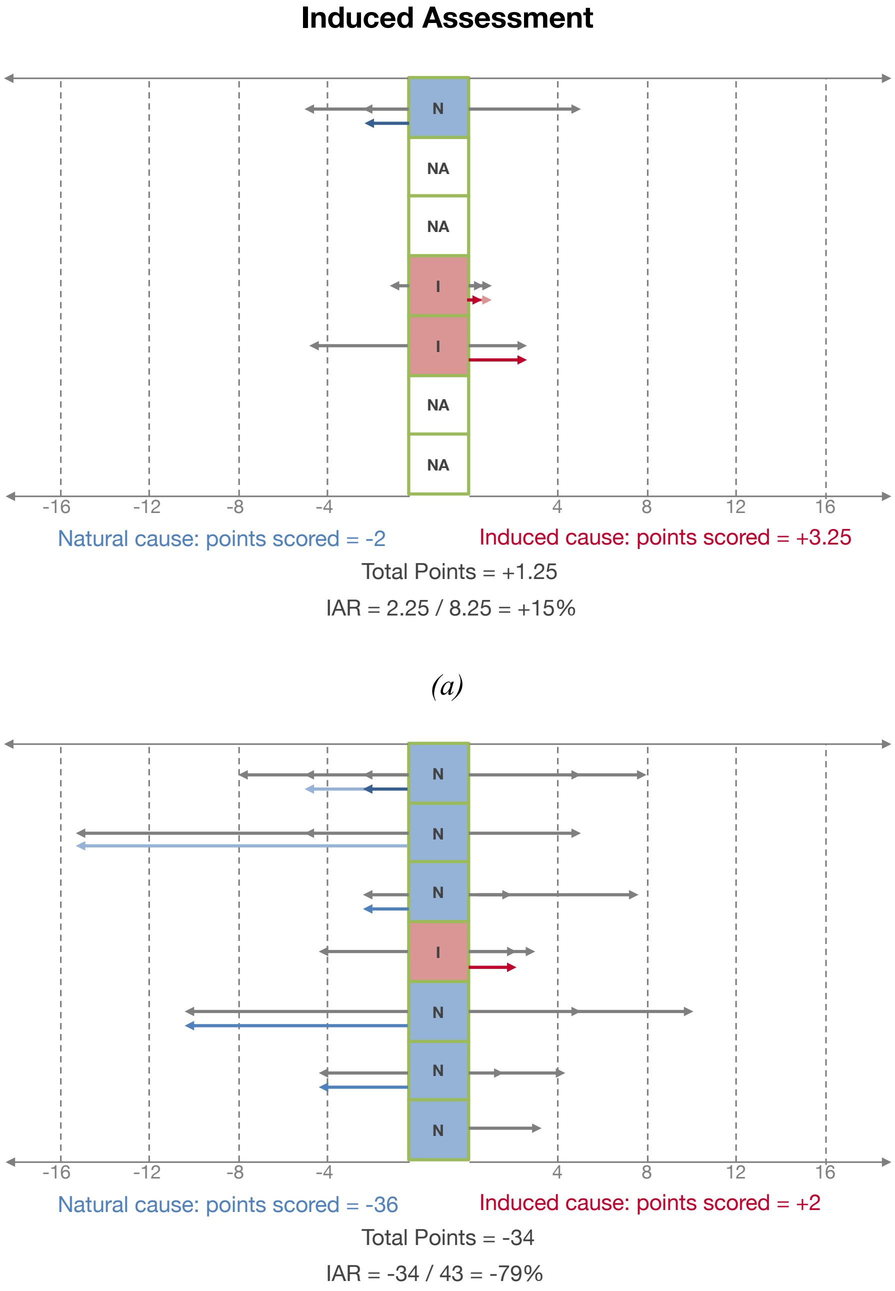


(a)

(b)

Figure 2. Schematic illustration of the Evidence Strength Ratio (ESR), for two examples with (a) a relatively weak ESR and (b) a relatively strong ESR. The grey arrows show the maximum points available for each question given the best possible quality evidence. However, some questions (2, 3, 6 and 7 in (a)) cannot be answered given the available evidence, and so are removed from the analysis. Some questions (4 and 5 in (a), 3, 6 and 7 in (b)) can be answered, but with a reduced degree of certainty. This reduced certainty is manifested in a corresponding reduction in the number of points that can be scored. For case (a), given the available evidence, only 19.25 of the overall 96 available points (see Figure 1) could be scored, an ESR of 20%. For (b), 83.5 of 96 points could be scored, so ESR is 87%.

This figure is based on our scoring for the Newdigate sequence relative to the Horse Hill well as assessed in (a) June 2018 and (b) after a full study of the sequence (see Section 5).



(a)

(b)

Figure 3. Schematic illustration of the Induced Assessment Ratio. Having quantified the available evidence (Figure 2), we now decide whether the evidence for each question points to an induced or a natural cause, summing the resulting scores. In (a), 2 negative points are scored, and 3.25 positive points, giving a total of +1.25 points. This score is compared against the maximum possible positive score (+8.25, see Figure 2) to give an IAR of +15%.

In (b), 36 negative points and 2 positive points are scored, giving an IAR of -34/43 = -79%. The initial low, but positive, IAR for (a) suggests that the available evidence is quite ambiguous, but leaning towards an induced cause. After collection of additional evidence, in (b) the IAR becomes strongly negative, indicating that the evidence points strongly towards these events not being induced by the industrial activity being examined. This figure is based on our scoring for the Newdigate sequence relative to the Horse Hill well as assessed in (a) June 2018 and (b) after a full study of the sequence (see Section 5).

One could consider combing the two numbers into a single score but we believe it is valuable to preserve the IAR and ESR as separate measures, especially since over time the evolution of the IAR with an increasing ESR could be reported. A low IAR score (either rositive or negative) associated with an ESR of 20% might suggest that judgment should be suspended while additional data are gathered; conversely, a low IAR score with an ESR of 80% would suggest that we are unlikely to be able to know whether a particular seismic sequence was due to an industrial process or not (although this might be revealed should the industrial activity continue, generating additional observations and data).

4. THE PROPOSED CRITERIA FOR FLUID INJECTION AND EXTRACTION

Here we propose an implementation of this framework for application to fluid extraction and fluid injection processes, which we treat together since they are often concurrent (as for example, in conventional oil production and re-injection of saltwater), and because some studies have identified the net fluid balance as the best indicator for induced seismicity (e.g., Brodsky and Lajoie, 2013). We wish to emphasize two particular points, the first being that both the criteria/questions and the associated scores presented herein are our own best judgment put forward as a suggestion; these are not intended as a prescription. We provide these suggestions to illustrate the practical application of our proposed framework, but we would expect users to make their own choices regarding the details, both with regard to the questions asked, and the scores assigned to them. For example, with larger datasets, questions pertaining to event population statistics, such as frequency-magnitude distributions, or “swarm-like” versus “burst-like” sequences (e.g., Zaliapin and Ben-Zion, 2016) could be included. We would also hope that the application of the framework will evolve precisely through adoption and adaptation by others, and as our knowledge of induced seismicity improves. The second point follows directly: adaptation to other industrial operations, such as mining and reservoir impoundment for example, would require consideration of alternative criteria but we believe that the framework could still be applied to such cases.

Our questions, together with a possible scoring scheme, are listed below. We follow this list with a broader discussion as to how each question should be answered, and the issues that might affect the confidence with which they can be answered. As we emphasize several times, the overall structure of the framework is the essence of our proposal, whereas the individual numerical values could – and probably should – be revised on the basis of experience attained through applications, or indeed because of different views of other users.

