

1 **An improved framework for discriminating seismicity**  
2 **induced by industrial activities from natural**  
3 **earthquakes**

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## ABSTRACT

19 *Heightened concerns regarding induced seismicity necessitate robust methods to assess*  
20 *whether detected earthquakes near to industrial sites are natural, or induced by the industrial*  
21 *activity. These assessments are required rapidly, which often precludes detailed modeling of*  
22 *fluid pressures and the geomechanical response of the reservoir and nearby faults. Simple*  
23 *question-based assessment schemes in current use are a useful tool but suffer from several*  
24 *shortcomings: they do not specifically address questions regarding whether available*  
25 *evidence supports the case for natural seismicity; they give all questions equal weighting*  
26 *regardless of the relative influence of different factors; they are not formulated to account for*  
27 *ambiguous or uncertain evidence; and the final outcomes can be difficult to interpret. We*  
28 *propose a new framework that addresses these shortcomings by assigning numerical scores*  
29 *to each question, with positive values for answers that support induced seismicity and*  
30 *negative values for responses favoring natural seismicity. The score values available for each*  
31 *question reflect the relative importance of the different questions, and for each question the*  
32 *absolute value of the score is modulated according to the degree of uncertainty. The final*  
33 *outcome is a score, the Induced Assessment Ratio (IAR), either positive or negative (or zero),*  
34 *that reflects whether events were induced or natural. A second score, the Evidence Strength*  
35 *Ratio (ESR), is assigned that characterizes the strength of the available evidence, expressed*  
36 *as the ratio of the maximum score possible with the available evidence relative to the*  
37 *maximum score that could be obtained if all desired data were available at a site. We*  
38 *demonstrate this approach by application to two case studies in the UK, one widely regarded*  
39 *as a case of induced seismicity, the other more likely to be a series of tectonic earthquakes.*  
40

## 41 **1. INTRODUCTION**

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

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

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

67 In this paper, we propose a new framework for making assessments that can be  
68 applied rapidly, but also be updated as more information becomes available, avoiding the  
69 vagueness and ambiguity that can result with existing approaches. We begin with a critical  
70 review of the existing approaches and then present the proposed new framework, explaining  
71 how it meets the requirements for such a scheme to be useful for practical application. As  
72 well as proposing an improved general framework, we also put forward numerical values for  
73 this quantitative approach based on our current judgement and apply these to some case  
74 histories. However, we stress that the specific details of the framework are only a suggestion  
75 and others may wish to adapt and adjust these features. Moreover, we only present illustrative

76 applications for activities related to fluid injection and extraction, but we believe that the  
77 framework could be adapted to other potential causes of induced seismicity such as mining  
78 and reservoir impoundment.

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

96

## 97 **2. CRITIQUE OF EXISTING INDUCED SEISMICITY ASSESSMENT**

### 98 **FRAMEWORKS**

99 The pioneering work of Davis and Frohlich (1993) provided the first such set of  
100 criteria for assessing induced seismicity. This approach, and derivatives thereof (e.g. Davis et  
101 al., 1995; Frohlich et al., 2016a), remain widely used today (e.g., Montalvo-Arrieta et al.,  
102 2018; Grigoli et al., 2018). Hereafter we refer to Davis and Frohlich (1993) and the various  
103 frameworks derived from it as “Frohlich-based” (in honor of the common author among all of  
104 these papers).

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

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

- 109 2. Temporal Correlation: Is there a clear correlation between the time of injection and the  
110 times of seismic activity?
- 111 3a. Spatial Correlation: Are epicenters near the wells?
- 112 3b. Spatial Correlation: Do some earthquakes occur at depths comparable to the depth of  
113 injection?
- 114 3c. Local Geology: If some earthquakes occur away from wells, are there known  
115 geologic structures that may channel fluid flow to the sites of the earthquakes?
- 116 4a. Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or  
117 aseismic failure at the bottom of the well?
- 118 4b. Injection Practices: Are changes in fluid pressure sufficient to encourage seismic or  
119 aseismic failure at the hypocentral locations?

120

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

126 Recognizing that seismicity may also be caused by fluid withdrawal, Davis et al.  
127 (1995) adapted these questions for extraction scenarios, where in this case seven or more  
128 “yes” answers provide strong evidence that the earthquakes are induced:

- 129 1a. Are these the first known earthquakes of this character in the region?
- 130 1b. Did the events only begin after fluid withdrawal had commenced?
- 131 1c. Is there a clear correlation between withdrawal and seismicity?
- 132 2a. Are epicenters within 5 km of wells?
- 133 2b. Do some earthquakes occur at production depths?
- 134 2c. Do epicenters appear spatially related to the production region?
- 135 3a. Did production cause a significant change in fluid pressures?
- 136 3b. Did seismicity begin only after fluid pressures had dropped significantly?
- 137 3c. Is the observed seismicity explainable in terms of current models relating to fault  
138 activity?

139

140 While investigating historic cases of potential induced seismicity in Texas, Frohlich  
141 et al. (2016a) recognized that robust evidence regarding pressure changes would not be  
142 available. Therefore, they reduce the number of questions to five, with scores of 1.0, 0.5 and  
143 0.0 for answers of “yes”, “possibly” and “no”, to obtain a scheme specifically designed to  
144 address historical cases of seismicity, rather than recent, modern cases where more  
145 information is likely to be available:

146 QT: Do the earthquakes occur only after potentially influential human activities begin?

147 QS: Are the earthquakes and human activities close enough so that a causal relationship  
148 is plausible?

149 QD: Is there evidence from the pattern of felt reports, surficial features, or credible  
150 hypocentral locations that is consistent with a relatively shallow depth and a possible  
151 causal relationship?

152 QF: Near the epicenter, are there known faults, either as mapped or as inferred from  
153 linear groupings of epicenters, that might support an earthquake, or enhance movement  
154 of fluids?

155 QP: Have credible scientists investigated these events and concluded a human cause is  
156 plausible?

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

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

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

174           Indeed, the same “score” means very different things for the different versions of the  
175 Frohlich-based frameworks. This is confusing to a non-expert audience: a score of 3 is  
176 “ambiguous” on the Davis and Frohlich (1993) scale (3 out of 7); probably not induced on the  
177 Davis et al. (1995) scale [3 out of 9, although Davis et al. (1995) never explicitly state how  
178 lower values should be classified]; but “probably induced” (3 out of 5) on the Frohlich et al.  
179 (2016a) scale. Hence communication with stakeholders requires the full framework to be  
180 described in detail first.

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

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

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

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

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

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

231           An alternative family of schemes, based on recommendations made by Dahm et al.  
232 (2013), has recently been developed. Dahm et al. (2013) suggest three mechanisms by which  
233 anthropogenic and natural seismicity might be discriminated. The first mechanism involves  
234 physics-based probabilistic modeling, whereby a physical model of the causative mechanism  
235 is used to compute the expected change in Mohr-Coulomb stress at the hypocenter location(s)  
236 (e.g., Passarelli et al., 2012; Dahm et al., 2015). The simulated anthropogenic seismicity is  
237 compared against the probability of a natural event occurring at this location, as estimated  
238 from background seismicity rates.