1. Has there been previous (either historical or instrumental) seismicity at the same site, or within the same regional setting?

a) Earthquakes have previously occurred in vicinity to the site, with similar rates and magnitudes: -5

b) Earthquakes have previously occurred within the same regional setting, with similar rates and magnitudes: -2

c) Earthquakes have not occurred at similar rates or magnitudes within the regional setting: +5

d) Past earthquakes have occurred at similar depths within the regional setting: -3

e) Earthquakes are significantly shallower than any past events that have been observed within the regional setting: +3

2. Is there temporal co-incidence between the onset of events and the industrial activities?

a) The earthquake sequence began prior to the commencement of industrial activity: -15

b) The earthquake sequence did not begin until a significant period of time after the cessation of industrial activity: -5.

c) The earthquake sequence began while the industrial activity was ongoing: +5

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

a) The earthquakes are co-incident with the industrial activity, but there is minimal correlation: -4

b) There is some temporal correlation between the seismicity and the industrial activity: +4

c) There is strong temporal correlation between the seismicity and the industrial activity (e.g., between rates of injection and rates of seismicity): +15

4. Do the events occur at similar depths to the activities?

a) Earthquakes do not occur at the same depth, and there is no plausible mechanism by which stress or pressure changes could be transferred to these depths: -4

b) Earthquakes do not occur at the same depth, but plausible mechanisms exist by which stress or pressure changes could be transferred to these depths: +2

c) Earthquakes occur at similar depths to the industrial activity: +3

5. Is there spatial co-location between events and the activities?

a) Earthquakes are distant to the activities, given the putative causative mechanism: -10

b) Earthquakes are sufficiently close to the activities, given the putative causative mechanism: +5

c) If earthquake loci change with time, this change is consistent with the industrial activity, for example growing radially from a well, or shifting in response to the start of a new well: +10

6. Is there a plausible mechanism to have caused the events?

a) No significant pore pressure increase or decrease has occurred that can be linked in a plausible manner to the event hypocentral position: -5

b) Some pore pressure or poro-elastic stress change has occurred that can be linked in a plausible manner to the event hypocentral position: +2

c) A large pore pressure or poro-elastic stress change has occurred, that can be linked in a plausible manner to the event hypocentral position: +5

7. Do the source mechanisms indicate an induced event mechanism?

a) The source mechanisms are consistent with the regional stress conditions: 0

b) Source mechanisms are not consistent with the regional stress conditions, but are consistent with a putative causative mechanism (e.g. thrust faults above a subsiding reservoir): +4

Some discussion of each of the criteria and the rationale behind the scores assigned to the various responses is clearly in order. We provide this on a question-by-question basis in the following paragraphs.

1. Has there been previous (either historical or instrumental) seismicity at the same site or in the same regional setting?

This question aims to establish whether the seismicity is substantially different to past natural seismicity in the region, with the inference that rates, magnitudes or loci of seismicity that are substantially different to past seismicity would indicate that events have a different cause, i.e. they are induced. The question as to what constitutes a significant change from the baseline seismicity is not trivial, but broadly speaking the consideration is whether events have higher magnitudes than previous seismicity, or are occurring at faster rates than previously. The quality of past monitoring arrays deployed in the area must be taken into account when performing this assessment. For example, improved seismic network coverage may produce an illusion of an increased seismicity rate that is in fact simply the product of improved detection threshold. The lack of sufficient network coverage to adequately characterize the baseline seismicity is a key reason why this question may not be answerable with sufficient certainty. Seismic events typically cluster in space and time, so the clustering of several events within a short window may not actually represent a change in rate, unless this increase in rate is sustained over a substantial period of time.

The definition of the area of interest, both laterally and in depth, is also not trivial. For obvious reasons, past seismicity in the same location is a strong indication that seismicity is natural. However, the area that should be considered relevant in such an assessment is somewhat subjective, and so we do not define a radius of consideration based on distance. Our judgement is that past seismicity within the relevant tectonic setting is germane to our assessment (albeit with less significance than previous events at the same location), the relevant tectonic setting being an area within which similar geological, structural and geomechanical properties are found. For example, for oil and gas sites this may correspond to the play or basin in question.

Induced seismicity caused by fluid injection or extraction typically occurs within < 4 km depth of the industrial activity (e.g., Verdon, 2014). Given that most such activities take place at relatively shallow depths, most cases of induced seismicity occur at relatively shallow depths when compared to the overall seismogenic thickness of the crust, which typically extends > 20 km in depth. Therefore the occurrence of seismicity at relatively shallow depths, if past natural seismicity has not previously occurred at such depths, may be taken as an indicator that events are induced. However, in many cases it is not possible to make this assessment because event depths for past seismicity are very poorly constrained (indeed in some cases the depths of the candidate events are also poorly constrained), in which case this element of the question cannot be answered.

2. Is there temporal co-incidence between the onset of events and the industrial activities?

This question seeks to address the temporal coincidence of seismicity and the industrial activity, for the obvious reason that if the seismicity begins before the industrial activity does, then the events are very unlikely to be induced. Similarly, if events commence a long time after the end of industrial activity then events are also unlikely to be induced, although this evidence would be less strong because the disturbance caused by an industrial activity may persist in the subsurface, ultimately producing seismicity that begins after end of activity. However, in practice we are not aware of any cases of induced seismicity where no events occurred during activities but began after they stopped. This question is usually answerable with a relatively high certainty, since it requires knowledge only of the dates when the industrial site was operating, and the dates of the seismic events.

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

Strong temporal correlation between seismicity and industrial activities represents strong evidence that the events are induced (e.g., Oprsal and Eisner, 2014; Goebel et al., 2015; Schoenball et al., 2015). By correlation we do not just mean that the occurrence of events overlaps with the industrial activity (see Question 2), but that changes in the rate of seismicity are temporally correlated with changes in the rate of industrial activity (the rate of fluid injection or removal, for example). This correlation may be expressed quantitatively as a correlation coefficient between the two rates (e.g., Oprsal and Eisner, 2014), but may in some case be examined qualitatively, for example that events occur when injection starts, and stop when injection stops. To answer this question robustly requires that data pertaining to the industrial activities is publicly available and has sufficient temporal resolution to assess correlation, which may not always be the case depending on the regulatory system in place;

and it requires that a sufficient number of events have occurred such that potential correlation can be assessed.

4. Do the events occur at similar depths to the activities?

It might be expected that induced seismicity will occur at similar depths to the depth at which industrial activities are taking place, while natural seismicity typically occurs at greater depths. However, this assessment is complicated by the fact that many cases of induced seismicity have in fact occurred several km deeper than the industrial activity (e.g., Verdon, 2014). These observations are explained by the presence of hydraulic and/or geomechanical connections, usually faults, from shallow to deeper layers (e.g., Ellsworth, 2013). If events occur at the same depth as the industrial activity then we consider this to be evidence that they are induced. If events are deeper than the activity, but plausible hydraulic or geomechanical connections between the two are present, then we also consider this as evidence in favor that the events are induced. If there is significant difference in depths between the events and the industrial activity, and plausible connections between these depths can be ruled out, then this represents evidence that events are not induced.

There are two sources of uncertainty that can affect the answer to this question. Uncertainties in the depths of the events, if sufficiently large, can render this question unanswerable. If a hydraulic or geomechanical connection is postulated to link industrial activities and events at different depths then this requires a sufficient degree of geological knowledge as to the presence or absence of such features. Such information may be provided by geophysical surveys combined with geological interpretation, but in the absence thereof it may not be possible to address this question.

5. Is there spatial co-location between events and the activities?

Spatial co-location between industrial activities and seismic events is of obvious significance. The distances at which events might be considered to be induced will vary depending on the type of industrial activity under consideration. Seismicity associated with hydraulic fracturing typically occurs within 1 km of the well (e.g., Bao and Eaton, 2016; Schultz et al., 2017). Seismicity associated with fluid extraction and subsidence typically occurs within, or at the edge of, the footprint of the depleting reservoir (e.g., Bourne et al., 2015).

High volume (e.g., >20,000 m^3 per month) wastewater disposal wells can have a large footprint, with seismicity occurring 10s of km from the injection (e.g., Verdon, 2014; Goebel et al., 2017; Goebel and Brodsky, 2018). Inevitably however, in such instances where the events extend 10s of km from the well, some seismicity is found within 5 km of the injection site. Therefore we suggest that larger distances between events and high-volume injection wells (e.g., > 10 km) are indicative of a natural cause unless some there is also seismicity located in closer proximity to the well.

Changes in location with time may also be a useful indication that events are induced. For example, events might be expected to migrate radially from an injection well with time (e.g., Shapiro, 2008). If the locus of operations changes (for example new wells are drilled), then corresponding changes in the loci of seismicity would provide strong evidence that events are induced.

The largest source of uncertainty that affects this question is with respect to event locations. For example, events located with regional arrays may have location errors of several km. Location uncertainties on this scale may render it impossible to determine whether the event is, or is not, sufficiently close to the industrial activity to be induced, in which case this question cannot be answered.

6. Is there a plausible mechanism to have caused the events?

An assessment of induced seismicity should incorporate a plausible mechanism that explains how the industrial activities have caused the events. Such mechanisms typically invoke either a rising pore pressure that reduces the normal stress acting on a fault, thereby enabling slip (e.g., Nicholson and Wesson, 1990), decreasing pore pressure that causes reservoir compaction and geomechanical deformation in the surrounding rocks (e.g., Segall, 1989), or poro-elastic stress transfer that causes an increases in the Mohr-Coulomb failure criteria (ΔCFS) (e.g., Deng et al., 2016). There are asymmetries between these mechanisms: small increases in pore pressure (e.g., Cesca et al., 2014), or small positive increases in ΔCFS (e.g., Deng et al., 2016) have been observed to be sufficient to induce seismicity, whereas comparatively large pore pressure decreases are required before compaction induced seismicity occurs (e.g., Bourne et al., 2014). In Q6 we posit 3 options: no pore pressure or positive ΔCFS change, moderate pore pressure or positive ΔCFS change, and large pore pressure or positive ΔCFS change. To reflect this asymmetry, we suggest that a large pore pressure change might be either an increase in pore pressure or positive ΔCFS >1 MPa, or a decrease of >5 MPa, while moderate pore pressure change might be either an increase of > 0.1 MPa or a decrease of > 1 MPa. Additionally, we require that a plausible mechanism exists capable of transferring pore pressure changes to the hypocentral locations.