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



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

252         The second mechanism proposed by Dahm et al. (2013) is based on establishing  
253 statistical correlation between rates of seismicity and industrial activities (such as injection or  
254 production rate). The observed population of seismic events is characterized statistically,  
255 primarily with respect to the rate of seismicity (e.g., Oprsal and Eisner, 2014; Goebel et al.,  
256 2015), but potentially also the magnitude distribution, spatial distribution and inter-event  
257 times (e.g., Schoenball et al., 2015). Changes in these statistics are then correlated to the onset  
258 of an industrial activity and/or changes in the rate of activity (such as changes in injection  
259 rate), with strong correlation implying that the events are likely to be induced. Much like the  
260 physics-based methods, observations of statistical correlation between seismicity and  
261 industrial activities can be a powerful indication of induced seismicity. However, it need not  
262 be a necessary condition: Keranen et al. (2013) show that for the 2011  $M_W = 5.7$  earthquake  
263 near Prague, Oklahoma, which is generally considered to have been induced by wastewater  
264 injection, there was no obvious correlation between injection rates and the observed  
265 seismicity. This approach also suffers from the same issues as described above for the  
266 physics-based models described above with the requirement of well-characterized records of  
267 historical seismicity, and for detailed records of operational data. Moreover, the statistical  
268 characterization of event populations requires a statistically significant number of events,  
269 which may not be available at the early stages of a seismic sequence, which is when an  
270 assessment of induced seismicity may be most critical in terms of mitigation.

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

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

282

### 283 **3. THE PROPOSED FRAMEWORK**

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

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

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

312 Finally, we note that the science around induced seismicity is currently a highly  
313 active one. It would not be surprising if our understanding of the causes and mechanisms of

314 induced seismicity change or improve in the coming years. Therefore, ideally an assessment  
315 framework should be adaptable such that new knowledge can be readily incorporated.

316 In summary, an induced seismicity assessment framework must:

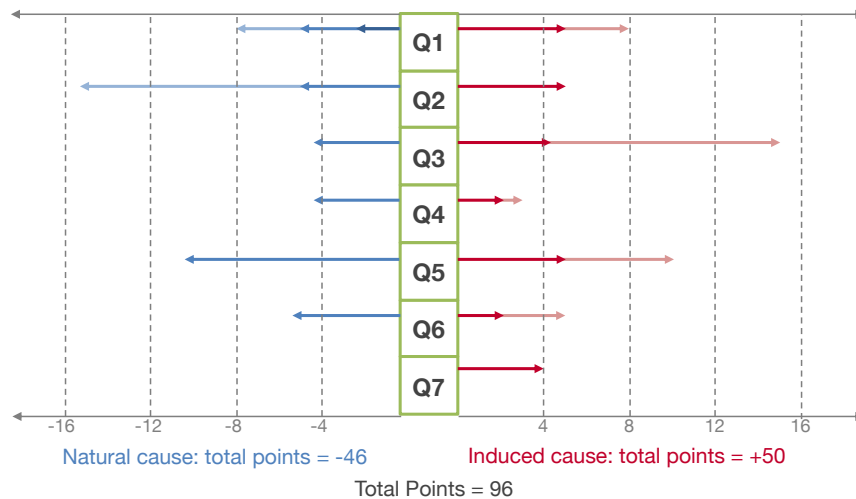
- 317 • provide results that are comprehensible to a wide audience, and it must be  
318 unbiased towards either conclusion (induced or not induced), and be seen to be so.
- 319 • weight different sources and types of evidence appropriately according to their  
320 significance.
- 321 • be capable of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

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

339

340

### **Framework Criteria**



341

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

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

361 When applying the framework, the first step would be to assess how much  
 362 information is available. In some cases, particularly when the assessment is being made very  
 363 soon after the seismicity has occurred, there may be some questions that cannot be answered  
 364 at all, and others that can only be answered to a degree (such as not having well-constrained  
 365 depths for past natural seismicity in the example given above). If the judgment of the assessor  
 366 is that there is ambiguity or uncertainty in the available information (such as poorly-

367 constrained focal depths, for example), then this judgment may be expressed as a percentage  
 368 and then applied to the available scores (Figure 2). This then defines our first outcome, which  
 369 we call the Evidence Strength Ratio, which is the ratio of the maximum score that can be  
 370 assigned with the available data to the maximum score that would be available in an ideal  
 371 case with all desirable data fully available:

$$372 \quad ESR = \frac{(|\text{Maximum -ve points given available data}| + |\text{Maximum +ve points given available data}|)}{\text{Total number of +ve and -ve points that can be scored in the framework}} \times 100 \quad (1)$$

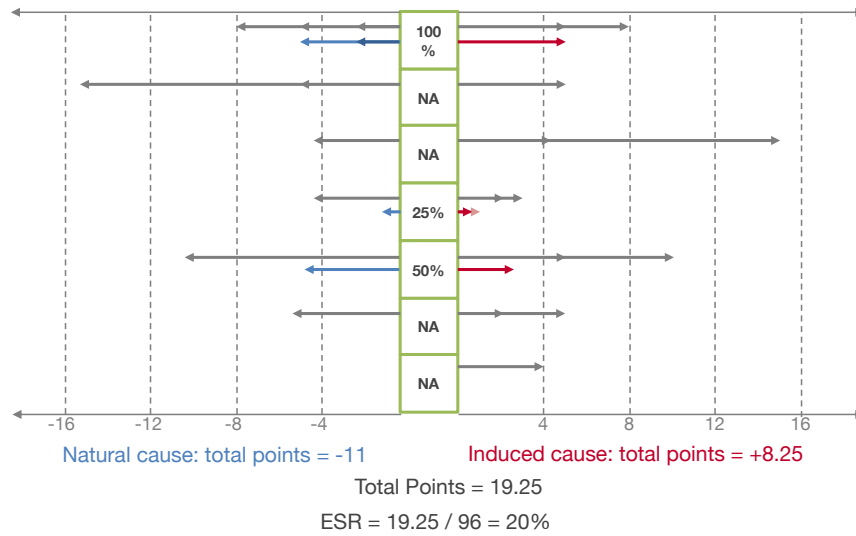
373 In Figure 2a, the ESR would be equal to 20%  $[(|-11| + 8.25)/(|-46| + 50)]$ , and in  
 374 Figure 2b the ESR would be equal to 87%  $[(|-43| + 40.5)/(|-46| + 50)]$ . The value of ESR may  
 375 grows over time as evidence is accumulated. This means that a preliminary assessment could  
 376 be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

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

$$385 \quad IAR = \frac{\text{Summed score}}{|\text{Maximum points given available data}|} \times 100 \quad (2)$$

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

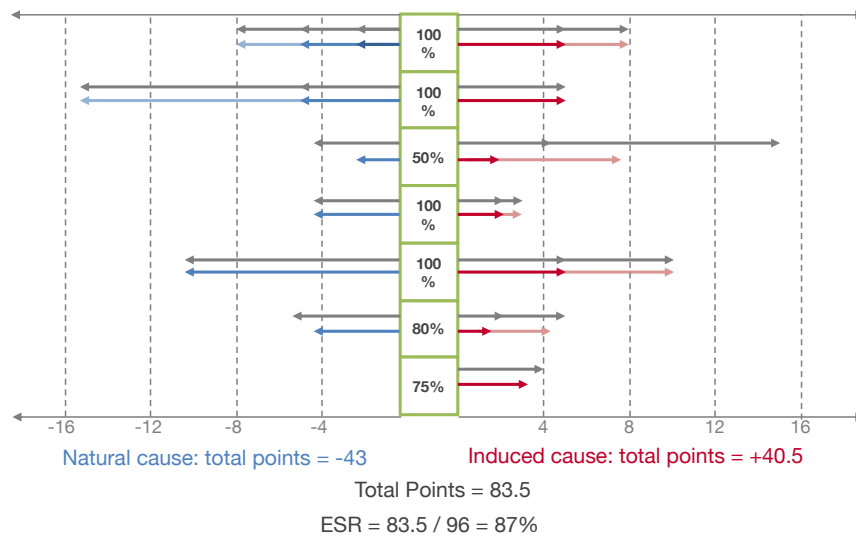
### 398 **Evidence Strength Assessment**



399

400

(a)



401

402

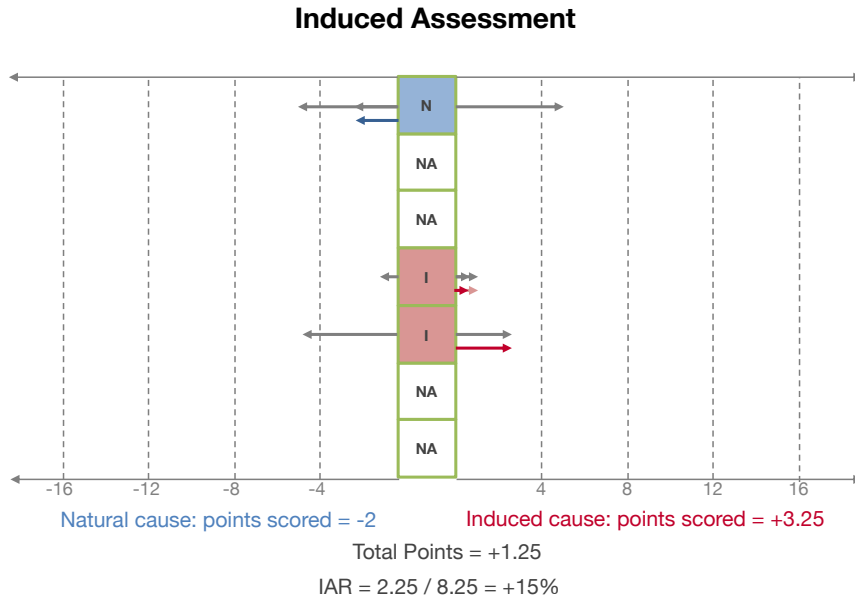
(b)

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

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

414

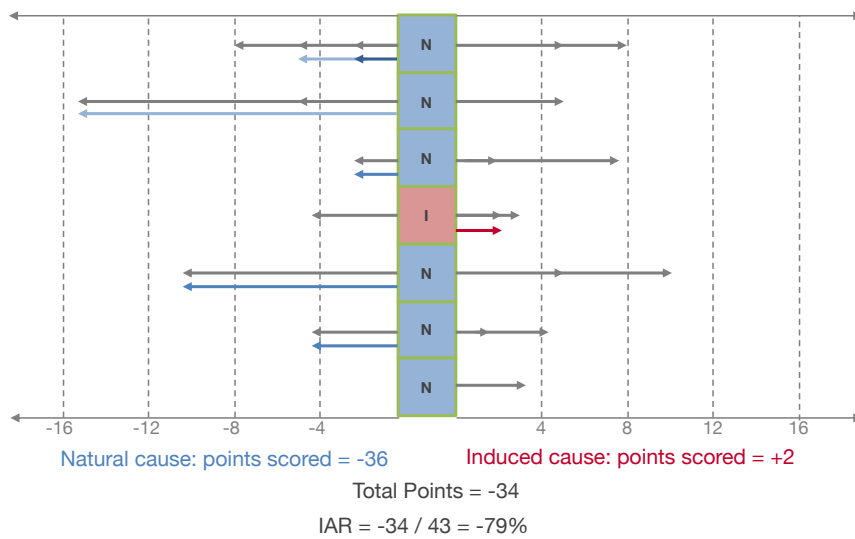
415



416

417

(a)



418

419

(b)

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

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

432

433           One could consider combing the two numbers into a single score but we believe it is  
434 valuable to preserve the IAR and ESR as separate measures, especially since over time the  
435 evolution of the IAR with an increasing ESR could be reported. A low IAR score (either  
436 positive or negative) associated with an ESR of 20% might suggest that judgment should be  
437 suspended while additional data are gathered; conversely, a low IAR score with an ESR of  
438 80% would suggest that we are unlikely to be able to know whether a particular seismic  
439 sequence was due to an industrial process or not (although this might be revealed should the  
440 industrial activity continue, generating additional observations and data).

441

442

#### 443 **4. THE PROPOSED CRITERIA FOR FLUID INJECTION AND EXTRACTION**

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



459 mining and reservoir impoundment for example, would require consideration of alternative  
460 criteria but we believe that the framework could still be applied to such cases.

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

467

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

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

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

474 c) Earthquakes have not occurred at similar rates or magnitudes within the regional setting:  
475 +5

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

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

479

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

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

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

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

486

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

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

- 491 b) There is some temporal correlation between the seismicity and the industrial activity: +4  
492 c) There is strong temporal correlation between the seismicity and the industrial activity (e.g.,  
493 between rates of injection and rates of seismicity): +15

494

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

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

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

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

501

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

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

504 b) Earthquakes are sufficiently close to the activities, given the putative causative mechanism:  
505 +5

506 c) If earthquake loci change with time, this change is consistent with the industrial activity,  
507 for example growing radially from a well, or shifting in response to the start of a new well:  
508 +10

509

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

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

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

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

517

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

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

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

522

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

526

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

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

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

552 Induced seismicity caused by fluid injection or extraction typically occurs within < 4  
553 km depth of the industrial activity (e.g., Verdon, 2014). Given that most such activities take

554 place at relatively shallow depths, most cases of induced seismicity occur at relatively shallow  
555 depths when compared to the overall seismogenic thickness of the crust, which typically  
556 extends > 20 km in depth. Therefore the occurrence of seismicity at relatively shallow depths,  
557 if past natural seismicity has not previously occurred at such depths, may be taken as an  
558 indicator that events are induced. However, in many cases it is not possible to make this  
559 assessment because event depths for past seismicity are very poorly constrained (indeed in  
560 some cases the depths of the candidate events are also poorly constrained), in which case this  
561 element of the question cannot be answered.