This question may often be difficult to answer, since it requires that the pressure changes and/or poro-elastic effects caused by the industrial activity are known or can be modeled. Wellbore pressures are often not publicly available (such data is often commercially sensitive), and accurate models require detailed subsurface characterization. To determine whether it is plausible that pressure changes have reached the hypocentral locations, these locations must be well constrained both laterally and in depth, which also may not be the case.

7. Do the focal mechanisms indicate an induced event?

In some cases of induced seismicity, the putative causative mechanism for induced events implies a particular focal mechanism (e.g., Cesca et al., 2012). Typically, this is the case where seismicity is induced by depletion and compaction of reservoirs (e.g., Ottemöller et al., 2005; Willacy et al., 2018), where the source mechanism will be determined by the position of the event relative to the compacting zone (Segall, 1989). In contrast, for many cases of induced seismicity the focal mechanisms are consistent with the regional stress conditions (e.g., Clarke et al., 2014; Eaton and Mahani, 2015; McNamara et al., 2015). Therefore, focal mechanisms that are consistent with the regional stress field do not point towards either a natural or induced cause, since this is observed in both induced and natural cases. However, focal mechanisms that are not consistent with the regional stress, but are consistent with the proposed causative mechanism, can be used as evidence that events are induced.

This question will be affected by uncertainties both in the focal mechanisms and in the estimation of regional stress conditions. Robust determination of focal mechanisms requires good signal to noise ratios, and good coverage of the focal sphere. If focal mechanisms cannot be determined, this question cannot be answered.

5. APPLICATION TO CASE STUDIES

To demonstrate the proposed framework, we apply it to two UK cases studies (Figure 4): the Preese Hall sequence in 2011 (Clarke et al., 2014), and the Newdigate sequence in 2018 (Baptie and Luckett, 2018). In both cases, the quality and quantity of evidence changed dramatically through time as additional seismometers were deployed and industrial data was made public. In both cases the regulator (the OGA) was called upon at a relatively early stage by various stakeholders to make decisions that would have had major operational consequences for nearby industrial activities (e.g., Gilfillan et al., 2018).

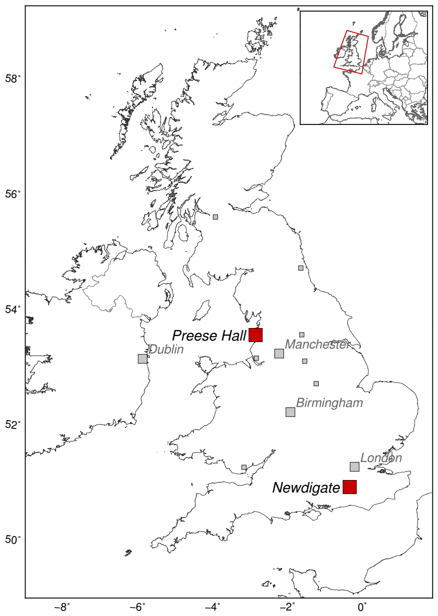


Figure 4: Map of the UK showing the locations of our two case studies: Preese Hall and Newdigate.

To demonstrate the challenges faced by a regulator in such circumstances, we do not just present a final assessment using what we now know about these sites, but instead we apply the proposed framework using the state of knowledge that existed at the time the regulator was first called upon to make decisions regarding these sites. In doing so we show the importance of tracking not just what the evidence suggests in terms of a natural or an induced cause, but also the quality of evidence used in the assessment, as defined by the ESR.

5.1. Preese Hall Sequence

The Preese Hall sequence (Figure 5) consists of 58 earthquakes, with a largest magnitude of M_L = 2.3, that occurred between March and August 2011 near to Blackpool, Lancashire. Most of the seismicity occurred in two clusters, the first beginning on 31st March 2011, and the second on the 26th May. The largest events were felt by local populations, and the seismicity was linked to hydraulic fracturing of the Preese Hall shale gas well. This potential linkage was noted after the first cluster of events. No mitigating actions were taken by the operator or the regulator at this time, except that a local seismic monitoring array was installed. After the second cluster of events, recorded by the local array, the operator decided to pause activities pending an investigation into the events. The net result of these investigations was the imposition of a Traffic Light System that now applies to onshore hydraulic fracturing operations in the UK (Green et al., 2012).

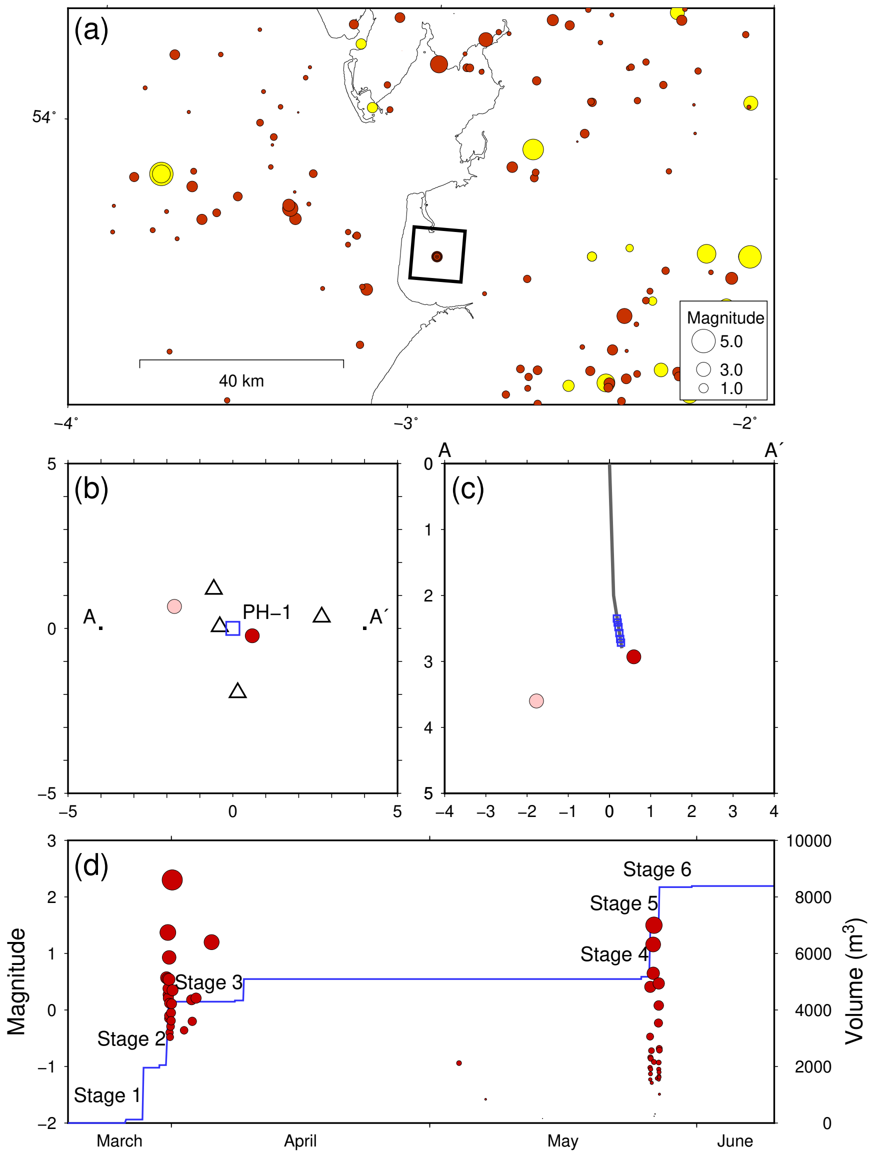


Figure 5: Summary of the Preese Hall 2011 earthquake sequence. In (a) we provide a regional map showing historical earthquakes (yellow dots) and past instrumentally-recorded earthquakes (red dots), along with a 10 by 10 km area of interest centered on the 2011 events (dark red dot). In (b) we show a map of the area of interest showing the Preese Hall well (blue square), and the local monitoring network that was deployed after the first sequence of events (black triangles). The light-red dot shows the earthquake locations provided by the BGS national seismic network, the nearest station of which was 80 km distant, while the dark-red dot shows the more accurate location provided for a later event by the local network. In (c) we show a cross section of the same situation, from A to A' (marked in (b)), along with the wellbore trajectory (grey line) and hydraulic stimulation intervals (blue dots). In (d) we show a timeline of event occurrence and magnitudes (dots) relative to the cumulative fluid injection into the Preese Hall well (blue line).

We perform our assessment based on the data that was available at two different times: after the first cluster had been detected by the BGS national monitoring array, at which time the first links between the seismicity and the Preese Hall well were suggested but not confirmed, and then after the second cluster had been detected using the local monitoring network.

5.1.1. Preese Hall Assessment, using data available in April 2011

At this time events had been detected by the national BGS monitoring network, the nearest station of which was 80 km away. Event locations uncertainties were large, in particular the depth uncertainty was ± 7.1 km. The initial epicenters were 2 km from the Preese Hall well. Detailed hydraulic fracturing pumping data had not been released by the operator.

1. Has there been previous (either historical or instrumental) seismicity at the same site or in the same regional setting?

Evidence assessment: the earthquake catalog is of reasonable quality and contains both historical and instrumentally recorded seismicity. However, the magnitudes of interest (c. $M_L = 2.0$) are close to the estimated magnitude of completeness for the BGS national monitoring array. Instrumentally recorded events have depth uncertainties of several kilometers, and historical event depths are poorly constrained. The depths of the events in question were also poorly constrained. Therefore rates and magnitudes could be assessed, but not depths. Answer rating = 50% given the completeness of the historical catalog at these magnitudes. The maximum points scoreable (used to determine the ESR) is -2.5 or +2.5.

Answer: Earthquakes have occurred within the regional setting, at similar rates and magnitudes but not at this specific site: -1

2. Is there temporal co-incidence between the onset of events and the industrial activities?

Evidence assessment: It was known that operator had commenced hydraulic fracturing the Preese Hall well, so the required evidence to assess whether there was temporal coincidence between the events and the industrial activities was available. Answer rating = 100%. The maximum points scoreable for this question is -15 or +5.

Answer: The onset of events was temporally coincident with the industrial activities: +5

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

Evidence assessment: While it was known that the hydraulic fracturing was taking place at the Preese Hall well, detailed records of pumping rates were not publicly available at this time. Therefore assessments of correlation could not be made. This question could not be answered. 0 points scoreable for this question.

Answer: Not Answerable

4. Do the events occur at similar depths to the activities?

Evidence assessment: The earthquakes located using the BGS national network had depth uncertainties of ±7.1 km. Therefore it was not possible to assess whether the events were occurring at the same depth as the hydraulic fracturing. This question could not be answered. 0 points scoreable for this question.

Answer: NA

5. Is there spatial co-location between events and the activities?

Evidence assessment: The events were located 2 km from the well. Epicentral uncertainties were ±2 km, which means that the event could have been very close to the well, or could have been up to 4 km away. Spatial changes in event loci through time could not be robustly constrained, so 5(c) could not be answered. Answer rating = 50%, reflecting the epicentral uncertainties. Maximum points scoreable for this question is -5 or +2.5.

Answer: Earthquakes potentially occurred in close proximity to the well: +2.5

6. Is there a plausible mechanism to have caused the events?

Evidence assessment: while hydraulic fracturing pumping data were not available at this time, it is reasonable to expect that high injection pressures had been used to stimulate the shale reservoir. Answer rating = 80%, reflecting the fact that injection pressures were not publicly available, but are expected to be high. Maximum points scoreable for this question is -4 or +4

Answer: High pore pressures associated with hydraulic fracturing are expected: +4

7. Do the source mechanisms indicate an induced event mechanism?

Evidence assessment: no source mechanisms could be computed for these events given the available focal sphere coverage. This question could not be answered. 0 points scoreable for this question.

Answer: NA

5.1.2. Preese Hall using data available in April 2011: Summary

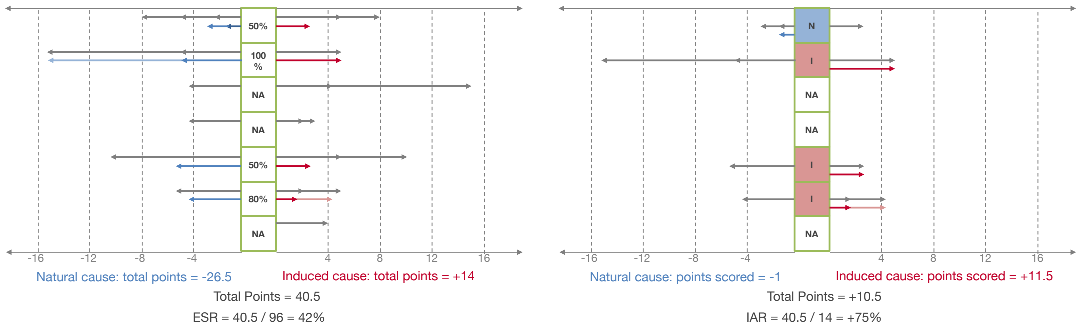
The assessment results are shown schematically in Figure 6. The Evidence Strength Ratio, which describes the total points that could have been scored at this time as a ratio of the total points available within the framework, is given by:

$$\mathrm{ESR} = \frac{(|-26.5|+|14|)}{96} \times 100 = 42\% \tag{3}$$

The Induced Assessment Ratio, which assesses whether the available evidence points towards an induced or a natural cause, is given by:

$$\mathrm{IAR} = \frac{10.5}{|14|} \times 100 = +75\% \tag{4}$$

We conclude that at this time, the IAR was strongly positive, indicating that the evidence available at this time pointed to an induced cause. However, the ESR was moderate, implying that this judgement is a long way from being certain, and that more evidence could be collected to produce a more robust judgement.



(a) *(b)*

Figure 6: The results of our assessment as applied to the Preese Hall sequence using data available in April 2011. In (a) we show the ESR assessment, and in (b) we show the IAR assessment.

5.1.3. Preese Hall Assessment, using all available data

We now repeat our analysis using all data from the Preese Hall site that is available at the present day (Green et al., 2012; Clarke et al., 2014). The local monitoring network reduced location uncertainties of the second event cluster to as low as ±500 m in both depth and epicenter. A matched-filter detection algorithm was used to increase the number of events detected in both clusters. The hydraulic fracturing pumping data had been released by the operator.

1. Has there been previous (either historical or instrumental) seismicity at the same site or in the same regional setting?

Evidence Assessment: The quality of the historical catalog is unchanged from the previous assessment. Depths of past events are poorly constrained, and the magnitudes of interest are close to the completeness of the BGS national monitoring array. Answer rating = 50%. The maximum points scoreable is -2.5 or +2.5.

Answer: Earthquakes have occurred within the regional setting, at similar rates and magnitudes but not at this specific site: -1

2. Is there temporal co-incidence between the onset of events and the industrial activities?

Evidence assessment: As per the previous assessment, we have sufficient information to answer this question. Answer rating = 100%. The maximum points scoreable is -15 or +5.

Answer: The onset of events was temporally coincident with the industrial activities: +5

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

Evidence assessment: With detailed pumping data provided by the operator, and an improved catalog of over 50 events provided by the matched-filter detection method, it becomes possible to assess the correlation between the induced events and the activity in detail. Answer rating = 100%. The maximum points scoreable is -4 or +15.

Answer: The events are observed to occur in bursts during periods of hydraulic fracturing and for c. 24 hours afterwards. There is an almost complete absence of seismicity at other times. There is therefore strong correlation between injection and seismicity: +15.

4. Do the events occur at similar depths to the activities?

Evidence assessment: The local monitoring network reduced the depth uncertainties to ±500 m, sufficient to assess whether the events are at similar depths to the hydraulic fracturing. Answer rating = 100%. The maximum points scoreable is -4 or +3.

Answer: The events are located with 330 m of the injection depth. Given the uncertainties, we conclude that the events have occurred at the injection depths: +3.

5. Is there spatial co-location between events and the activities?

Evidence assessment: The local monitoring network reduced epicentral uncertainties to ±500 m. However, no spatial changes in event loci through time were observed, so 5(c) cannot be answered. Answer rating = 100%. The maximum points scoreable is -10 or +5.

Answer: Earthquakes occurred within 300 m of the well: +5.

6. Is there a plausible mechanism to have caused the events?

Evidence assessment: Hydraulic fracture pumping data show that high injection pressures had been used to stimulate the shale reservoir. Answer rating = 100%. The maximum points scoreable is -5 or +5

Answer: High pore pressures were created to conduct hydraulic fracturing: +5

7. Do the source mechanisms indicate an induced event mechanism?

Evidence assessment: A robust source mechanism was determined for one of the final events to occur in the sequence. The focal plane uncertainties are estimated to be ±20^{o}. The regional stress conditions are well-constrained by borehole measurements. Answer rating = 75%, reflecting the fact that a source mechanism could be inverted for only one event, but based on waveform similarities this mechanism is expected to match many of the other events. The maximum points scoreable is 0 or +3.