562

563 **2. Is there temporal co-occurrence between the onset of events and the industrial**  
564 **activities?**

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

575

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

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

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

591

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

593 It might be expected that induced seismicity will occur at similar depths to the depth at  
594 which industrial activities are taking place, while natural seismicity typically occurs at greater  
595 depths. However, this assessment is complicated by the fact that many cases of induced  
596 seismicity have in fact occurred several km deeper than the industrial activity (e.g., Verdon,  
597 2014). These observations are explained by the presence of hydraulic and/or geomechanical  
598 connections, usually faults, from shallow to deeper layers (e.g., Ellsworth, 2013). If events  
599 occur at the same depth as the industrial activity then we consider this to be evidence that they  
600 are induced. If events are deeper than the activity, but plausible hydraulic or geomechanical  
601 connections between the two are present, then we also consider this as evidence in favor that  
602 the events are induced. If there is significant difference in depths between the events and the  
603 industrial activity, and plausible connections between these depths can be ruled out, then this  
604 represents evidence that events are not induced.

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

612

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

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

620 High volume (e.g., >20,000 m<sup>3</sup> per month) wastewater disposal wells can have a large  
621 footprint, with seismicity occurring 10s of km from the injection (e.g., Verdon, 2014; Goebel  
622 et al., 2017; Goebel and Brodsky, 2018). Inevitably however, in such instances where the events

623 extend 10s of km from the well, some seismicity is found within 5 km of the injection site.  
624 Therefore we suggest that larger distances between events and high-volume injection wells  
625 (e.g., > 10 km) are indicative of a natural cause unless some there is also seismicity located in  
626 closer proximity to the well.

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

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

637

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

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

656           This question may often be difficult to answer, since it requires that the pressure  
657 changes and/or poro-elastic effects caused by the industrial activity are known or can be  
658 modeled. Wellbore pressures are often not publicly available (such data is often commercially  
659 sensitive), and accurate models require detailed subsurface characterization. To determine  
660 whether it is plausible that pressure changes have reached the hypocentral locations, these  
661 locations must be well constrained both laterally and in depth, which also may not be the case.  
662

#### 663 **7. Do the focal mechanisms indicate an induced event?**

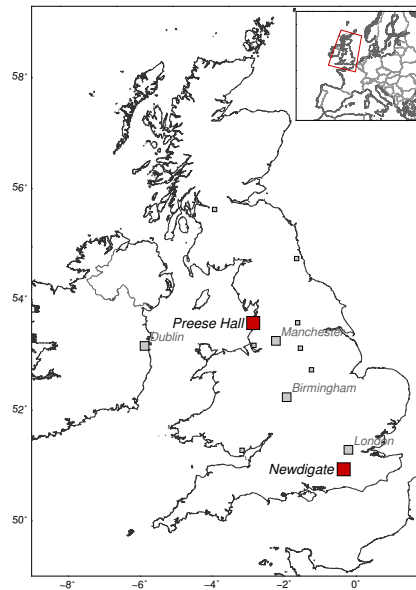
664           In some cases of induced seismicity, the putative causative mechanism for induced  
665 events implies a particular focal mechanism (e.g., Cesca et al., 2012). Typically, this is the case  
666 where seismicity is induced by depletion and compaction of reservoirs (e.g., Ottemöller et al.,  
667 2005; Willacy et al., 2018), where the source mechanism will be determined by the position of  
668 the event relative to the compacting zone (Segall, 1989). In contrast, for many cases of induced  
669 seismicity the focal mechanisms are consistent with the regional stress conditions (e.g., Clarke  
670 et al., 2014; Eaton and Mahani, 2015; McNamara et al., 2015). Therefore, focal mechanisms  
671 that are consistent with the regional stress field do not point towards either a natural or induced  
672 cause, since this is observed in both induced and natural cases. However, focal mechanisms  
673 that are not consistent with the regional stress, but are consistent with the proposed causative  
674 mechanism, can be used as evidence that events are induced.

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

679

### 680 **5. APPLICATION TO CASE STUDIES**

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



688

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

691

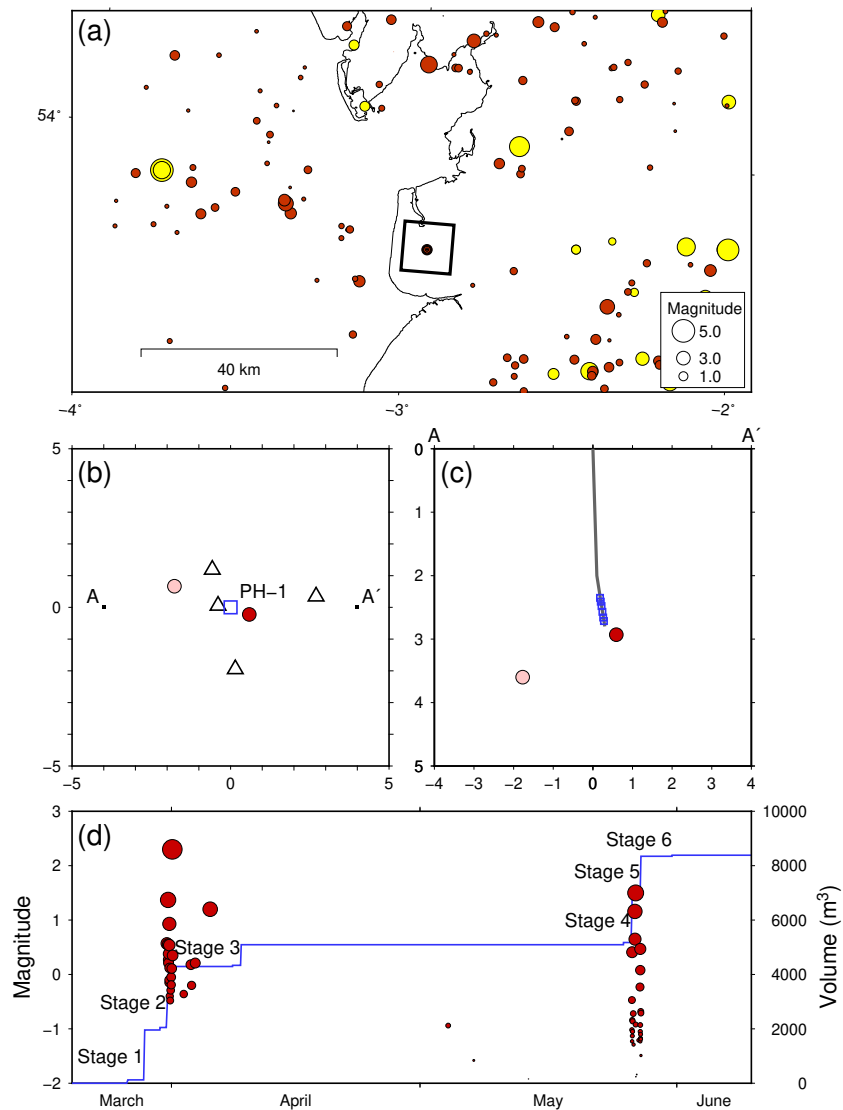
692 To demonstrate the challenges faced by a regulator in such circumstances, we do not  
 693 just present a final assessment using what we now know about these sites, but instead we apply  
 694 the proposed framework using the state of knowledge that existed at the time the regulator was  
 695 first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