Answer: The source mechanism is consistent with the regional stress state: 0.

5.1.4. Preese Hall, using all available data: Summary

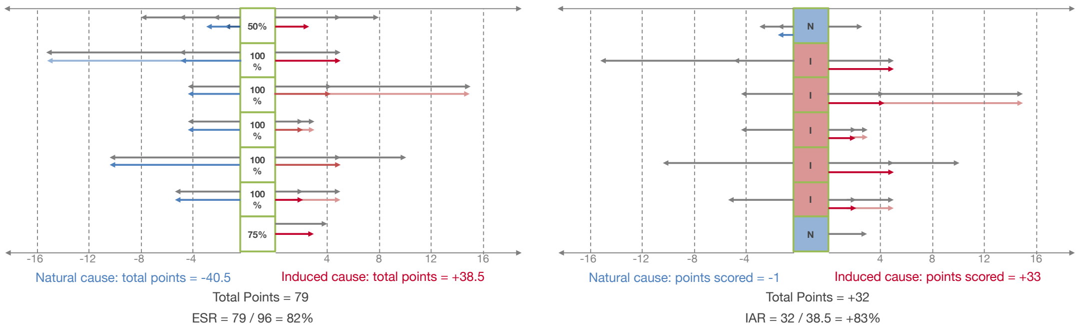
The assessment results are shown schematically in Figure 7. The Evidence Strength Ratio is calculated as:

$$\mathrm{ESR} = \frac{(|-40.5|+|38.5|)}{96} \times 100 = 82\% \qquad (5)$$

The Induced Assessment Ratio, which assesses whether the available evidence points towards an induced or a natural cause, is calculated as:

$$\mathrm{IAR} = \frac{32}{|38.5|} \times 100 = 83\% \qquad (6)$$

The IAR has become more positive, strengthening the conclusion that the events were induced. More importantly, the ESR is now high, indicating that this judgement is robust, and that most of the desired evidence is available.



(a) *(b)*

Figure 7: The results of our assessment as applied to the Preese Hall sequence using all available data. In (a) we show the ESR assessment, and in (b) we show the IAR assessment.

5.2. The Newdigate sequence

The Newdigate sequence (Figure 8) consists of 18 earthquakes with a largest magnitude of M_L = 3.0 that occurred between April and August 2018 near to Gatwick Airport, southeast England (Baptie and Luckett, 2018). Seven of the events were felt by the local public, and potential links were suggested to two different oil exploration sites (Gilfillan et al., 2018): the Brockham oilfield, which is a small conventional oilfield that has been under production and waterflood for 16 years, and the Horse Hill well (HH-1), which was drilled in 2014, with small flow tests taking place in both 2016 and 2018, and which had attracted substantial media attention as the “Gatwick Gusher”.

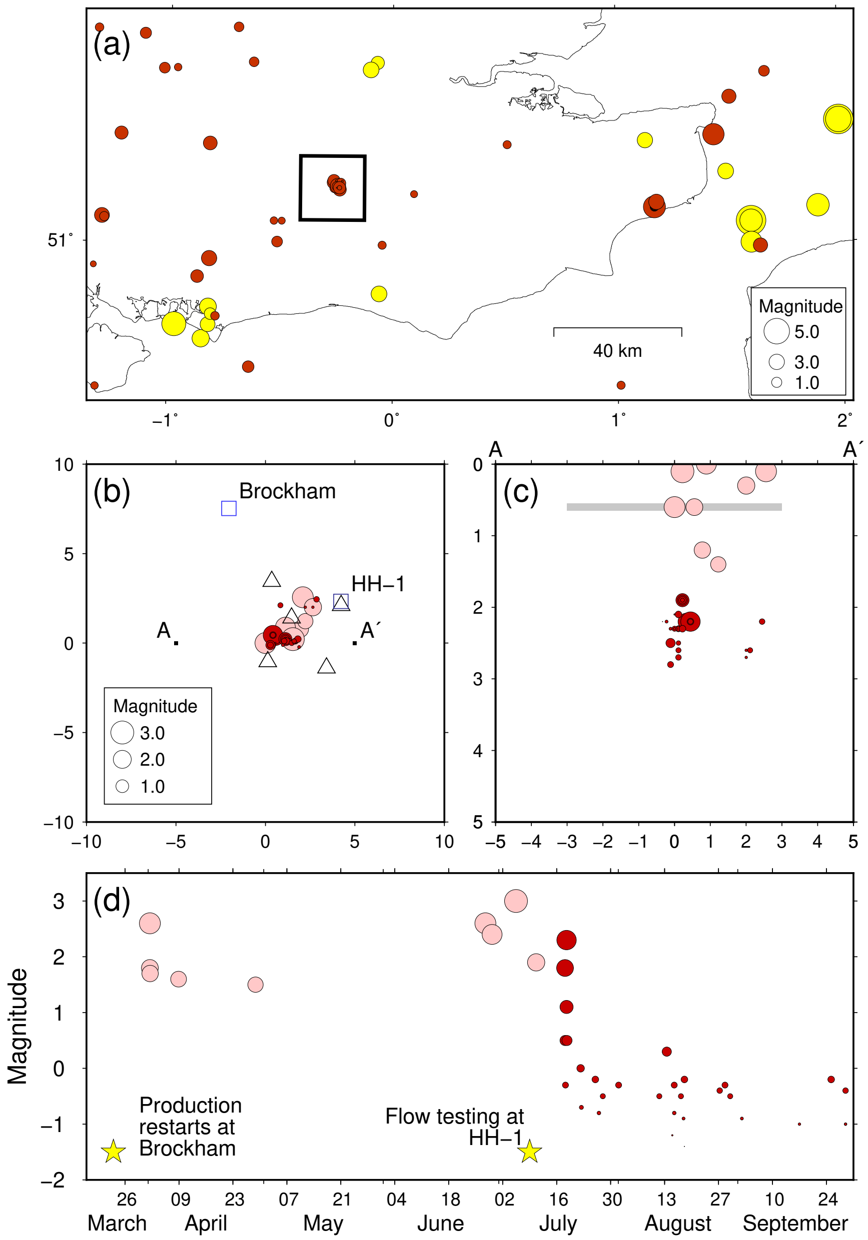


Figure 8: The Newdigate 2018 earthquake sequence. In (a) we show a regional map of past historical (yellow) and instrumentally-recorded (red) earthquakes, and the 10 x 10 km area of interest around the 2018 events (dark red). In (b) we show a map of the area of interest showing the Brockham and Horse Hill wells (squares) and the local monitoring stations deployed in July 2018 (triangles). As per Figure 4, the light-red dots show the early events with poorly-constrained locations provided by the BGS national array, while the dark-red dots show the locations of later events with well constrained locations provided by the local array. In (c) we show a cross section of the same events from A to A' (marked in (b)). The grey bar marks the depth of the Portland Sandstone reservoir. In (d) we show a timeline of event occurrence relative to the major activities that occurred in the nearby wells: the re-start of both injection and production at Brockham, and the start of flow testing at Horse Hill.

Much like the Preese Hall sequence, the initial events were detected using the BGS national monitoring array, and so had large uncertainties. A local monitoring network was deployed in July 2018, significantly reducing the location uncertainties of the later events. Again, we perform our assessment at two different times: prior to the installation of the local network, at which time concerned locals were calling for a moratorium on oil and gas activity in the area; and then using data available after the OGA workshop in October 2018 (Oil and Gas Authority, 2018), as described by Baptie and Luckett (2018). Because two different sites had been suggested as the potential cause, we perform an assessment for both the Brockham oilfield and for HH-1.

5.2.1. The Newdigate sequence using data available in June 2018

1. Has there been previous (either historical or instrumental) seismicity at the same site or in the same regional setting?

Evidence assessment: The earthquake catalog is of reasonable quality and contains both historical and instrumentally recorded seismicity. The instrumental catalog has an estimated magnitude of completeness of $M_L = 2.0$, which is lower than the largest events detected in the Newdigate sequence. The depths of catalog events are poorly constrained, although they are believed to be shallow (< 10 km), and the detected events also had large uncertainties (±5 km). Therefore rates and magnitudes of past events could be assessed, but not depths. Answer rating = 100%. The maximum points scoreable is -5 or +5.

Answer: Earthquakes have not previously occurred at this site. However, earthquakes with similar magnitudes have occurred elsewhere within the Weald Basin. The rate of seismicity is not dissimilar to event clusters that have occurred in the past, such as at Billingshurst in 2005 (Baptie, 2006): -2.

2. Is there temporal co-incidence between the onset of events and the industrial activities?

Evidence assessment: For the Brockham oilfield, monthly production and injection data was publicly available via the Oil and Gas Authority. Answer rating = 100%. The maximum points scoreable is -15 or +5. For the HH-1 well, dates on which flow testing had been conducted were not publicly available, so this question could not be answered (0 points scoreable). In retrospect, this apparent lack of data was because the operator at HH-1 had not started flow testing at this time, so there was no data to be made public. The start of flow testing was publicly announced by the operator in late June 2018 (UKOG, 2018).

Answer: For Brockham, the seismicity was temporally co-incident with the re-start of production and waterflood after a substantial hiatus: +5. For HH-1: NA.

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

Evidence assessment: For the Brockham oilfield, we have monthly injection and production volumes available. At this time only 3 events had been detected, making any assessment of correlation extremely tentative. Answer rating = 25%. The maximum points scoreable is -1 or +3.75. For HH-1, no information about flow testing was available, so this question could not be answered (0 points scoreable).

Answer: The Brockham oilfield has been under production for 16 years, and under waterflood for over 8 years, during which time no seismicity was recorded. There is therefore no correlation between seismicity and injection or production at Brockham: -1. For HH-1: NA.

4. Do the events occur at similar depths to the activities?

Evidence assessment: Event depths were not well constrained at this time. However, there was reasonable evidence to indicate that the events were at shallow depths. Both the HH-1 and Brockham oilfield are targeting the Portland Sandstone at 600 – 700 m depth, while the HH-1 well had also produced a small volume from the Kimmeridge Clay at 800 - 900 m depth. Answer rating = 25% (reflecting poorly constrained locations, but with some evidence that events are shallow). Maximum points scoreable for both Brockham and HH-1 is -1 or +0.75.

Answer: The indication of shallow depths for these events suggest that they may have occurred at similar depths to both oilfield activities: +0.75.

5. Is there spatial co-location between events and the activities?

Evidence assessment: Initial epicentral uncertainties for these events were ±5 km. Spatial changes in event loci through time could not be robustly constrained, so 5(c) could not be answered. Answer rating = 50%, reflecting the epicentral uncertainties. Maximum points scoreable for this question is -5 or +2.5.

Answer: For Brockham, the events were located at least 8 km from the field. Even taking uncertainties into account, these events appear to be too far from the field to have been induced:

-5. For HH-1, the events were located roughly 2 km from the well which, taking uncertainties into account suggests possible co-location: +2.5.

6. Is there a plausible mechanism to have caused the events?

Evidence assessment: No information about pressure changes at Brockham or at HH-1 had been made available by the operators of either site. This question could not be answered. 0 points scoreable for this question.

Answer: NA

7. Do the source mechanisms indicate an induced event mechanism?

Evidence assessment: no source mechanisms could be computed for these events given the available focal sphere coverage. This question could not be answered. 0 points scoreable for this question.

Answer: NA

5.2.2. Newdigate using data available in June 2018: Summary

The assessment results for Brockham are shown schematically in Figure 9, while the results for Horse Hill are shown in Figures 2 and 3. The Evidence Strength Ratio is calculated for the Brockham oilfield as:

$$\mathrm{ESR} = \frac{(|-27|+|17|)}{96} \times 100 = 46\% \tag{7}$$

and for the HH-1 well as:

$$\mathrm{ESR} = \frac{(|-11|+|8.25|)}{96} \times 100 = 20\% \tag{8}$$

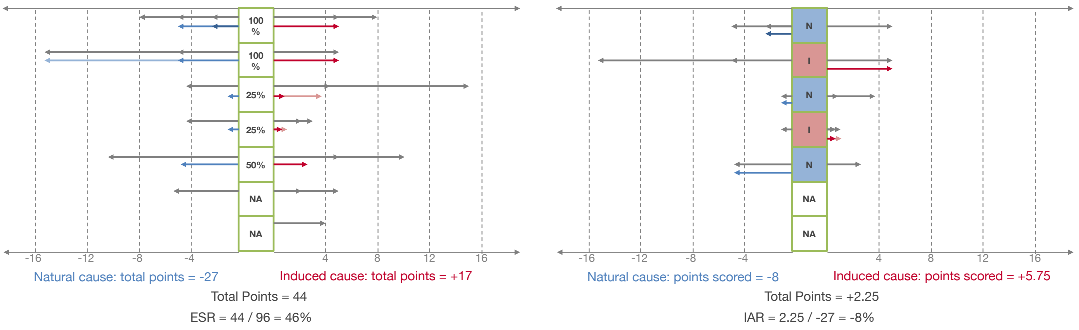
The Induced Assessment Ratio, which assesses whether the available evidence points towards an induced or a natural cause, is calculated for the Brockham oilfield as:

$$\mathrm{IAR} = \frac{-2.25}{|-27|} \times 100 = -8\% \tag{9}$$

and for the HH-1 well as:

$$\mathrm{IAR} = \frac{1.25}{|-8.25|} \times 100 = +15\% \tag{10}$$

We conclude that at this time, the ESRs were low for both cases, implying that any judgement would be tentative. The ESR for the HH-1 well was particularly low, implying that more evidence would be required for a robust assessment. The IARs for both sites were close to 0, implying that the limited evidence that was available was ambiguous at this point in time.



(a) *(b)*

Figure 9: The results of our assessment as applied to the Newdigate sequence relative to the Brockham oilfield, using data available in June 2018. In (a) we show the ESR assessment, and in (b) we show the IAR assessment.

5.2.3. Newdigate Assessment, using data available in October 2018

We now repeat our analysis using data from the Newdigate sequence that was available in October 2018 (Baptie and Luckett, 2018). The local monitoring network reduced location uncertainties to as low as ±500 m for both depth and epicenter for the later events. The operators have now provided more details about their operations at the two sites. The BGS have performed a re-analysis of past events (the Billingshurst 2005 sequence) that have occurred in the basin.

1. Has there been previous (either historical or instrumental) seismicity at the same site or in the same regional setting?

Evidence Assessment: The quality of the historical catalog has been improved from the previous assessment, as further analysis by the BGS has indicated that the Billingshurst 2005 events also had shallow depth. Therefore we can compare not only magnitude and rates, but also depths of past events. Answer rating = 100%. The maximum points scoreable is -8 or +8.

Answer: Earthquakes have occurred within the regional setting, at similar rates, magnitudes and depths, but not at this specific site: -2 + -3 = -5.

2. Is there temporal co-incidence between the onset of events and the industrial activities?

Evidence assessment: As per the previous assessment, for the Brockham oilfield we have sufficient data. For HH-1, the operator has now provided operations logs for the well, showing the dates and times that the well was flowing. Answer rating = 100%. The maximum points scoreable is -15 or +5 for both cases.

Answer: For Brockham, the seismicity was temporally co-incident with the re-start of production and waterflood after a substantial hiatus: +5. For HH-1, a very small initial flow test was conducted in early 2016, while the main flow test was conducted in July 2018. The Newdigate sequence began in April 2018. There is no temporal coincidence with the onset of seismicity and flow testing in the HH-1 well: -15.

3. Are the observed seismic events temporally correlated with the injection and/or extraction activities?

Evidence assessment: For the Brockham oilfield, we have monthly injection and production volumes available. For HH-1, we have information from the well operations logs regarding when the well was under flow testing, but do not have detailed rates. We have a catalog of 18 events against which to compare this information. Therefore, while some assessment of correlation can be made, this could be improved with more detailed information and a larger event catalog. Answer rating = 50%. The maximum points scoreable is -2 or +7.5 for both sites.

Answer: The Brockham oilfield has been under production for 16 years, and under waterflood for over 8 years, during which time no seismicity was recorded. There is therefore no correlation between seismicity and injection or production at Brockham: -2. For HH-1 there is no correlation between days when flow testing was conducted and the seismicity: -2.

4. Do the events occur at similar depths to the activities?

Evidence assessment: The local monitoring network reduced the depth uncertainties to ±500 m, sufficient to assess whether the events are at similar depths to the production horizons. Also, publicly available 2D seismic profiles provide fault locations that are relatively well constrained. Answer rating = 100%. The maximum points scoreable is -4 or +3.

Answer: The depths of the well-located events is estimated to be 2 km. This is significantly below the production horizons at Brockham and HH-1. However, normal faults extending several kilometers in depth are present in the Weald Basin (e.g., Butler and Pullan, 1990), so a hydraulic or geomechanical connection to the hypocentral depths is plausible: +2.

5. Is there spatial co-location between events and the activities?

Evidence assessment: The local monitoring network reduced epicentral uncertainties to ±500 m. Spatial changes in event loci through time were observed, which can be compared with the well locations. Answer rating = 100%. The maximum points scoreable is -10 or +10.