698

### 699 **5.1. Preese Hall Sequence**

700 The Preese Hall sequence (Figure 5) consists of 58 earthquakes, with a largest  
 701 magnitude of  $M_L = 2.3$ , that occurred between March and August 2011 near to Blackpool,  
 702 Lancashire. Most of the seismicity occurred in two clusters, the first beginning on 31<sup>st</sup> March  
 703 2011, and the second on the 26<sup>th</sup> May. The largest events were felt by local populations, and  
 704 the seismicity was linked to hydraulic fracturing of the Preese Hall shale gas well. This potential  
 705 linkage was noted after the first cluster of events. No mitigating actions were taken by the  
 706 operator or the regulator at this time, except that a local seismic monitoring array was installed.  
 707 After the second cluster of events, recorded by the local array, the operator decided to pause  
 708 activities pending an investigation into the events. The net result of these investigations was the  
 709 imposition of a Traffic Light System that now applies to onshore hydraulic fracturing  
 710 operations in the UK (Green et al., 2012).





711

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

724

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

729

### 730 **5.1.1. Preese Hall Assessment, using data available in April 2011**

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

#### 735 **1. Has there been previous (either historical or instrumental) seismicity at the same site** 736 **or in the same regional setting?**

737 **Evidence assessment:** the earthquake catalog is of reasonable quality and contains both  
738 historical and instrumentally recorded seismicity. However, the magnitudes of interest (*c. M<sub>L</sub>*  
739 = 2.0) are close to the estimated magnitude of completeness for the BGS national monitoring  
740 array. Instrumentally recorded events have depth uncertainties of several kilometers, and  
741 historical event depths are poorly constrained. The depths of the events in question were also  
742 poorly constrained. Therefore rates and magnitudes could be assessed, but not depths. Answer  
743 rating = 50% given the completeness of the historical catalog at these magnitudes. The  
744 maximum points scoreable (used to determine the ESR) is -2.5 or +2.5.

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

747

#### 748 **2. Is there temporal co-incidence between the onset of events and the industrial** 749 **activities?**

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

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

755

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

758 **Evidence assessment:** While it was known that the hydraulic fracturing was taking place at the  
759 Preese Hall well, detailed records of pumping rates were not publicly available at this time.  
760 Therefore assessments of correlation could not be made. This question could not be answered.  
761 0 points scoreable for this question.

762 **Answer:** Not Answerable

763

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

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

769 **Answer:** NA

770

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

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

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

778

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

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

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

785

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

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

790 **Answer:** NA

791

792 **5.1.2. Preese Hall using data available in April 2011: Summary**

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

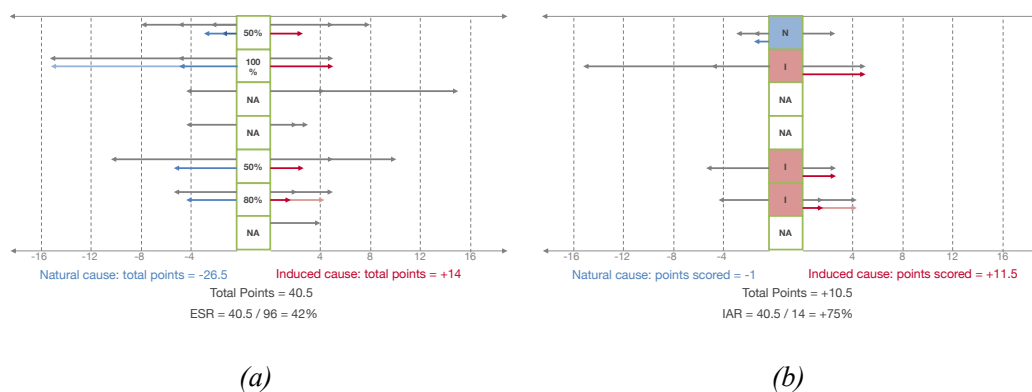
796 
$$ESR = \frac{(|-26.5|+|14|)}{96} \times 100 = 42\% \quad (3)$$

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

799 
$$IAR = \frac{10.5}{|14|} \times 100 = +75\% \quad (4)$$

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

804



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

808

809 **5.1.3. Preese Hall Assessment, using all available data**

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

816

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

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

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

825

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

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

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

831

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

834 **Evidence assessment:** With detailed pumping data provided by the operator, and an improved  
835 catalog of over 50 events provided by the matched-filter detection method, it becomes possible  
836 to assess the correlation between the induced events and the activity in detail. Answer rating =  
837 100%. The maximum points scoreable is -4 or +15.

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

841

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

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

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

848

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

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

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

854

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

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

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

860

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

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

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

869

870 **5.1.4. Preese Hall, using all available data: Summary**

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

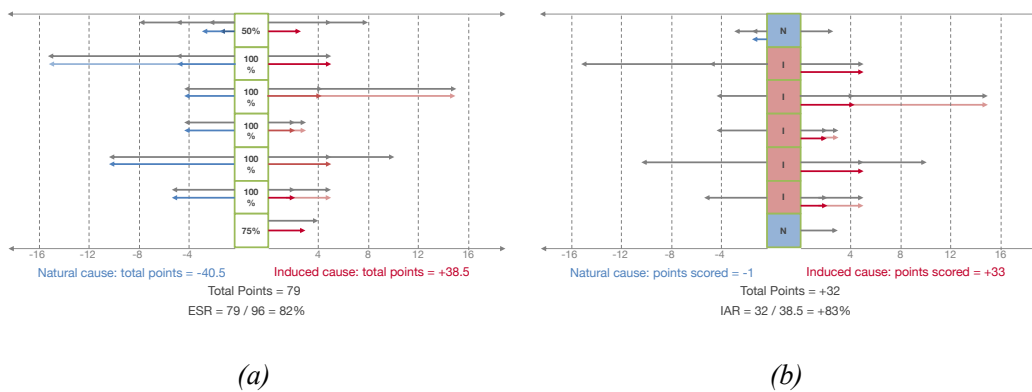
873 
$$ESR = \frac{(|-40.5|+|38.5|)}{96} \times 100 = 82\% \quad (5)$$