Answer: The events are located over 7 km from the Brockham oilfield. Given that this is a relatively small oilfield, the events appear to be too far away to have been induced: -10. The events are 2 km from the HH-1 well. However, the only activities to have taken place in this well are some small flow tests, so again this distance appears to be too large given the proposed causative mechanism. The sequence of events moves from west to east through time, which is towards, rather than radially away from the HH-1 well, which might be expected if events were induced: -10.

6. Is there a plausible mechanism to have caused the events?

Evidence assessment: Additional information has been provided about pressure changes by the operators of the Brockham oilfield, and information has been provided by the HH-1 operators about the flow testing in this well. Answer rating = 80%, reflecting the fact that pressure estimates are based on data from wells, and that reservoir models could be constructed to estimates how these pore pressure changes propagate through the reservoirs. The maximum points scoreable is -4 or +4.

Answer: The Brockham oilfield has experienced substantial pore pressure depletion during initial production, although at present the average net fluid extraction rate (production – injection) is 1 m^3/day, which is an extremely low rate. Of more significance is the fact that the Brockham reservoir is separated from the event locations by several fault blocks, the faults on which are known to act as baffles as they provide seals for the oilfields in the region, and indeed the reservoir unit is displaced significantly across these faults. Moreover, if pressure changes at Brockham were in communication with the hypocenter locations, then they would also be visible at the Horse Hill well (they are not). Therefore it is not plausible that any pore pressure changes in the Brockham oilfield could have been transferred to the loci of the seismicity: -4. At HH-1 the flow test volumes are small, and unlikely to have produced pore pressure perturbations extending more than a few 100 m from the well. As such, they would not have reached the loci of the seismicity: -4.

7. Do the source mechanisms indicate an induced event mechanism?

Evidence assessment: Source mechanisms were determined for some of the final events to occur in the sequence, which are reasonably well constrained by both polarities and amplitudes, though there is some uncertainty given the limited station coverage. The regional stress conditions are relatively well-constrained. Answer rating = 75%. The maximum points scoreable is 0 or +3.

Answer: The source mechanism is consistent with the regional stress state: 0.

5.2.4. Newdigate using data available in October 2018: Summary

The assessment results for Brockham are shown schematically in Figure 10, while the results for Horse Hill are shown in Figures 2 and 3. The Evidence Strength Ratio is calculated for both the Brockham oilfield and HH-1 as:

$$\mathrm{ESR} = \frac{(|-43|+|40.5|)}{96} \times 100 = 87\% \qquad (11)$$

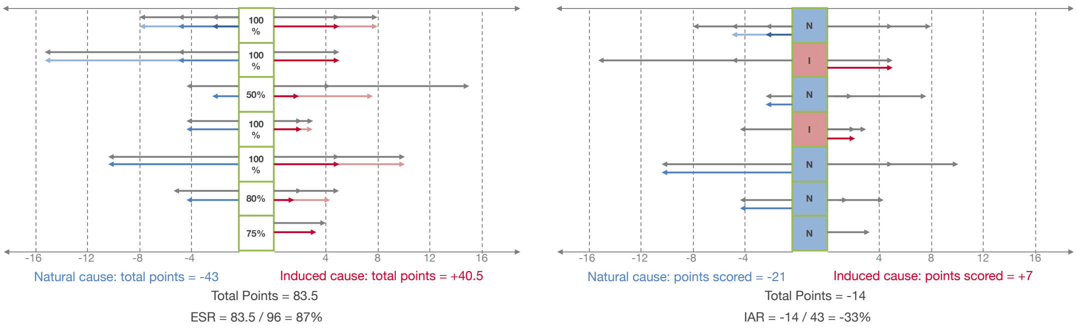
The Induced Assessment Ratio, which assesses whether the available evidence points towards an induced or a natural cause, is calculated for the Brockham oilfield as:

$$\mathrm{IAR} = \frac{-14}{|-43|} \times 100 = -33\% \qquad (12)$$

and for the HH-1 well as:

$$\mathrm{IAR} = \frac{-34}{|-43|} \times 100 = -79\% \qquad (13)$$

The negative IAR values indicate that neither Brockham nor HH-1 is a likely cause for these events, and they are therefore natural, although the evidence against Brockham as a cause is more ambiguous than the evidence against HH-1 as a cause. The high ESR value indicates that this judgement is robust, and that most of the desired evidence is available.



(a) *(b)*

Figure 10: The results of our assessment as applied to the Newdigate sequence relative to the Brockham oilfield, using data available in June 2018. In (a) we show the ESR assessment, and in (b) we show the IAR assessment.

6. CONCLUSIONS

The assessment as to whether or not a particular sequence of seismic events has been induced by industrial activities in the subsurface may in many cases be controversial. In such instances, a framework is required that allows stakeholders to perform this assessment in a robust and quantifiable manner. Such a framework must meet a number of requirements: it must provide results that are comprehensible to a variety of stakeholders; it must weight different categories of evidence appropriately; it must incorporate different pieces of evidence that may have different levels of uncertainty; and it must be flexible such that new questions and new types of evidence can be readily incorporated. In this paper we describe a framework that meets these objectives. The framework retains the simple, question-based format of previous assessment schemes. However, rather than simple “yes” or “no” answers, the questions are used to score positive or negative points, depending on whether the answers to these questions indicate an induced or a natural cause. The number of points scored for each question is scaled according to both the importance of the question being asked, and the level of certainty with which the question can be answered. The results of this framework are presented as two numbers: the Induced Assessment Ratio quantifies the summed answers to the questions posed, with a positive IAR indicating the events are induced and a negative IAR indicating the events are natural. The larger the absolute value of the IAR, the more unambiguous the evidence is as to this conclusion. The Evidence Strength Ratio describes the quality and quantity of evidence used to answer the questions, with a high ESR value indicating that the evidence used in the assessment is robust.

We have applied this framework to two case studies from the UK. In both cases we present two assessments, the first during the sequences of seismicity when many pieces of evidence were poorly constrained or not available. Nevertheless, at these times the regulator was under pressure to make decisions regarding oilfield operations near to these sequences. We then present a second assessment of each case using the full evidence base as is available to us today. By doing so we demonstrate how our proposed framework captures the changing levels and types of evidence via the ESR and IAR values.

In closing, we note that the key development of this paper is the framework itself. We recognize that other scientists and practitioners may wish to ask additional questions to those specified here, or to change the relative score values assigned to the different questions, and that their doing so will probably reflect our growing understanding of induced seismicity going forward.

Data and Resources

The data pertaining to the two case studies presented here are derived from existing literature, specifically Clarke et al. (2014) for Preese Hall, and Baptie and Luckett (2018) for Newdigate.

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References

Baptie, B., 2006. UK Earthquake Monitoring 2005/2006. British Geological Survey. Available at: http://www.earthquakes.bgs.ac.uk/publications/annual_reports/2006_17th_annual_report.pdf

Baptie, B. and R. Luckett, 2018. The Newdigate earthquake sequence, 2018: British Geological Survey Internal Report OR/18/059.

Bao, X. and D.W. Eaton, 2016. Fault activation by hydraulic fracturing in western Canada: Science 354, 1406-1409.

Bourne, S.J., S.J. Oates, J. van Elk, D. Doornhof, 2014. A seismological model for earthquakes induced by fluid extraction from a subsurface reservoir: Journal of Geophysical Research 119, 8991-9015.

Bourne, S.J., S.J. Oates, J.J. Bommer, J. van Elk, D. Doornhof, 2015. A Monte Carlo method for probabilistic hazard assessment of induced seismicity due to conventional natural gas production: Bulletin of the Seismological Society of America 105, 1721-1738.

Brodsky, E.E. and L.J. Lajoie, 2013. Anthropogenic seismicity rate and operational parameters at the Salton Sea geothermal field, Science 341, 543-546.

Butler M. and C. Pullan, 1990. Tertiary structures and hydrocarbon entrapment in the Weald Basin of southern England: in R.F.P. Hardman and J. Brooks (eds), *Tectonic events* *responsible for Britain's oil and gas reserves*: Geological Society Special Publication 55, 371-391.

Cesca, S., A. Rohr, T. Dahm, 2012. Discrimination of induced seismicity by full moment tensor inversion and decomposition: Journal of Seismology 17, 147-163.

Cesca, S., F. Grigoli, S. Heimann, Á. González, E. Buforn, S. Maghsoudi, E. Blanch, T. Dahm, 2014. The 2013 September-October seismic sequence offshore Spain: a case of seismicity triggered by gas injection: Geophysical Journal International 198, 941-953.

Clarke, H., L. Eisner, P. Styles, P. Turner, 2014. Felt seismicity associated with shale gas hydraulic fracturing: The first documented example in Europe: Geophysical Research Letters 41, 8308-8314.

Dahm, T., D. Becker, M. Bischoff, S. Cesca, B. Dost, R. Fritschen, S. Hainzl, C.D. Klose, D. Kühn, S. Lasocki, Th. Meier, M. Ohrnberger, E. Rivalta, U. Wegler, S. Husen, 2013. Recommendation for the discrimination of human-related and natural seismicity: Journal of Seismology 17, 197-202.

Dahm, T., S. Cesca, S. Hainzl, T. Braun, F. Krüger, 2015. Discrimination between induced, triggered, and natural earthquakes close to hydrocarbon reservoirs: A probabilistic approach based on the modeling of depletion-induced stress changes and seismological source parameters: Journal of Geophysical Research, 120, 2491-2509.

Davis, S.D. and C. Frohlich, 1993. Did (or will) fluid injection cause earthquakes? Criteria for a rational assessment: Seismological Research Letters 64, 207-224.

Davis, S.D., P.A. Nyffenegger, C. Frohlich, 1995. The 9 April 1993 earthquake in south-central Texas: was it induced by fluid withdrawal? Bulletin of the Seismological Society of America 85, 1888-1895.

Dreger, D.S., S.R. Ford, W.R. Walter, 2008. Source analysis of the Crandall Canyon, Utah, mine collapse: Science 321, 217.

Eaton, D.W. and A.B. Mahani, 2015. Focal mechanisms of some inferred induced earthquakes in Alberta, Canada: Seismological Research Letters 86, 1078-1085.

Ellsworth, W.L., 2013. Injection-induced earthquakes: Science 341, 1225942.

Everley, S., 2016. Comment on "A historical review of induced earthquakes in Texas" by Cliff Frohlich, Heather DeShon, Brian Stump, Chris Hayward, Matt Hornbach, and Jacob I. Walter: Seismological Research Letters 87, 1378-1380.

Frohlich, C., H. DeShon, B. Stump, C. Hayward, M. Hornbach, J.I. Walter, 2016a. A historical review of induced earthquakes in Texas: Seismological Research Letters 87, 1022-1038.

Frohlich, C., H. DeShon, B. Stump, C. Hayward, M. Hornbach, J.I. Walter, 2016b. Reply to "Comment on 'A Historical Review of Induced Earthquakes in Texas' by Cliff Frohlich, Heather DeShon, Brian Stump, Chris Hayward, Matt Hornbach, and Jacob I. Walter" by Steve Everley: Seismological Research Letters 87, 1381-1383.

Gilfillan, S., S. Haszeldine, B. McGuire, R. Selley, 2018. Surrey Quake Fears: Letter to The Editor of the Times, August 6th, 2018.

Goebel, T.H.W. and E.E. Brodsky, 2018. The spatial footprint of injection wells in a global compilation of induced earthquake sequences: Science 361, 899-904.

Goebel, T.H.W., E. Hauksson, F. Aminzadeh, J-P. Ampuero, 2015. An objective method for the assessment of fluid injection-induced seismicity and application to tectonically active regions in central California: Journal of Geophysical Research 120, 7013-7032.

Goebel, T.H.W., M. Weingarten, X. Chen, J. Haffener, E.E. Brodsky, 2017. The 2016 Mw5.1 Fairview, Oklahoma earthquakes: evidence for long-range poroelastic triggering at > 40 km from fluid disposal wells: Earth and Planetary Science Letters 472, 50-61.

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

Change. Available at: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/48330/5055-preese-hall-shale-gas-fracturing-review-and-recomm.pdf

Grigoli, F., S. Cesca, E. Priolo, A.P. Rinaldi, J.F. Clinton, T.A. Stabile, B. Dost, M.G. Fernandez, S. Wiemer, T. Dahm, 2017. Current challenges in monitoring, discrimination and management of induced seismicity related to underground industrial activities: A European perspective: Reviews of Geophysics 55, 310-340.

Grigoli, F., S. Cesca, A.P. Rinaldi, A. Manconi, J.A. López-Comino, J.F. Clinton, R. Westaway, C. Cauzzi, T. Dahm, S. Wiemer, 2018. The November 2017 M_w 5.5 Pohang earthquake: a possible case of induced seismicity in South Korea: Science 360, 1003-1006.

Keranen, K.M. and M. Weingarten, 2018. Induced Seismicity: Annual Review of Earth and Planetary Sciences 46, 149–174.

Keranen, K.M., H.M. Savage, G.A. Abers, E.S. Cochran, 2013. Potentially induced earthquakes in Oklahoma, USA: Links between wastewater injection and the 2011 M_w 5.7 earthquake sequence: Geology 41, 699-702.

McNamara, D.E., H.M. Benz, R.B. Herrmann, E.A. Bergman, P. Earle, A. Holland, R> Baldwin, A. Gassner, 2015. Earthquake hypocenters and focal mechanisms in central Oklahoma reveal a complex system of reactivated subsurface strike-slip faulting: Geophysical Research Letters 42, 2742-2749.

Montalvo-Arrieta, J.C., X. Pérez-Campos, L.G. Ramos-Zuñiga, E.G. Paz-Martínez, J.A. Salinas-Jasso, I. Navarro de León, J.A. Ramírez-Fernández, 2018. El Cuchillo seismic sequence of October 2013-July 2014 in the Burgos Basin, Northeastern Mexico: hydraulic fracturing or reservoir-induced seismicity? Bulletin of the Seismological Society of America 108, 3092-3106.

Musson, R.M.W. 1994. A catalogue of British earthquakes. British Geological Survey Global Seismology Report, WL/94/04.

Nicholson, C. and Wesson R.L., 1990. Earthquake hazard associated with deep well injection – a report to the US Environmental Protection Agency: US Geological Survey Bulletin 1951.

Oil and Gas Authority, 2018. OGA Newdigate Seismicity Workshop – 3 October 2018 Summary and Conclusion. London. Available at: https://www.ogauthority.co.uk/media/5174/2018_11_23-newdigate-workshop-summary-finalv3.pdf

Oprsal, I. and L. Eisner, 2014. Cross-correlation – an objective tool to indicate induced seismicity: Geophysical Journal International 196, 1536-1543.

Ottemöller, L., H.H. Neilsen, K. Atakan, J. Braunmiller, J. Havskov, 2005. The 7 May 2001 induced seismic event in the Ekofisk oil field, North Sea: Journal of Geophysical Research 110, B10301.

Passarelli, L., F. Maccaferri, E. Rivalta, T. Dahm, E. Abebe Boku, 2013. A probabilistic approach for the classification of earthquakes as 'triggered' or 'not triggered': Journal of Seismology 17, 165-187.

Ross, A., G.R. Foulger, B.R. Julian, 1996. Non-double-couple earthquake mechanisms at The Geysers geothermal area, California: Geophysical Research Letters 23, 877-880.

Schoenball, M., N.C. Davatzes, J.M.G. Glen, 2015. Differentiating induced and natural seismicity using space-time-magnitude statistics applied to the Coso Geothermal field: Geophysical Research Letters 42, 6221-6228.

Schultz, R., R. Wang, Y.J. Gu, K. Haug, G. Atkinson, 2017. A seismological overview of the induced earthquakes in the Duvernay play near Fox Creek, Alberta: Journal of Geophysical Research 122, 492-505.

Segall, P., 1989. Earthquakes triggered by fluid extraction: Geology 17, 942-946.

Shapiro, S.A., 2008. Microseismicity a tool for reservoir characterization: EAGE Education Tour Series, EAGE Publications, The Netherlands.

UKOG, 2018. Production flow test operations commence, Horse Hill-1 Kimmeridge Limestone and Portland oil discovery, PEDL137, Weald Basin, UK. London Stock Exchange Regulatory News Service No. 6830S.

Verdon, J.P., 2014. Significance for secure CO_2 storage of earthquakes induced by fluid injection: Environmental Research Letters 9, 064022.

Verdon, J.P., J-M. Kendall, D.J. White, D.A. Angus, 2011. Linking microseismic event observations with geomechanical models to minimise the risks of storing CO_2 in geological formations: Earth and Planetary Science Letters 305, 143-152.

Verdon, J.P., A.L. Stork, R.C. Bissell, C.E. Bond, M.J. Werner, 2015. Simulation of seismic events induced by CO_2 injection at In Salah, Algeria: Earth and Planetary Science Letters 426, 118-129.

Willacy, C., E. van Dedem, S. Minisini, J. Li, J.W. Blokland, I. Das, A. Droujinine, 2018. Application of full-waveform event location and moment-tensor inversion for Groningen induced seismicity: The Leading Edge 37, 92-99.

Zaliapin, I. and Y. Ben-Zion, 2016. Discriminating characteristics of tectonic and human-induced seismicity: Bulletin of the Seismological Society of America 106, 846-859.

Zhao, P., D. Kühn, V. Oye, S. Cesca, 2014. Evidence for tensile faulting deduced from full waveform moment tensor inversion during the stimulation of the Basel enhanced geothermal system: Geothermics 52, 74-83.