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

876 
$$IAR = \frac{32}{|38.5|} \times 100 = 83\% \quad (6)$$

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

880



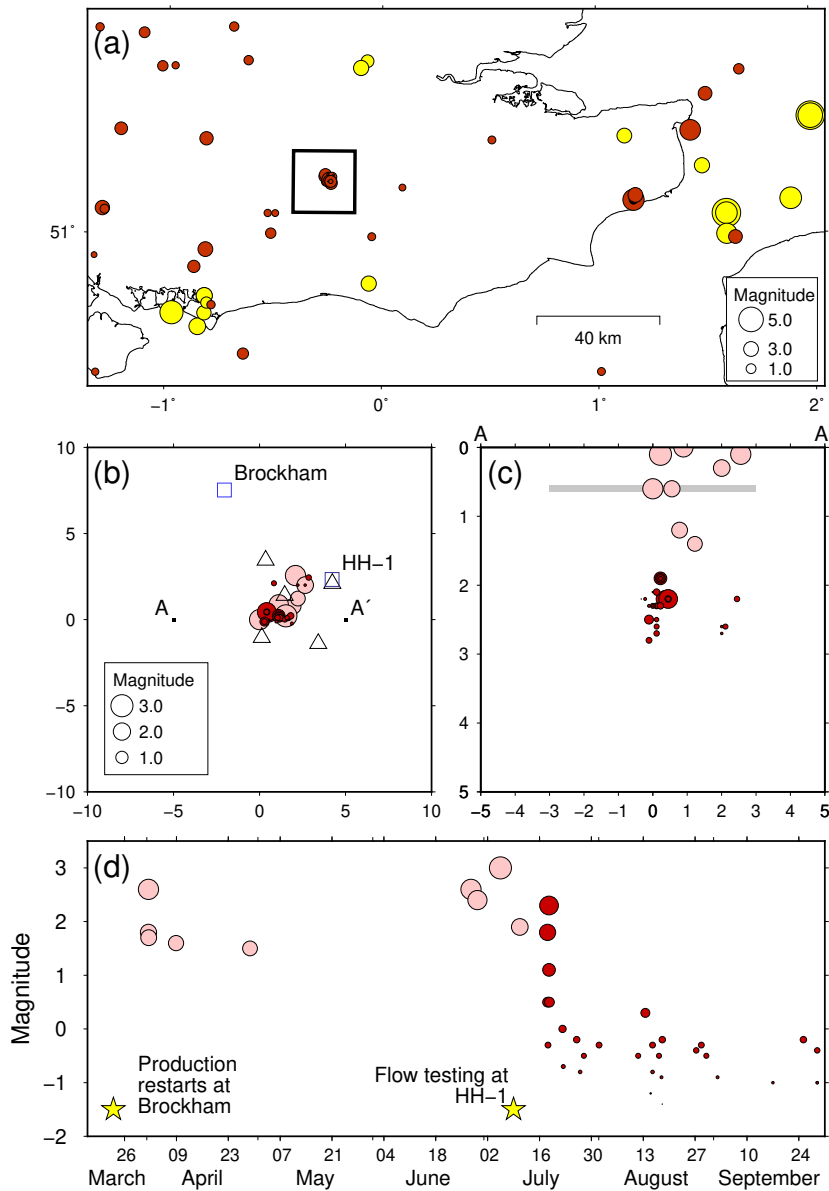
881 *Figure 7: The results of our assessment as applied to the Preese Hall sequence using*  
 882 *all available data. In (a) we show the ESR assessment, and in (b) we show the IAR assessment.*

883

884 **5.2. The Newdigate sequence**

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

893



894

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



906

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

916

### 917 **5.2.1. The Newdigate sequence using data available in June 2018**

#### 918 **1. Has there been previous (either historical or instrumental) seismicity at the same site** 919 **or in the same regional setting?**

920 **Evidence assessment:** The earthquake catalog is of reasonable quality and contains both  
921 historical and instrumentally recorded seismicity. The instrumental catalog has an estimated  
922 magnitude of completeness of  $M_L = 2.0$ , which is lower than the largest events detected in the  
923 Newdigate sequence. The depths of catalog events are poorly constrained, although they are  
924 believed to be shallow ( $< 10$  km), and the detected events also had large uncertainties ( $\pm 5$  km).  
925 Therefore rates and magnitudes of past events could be assessed, but not depths. Answer rating  
926 = 100%. The maximum points scoreable is -5 or +5.

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

931

#### 932 **2. Is there temporal co-incidence between the onset of events and the industrial** 933 **activities?**

934 **Evidence assessment:** For the Brockham oilfield, monthly production and injection data was  
935 publicly available via the Oil and Gas Authority. Answer rating = 100%. The maximum points  
936 scoreable is -15 or +5. For the HH-1 well, dates on which flow testing had been conducted were  
937 not publicly available, so this question could not be answered (0 points scoreable). In retrospect,  
938 this apparent lack of data was because the operator at HH-1 had not started flow testing at this

939 time, so there was no data to be made public. The start of flow testing was publicly announced  
940 by the operator in late June 2018 (UKOG, 2018).

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

943

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

946 **Evidence assessment:** For the Brockham oilfield, we have monthly injection and production  
947 volumes available. At this time only 3 events had been detected, making any assessment of  
948 correlation extremely tentative. Answer rating = 25%. The maximum points scoreable is -1 or  
949 +3.75. For HH-1, no information about flow testing was available, so this question could not  
950 be answered (0 points scoreable).

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

954

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

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

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

964

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

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

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

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

974

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

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

979 **Answer:** NA

980

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

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

985 **Answer:** NA

986

987 **5.2.2. Newdigate using data available in June 2018: Summary**

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

991 
$$\text{ESR} = \frac{(|-27|+|17|)}{96} \times 100 = 46\% \quad (7)$$

992 and for the HH-1 well as:

993 
$$\text{ESR} = \frac{(|-11|+|8.25|)}{96} \times 100 = 20\% \quad (8)$$

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

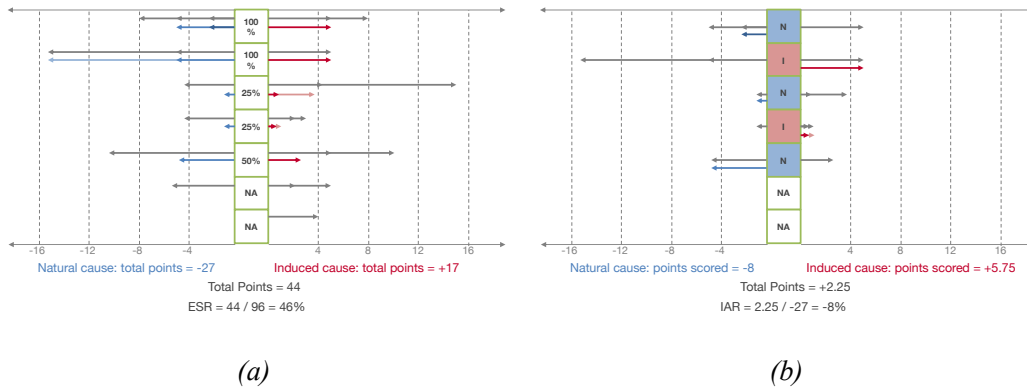
996 
$$\text{IAR} = \frac{-2.25}{|-27|} \times 100 = -8\% \quad (9)$$

997 and for the HH-1 well as:

998 
$$\text{IAR} = \frac{1.25}{|-8.25|} \times 100 = +15\% \quad (10)$$

999 We conclude that at this time, the ESRs were low for both cases, implying that any  
1000 judgement would be tentative. The ESR for the HH-1 well was particularly low, implying that

1001 more evidence would be required for a robust assessment. The IARs for both sites were close  
 1002 to 0, implying that the limited evidence that was available was ambiguous at this point in time.  
 1003



1004 *Figure 9: The results of our assessment as applied to the Newdigate sequence relative*  
 1005 *to the Brockham oilfield, using data available in June 2018. In (a) we show the ESR assessment,*  
 1006 *and in (b) we show the IAR assessment.*

1007

### 1008 5.2.3. Newdigate Assessment, using data available in October 2018

1009 We now repeat our analysis using data from the Newdigate sequence that was available in  
 1010 October 2018 (Baptie and Luckett, 2018). The local monitoring network reduced location  
 1011 uncertainties to as low as  $\pm 500$  m for both depth and epicenter for the later events. The operators  
 1012 have now provided more details about their operations at the two sites. The BGS have  
 1013 performed a re-analysis of past events (the Billingshurst 2005 sequence) that have occurred in  
 1014 the basin.

1015

#### 1016 1. Has there been previous (either historical or instrumental) seismicity at the same site 1017 or in the same regional setting?

1018 **Evidence Assessment:** The quality of the historical catalog has been improved from the  
 1019 previous assessment, as further analysis by the BGS has indicated that the Billingshurst 2005  
 1020 events also had shallow depth. Therefore we can compare not only magnitude and rates, but  
 1021 also depths of past events. Answer rating = 100%. The maximum points scoreable is -8 or +8.

1022 **Answer:** Earthquakes have occurred within the regional setting, at similar rates, magnitudes  
 1023 and depths, but not at this specific site:  $-2 + -3 = -5$ .

1024

1025 **2. Is there temporal co-incidence between the onset of events and the industrial**  
1026 **activities?**

1027 **Evidence assessment:** As per the previous assessment, for the Brockham oilfield we have  
1028 sufficient data. For HH-1, the operator has now provided operations logs for the well, showing  
1029 the dates and times that the well was flowing. Answer rating = 100%. The maximum points  
1030 scoreable is -15 or +5 for both cases.

1031 **Answer:** For Brockham, the seismicity was temporally co-incident with the re-start of  
1032 production and waterflood after a substantial hiatus: +5. For HH-1, a very small initial flow test  
1033 was conducted in early 2016, while the main flow test was conducted in July 2018. The  
1034 Newdigate sequence began in April 2018. There is no temporal coincidence with the onset of  
1035 seismicity and flow testing in the HH-1 well: -15.

1036

1037 **3. Are the observed seismic events temporally correlated with the injection and/or**  
1038 **extraction activities?**

1039 **Evidence assessment:** For the Brockham oilfield, we have monthly injection and production  
1040 volumes available. For HH-1, we have information from the well operations logs regarding  
1041 when the well was under flow testing, but do not have detailed rates. We have a catalog of 18  
1042 events against which to compare this information. Therefore, while some assessment of  
1043 correlation can be made, this could be improved with more detailed information and a larger  
1044 event catalog. Answer rating = 50%. The maximum points scoreable is -2 or +7.5 for both sites.

1045 **Answer:** The Brockham oilfield has been under production for 16 years, and under waterflood  
1046 for over 8 years, during which time no seismicity was recorded. There is therefore no  
1047 correlation between seismicity and injection or production at Brockham: -2. For HH-1 there is  
1048 no correlation between days when flow testing was conducted and the seismicity: -2.

1049

1050 **4. Do the events occur at similar depths to the activities?**

1051 **Evidence assessment:** The local monitoring network reduced the depth uncertainties to  $\pm 500$   
1052 m, sufficient to assess whether the events are at similar depths to the production horizons. Also,  
1053 publicly available 2D seismic profiles provide fault locations that are relatively well  
1054 constrained. Answer rating = 100%. The maximum points scoreable is -4 or +3.

1055 **Answer:** The depths of the well-located events is estimated to be 2 km. This is significantly  
1056 below the production horizons at Brockham and HH-1. However, normal faults extending

1057 several kilometers in depth are present in the Weald Basin (e.g., Butler and Pullan, 1990), so a  
1058 hydraulic or geomechanical connection to the hypocentral depths is plausible: +2.

1059

#### 1060 **5. Is there spatial co-location between events and the activities?**

1061 **Evidence assessment:** The local monitoring network reduced epicentral uncertainties to  $\pm 500$   
1062 m. Spatial changes in event loci through time were observed, which can be compared with the  
1063 well locations. Answer rating = 100%. The maximum points scoreable is -10 or +10.

1064 **Answer:** The events are located over 7 km from the Brockham oilfield. Given that this is a  
1065 relatively small oilfield, the events appear to be too far away to have been induced: -10. The  
1066 events are 2 km from the HH-1 well. However, the only activities to have taken place in this  
1067 well are some small flow tests, so again this distance appears to be too large given the proposed  
1068 causative mechanism. The sequence of events moves from west to east through time, which is  
1069 towards, rather than radially away from the HH-1 well, which might be expected if events were  
1070 induced: -10.

1071

#### 1072 **6. Is there a plausible mechanism to have caused the events?**

1073 **Evidence assessment:** Additional information has been provided about pressure changes by  
1074 the operators of the Brockham oilfield, and information has been provided by the HH-1  
1075 operators about the flow testing in this well. Answer rating = 80%, reflecting the fact that  
1076 pressure estimates are based on data from wells, and that reservoir models could be constructed  
1077 to estimates how these pore pressure changes propagate through the reservoirs. The maximum  
1078 points scoreable is -4 or +4.

1079 **Answer:** The Brockham oilfield has experienced substantial pore pressure depletion during  
1080 initial production, although at present the average net fluid extraction rate (production –  
1081 injection) is 1 m<sup>3</sup>/day, which is an extremely low rate. Of more significance is the fact that the  
1082 Brockham reservoir is separated from the event locations by several fault blocks, the faults on  
1083 which are known to act as baffles as they provide seals for the oilfields in the region, and indeed  
1084 the reservoir unit is displaced significantly across these faults. Moreover, if pressure changes  
1085 at Brockham were in communication with the hypocenter locations, then they would also be  
1086 visible at the Horse Hill well (they are not). Therefore it is not plausible that any pore pressure  
1087 changes in the Brockham oilfield could have been transferred to the loci of the seismicity: -4.  
1088 At HH-1 the flow test volumes are small, and unlikely to have produced pore pressure  
1089 perturbations extending more than a few 100 m from the well. As such, they would not have  
1090 reached the loci of the seismicity: -4.

1091

1092 **7. Do the source mechanisms indicate an induced event mechanism?**

1093 **Evidence assessment:** Source mechanisms were determined for some of the final events to  
1094 occur in the sequence, which are reasonably well constrained by both polarities and amplitudes,  
1095 though there is some uncertainty given the limited station coverage. The regional stress  
1096 conditions are relatively well-constrained. Answer rating = 75%. The maximum points  
1097 scoreable is 0 or +3.

1098 **Answer:** The source mechanism is consistent with the regional stress state: 0.

1099

1100 **5.2.4. Newdigate using data available in October 2018: Summary**

1101 The assessment results for Brockham are shown schematically in Figure 10, while the  
1102 results for Horse Hill are shown in Figures 2 and 3. The Evidence Strength Ratio is calculated  
1103 for both the Brockham oilfield and HH-1 as:

1104 
$$ESR = \frac{(|-43|+|40.5|)}{96} \times 100 = 87\% \quad (11)$$

1105 The Induced Assessment Ratio, which assesses whether the available evidence points  
1106 towards an induced or a natural cause, is calculated for the Brockham oilfield as:

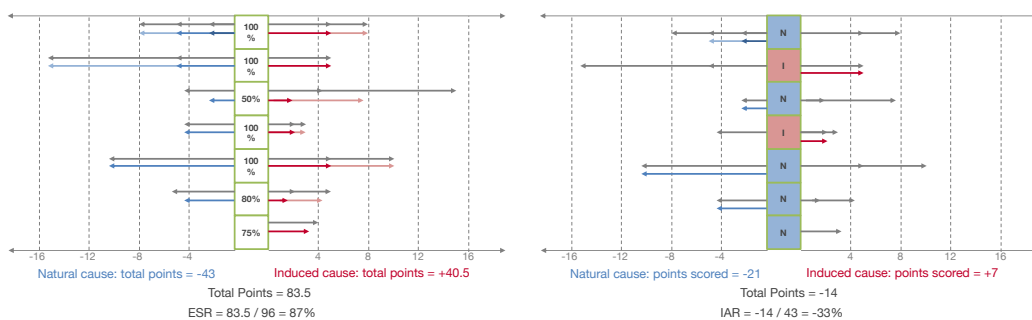
1107 
$$IAR = \frac{-14}{|-43|} \times 100 = -33\% \quad (12)$$

1108 and for the HH-1 well as:

1109 
$$IAR = \frac{-34}{|-43|} \times 100 = -79\% \quad (13)$$

1110 The negative IAR values indicate that neither Brockham nor HH-1 is a likely cause for  
1111 these events, and they are therefore natural, although the evidence against Brockham as a cause  
1112 is more ambiguous than the evidence against HH-1 as a cause. The high ESR value indicates  
1113 that this judgement is robust, and that most of the desired evidence is available.

1114



(a)

(b)

1115 *Figure 10: The results of our assessment as applied to the Newdigate sequence relative*  
1116 *to the Brockham oilfield, using data available in June 2018. In (a) we show the ESR assessment,*  
1117 *and in (b) we show the IAR assessment.*

1118

1119

## 1120 **6. CONCLUSIONS**

1121 The assessment as to whether or not a particular sequence of seismic events has been  
1122 induced by industrial activities in the subsurface may in many cases be controversial. In such  
1123 instances, a framework is required that allows stakeholders to perform this assessment in a  
1124 robust and quantifiable manner. Such a framework must meet a number of requirements: it  
1125 must provide results that are comprehensible to a variety of stakeholders; it must weight  
1126 different categories of evidence appropriately; it must incorporate different pieces of evidence  
1127 that may have different levels of uncertainty; and it must be flexible such that new questions  
1128 and new types of evidence can be readily incorporated. In this paper we describe a framework  
1129 that meets these objectives. The framework retains the simple, question-based format of  
1130 previous assessment schemes. However, rather than simple “yes” or “no” answers, the  
1131 questions are used to score positive or negative points, depending on whether the answers to  
1132 these questions indicate an induced or a natural cause. The number of points scored for each  
1133 question is scaled according to both the importance of the question being asked, and the level  
1134 of certainty with which the question can be answered. The results of this framework are  
1135 presented as two numbers: the Induced Assessment Ratio quantifies the summed answers to  
1136 the questions posed, with a positive IAR indicating the events are induced and a negative IAR  
1137 indicating the events are natural. The larger the absolute value of the IAR, the more  
1138 unambiguous the evidence is as to this conclusion. The Evidence Strength Ratio describes the  
1139 quality and quantity of evidence used to answer the questions, with a high ESR value  
1140 indicating that the evidence used in the assessment is robust.

1141 We have applied this framework to two case studies from the UK. In both cases we  
1142 present two assessments, the first during the sequences of seismicity when many pieces of  
1143 evidence were poorly constrained or not available. Nevertheless, at these times the regulator  
1144 was under pressure to make decisions regarding oilfield operations near to these sequences.  
1145 We then present a second assessment of each case using the full evidence base as is available  
1146 to us today. By doing so we demonstrate how our proposed framework captures the changing  
1147 levels and types of evidence via the ESR and IAR values.



1148           In closing, we note that the key development of this paper is the framework itself. We  
1149 recognize that other scientists and practitioners may wish to ask additional questions to those  
1150 specified here, or to change the relative score values assigned to the different questions, and  
1151 that their doing so will probably reflect our growing understanding of induced seismicity  
1152 going forward.

1153

#### 1154 **Data and Resources**

1155           The data pertaining to the two case studies presented here are derived from existing  
1156 literature, specifically Clarke et al. (2014) for Preese Hall, and Baptie and Luckett (2018) for  
1157 Newdigate.

1158

#### 1159 **Acknowledgements**

1160           We express our gratitude to the UK Oil & Gas Authority and the participants in the  
1161 workshops hosted on 3 October 2018 on the Newdigate earthquakes for prompting the work  
1162 presented in this paper. We would also like to thank Zhigang Peng and Cliff Frohlich for their  
1163 helpful comments and suggestions during the review process.

1164

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