Annexure "C"

OPINION ON INDUCED SEISMICITY RISK MANAGEMENT WITHIN THE PROPOSED REGULATIONS FOR EXPLORATION AND PRODUCTION OF ONSHORE OIL AND GAS REQUIRING HYDRAULIC FRACTURING TECHNOLOGY IN SOUTH AFRICA

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1. Introduction

This document provides my technical opinion; it shows how hydraulic fracturing for oil and gas has caused earthquakes around the world and then offers good practice guidelines for managing these risks. It then compares the proposed regulations and Minimum Information Requirements (MIRs) on onshore petroleum exploration and production out for consultation ("Consultation Documents") from the Department of Forestry, Fisheries, and Environment (DFFE) against the state-of-the-art good practice guidelines [DoFFE, 2025a; 2025b; 2025c]. It closes with a list of improvements regulators could make to the proposed regulations and MIRs to reduce risks from induced seismicity.

Earthquakes caused by human activity, known as 'induced seismicity,' pose serious risks. Shaking caused by hydraulic fracturing induced earthquakes is often strong enough to be felt, and in some cases has caused damage or injuries. The full extent of impacts from induced seismicity can vary significantly, but overall, the hazards and risks are similar to those caused by moderate magnitude earthquakes (M2-M5) in tectonic settings. In some cases, public concern over the perceived risks of these earthquakes has led to subsurface development moratoriums.

I begin by reviewing latest scientific evidence, which definitively shows that numerous human activities can create changes in the subsurface significant enough to trigger earthquakes. These activities include wastewater injection, gas storage, fluid extraction, mining, and enhanced geothermal systems. More recent scientific evidence indicates that hydraulic fracturing for oil and gas also causes seismicity.

Next, I outline recommended policies that are available to manage the risks of induced seismicity. These recommendations follow prior experiences with hydraulic fracturing cases in North America, and previously developed guidelines. Broadly, these recommendations for effective risk management and mitigation can be reduced to two major components: (i) a risk-based traffic light protocol (**TLP**), and (ii) robust and transparent earthquake monitoring.

i) A TLP requires operators to change or pause (yellow-light), and then stop (red-light) their activities if earthquakes grow in size/frequency alongside operations. I discuss state-of-the-art, good practice guidelines for designing TLP protocols, including the importance of open dialogue and interaction between regulators, operators, experts, and academics, criteria for establishing risk-based red-light and yellow-light thresholds, and mitigation strategies during yellow-light events.

ii) An earthquake monitoring system must be transparent and include enforcement mechanisms (*i.e.*, compliance assurance), open data sharing, and active participation from regulators, operators, and experts in compiling and providing these data. I detail key features of an effective monitoring network, and offer a specific, real-world example that employs these good practices.

Finally, I examine the relevant South African literature on earthquakes alongside the proposed regulations for hydraulic fracturing-induced seismicity within South Africa. The evidence suggests that induced seismicity caused by hydraulic fracturing is more likely than not in the Karoo Basin (*i.e.*, the prime target for hydraulic fracturing in South Africa). In terms of risk management, the government of South Africa currently does not have either a TLP designed or an adequate monitoring system in place. Moreover, the broader proposal for managing induced seismicity reflected in the Consultation Documents is based on outdated science and fails to take the risks of hydraulic fracturing induced seismicity seriously. I recommend that South Africa rebuild its requirements for mitigating induced seismicity from hydraulic fracturing, including by embedding a TLP into its regulatory framework and ensuring that their earthquake monitoring system is robust and transparent at both regional and local levels. I conclude this brief by summarizing a series of recommendations for the Consultation Documents, focused on the good practices of the TLP and earthquake monitoring system that are presently absent in the regulatory proposal.

2. Qualifications

On the topic of induced seismicity, I am an internationally recognized expert. Currently I am a senior researcher and co-lead the Induced Seismicity Group within the Swiss Seismological Service at ETH Zürich (Eidgenössische Technische Hochschule Zürich). There, I am interested in understanding induced seismicity – both in terms of fundamental research and practical solutions. Research themes include identifying cases of induced seismicity, understanding the conditions/physics leading to fault reactivation, modelling/forecasting seismic response, examining operational procedures for mitigating seismic risk, building risk-informed control systems, and guiding best practices. Ultimately, this research is aimed at better managing the risks of these earthquakes.

My first professional role was as a seismologist at the Alberta Geological Survey in Canada, starting in 2012 and continuing for approximately 8 years. During this time, I was responsible for the creation of Alberta's seismic monitoring network, cataloguing earthquakes, identifying induced seismicity cases, understanding the operational and geological factors driving these earthquakes, and developing regulations. This work was in support of the Alberta Energy Regulator, and their concerns over induced seismicity in Alberta. In Alberta, earthquakes were predominantly induced by hydraulic fracturing for oil and gas. Following this endeavour, I completed my Ph.D. at Stanford University. My thesis entailed the creation of a risk-based design for TLPs. Since the creation of this concept, it has been adopted within good practice guidelines, including by regulators improving their decision-making processes, and industry groups concerned with earthquake risks. My past experience has exposed me to a wide range of perspectives on the problem of induced seismicity.

I have recently applied my expertise to the proposed regulations within the Karoo Basin of South Africa and am familiar with the local monitoring [CG South Africa, 2005; Saunders et al., 2008] and relevant scientific literature [Durrheim et al., 2006; Krüger & Scherbaum, 2014; Kijko et al., 2016; Whitehead et al., 2026]; my opinions and recommendations are informed by this understanding. Furthermore, I have no conflicting interest in the outcome of this decision, no financial ties to industry in South Africa, or any other vested interests. My recommendations are motivated by a desire to resolve the problem of induced seismicity and to help those impacted by its consequences. Opinions expressed are solely my own and do not express the views or opinions of my employer.

3. Fully accepted scientific evidence shows that hydraulic fracturing can induce earthquakes

Natural earthquakes predominantly occur at the tectonic boundaries or ‘faults,’ which are large pieces of the Earth’s crust that are slowly moving against one another. When stress between these plates builds up, the stored energy is released in a sudden and violent event: an earthquake. That said, earthquakes can also occur well within these plate boundaries (*i.e.*, intra-cratonic), since the Earth’s crust is abundant in faults. Induced seismicity is a type of intra-cratonic earthquake that is caused by human activity.

Induced earthquakes were first recognized in 1894, following ground shaking felt in Johannesburg (South Africa), which researchers later linked to nearby gold mining operations [McGarr et al., 2002]. A pair of studies linking seismic events to wastewater disposal in Colorado were the first well-documented cases of induced seismicity: the first case established that seismicity was correlated to a wastewater disposal operation [Healy et al., 1968], while the second case verified that human activities could cause earthquakes through a controlled injection experiment [Raleigh et al., 1976]. Today, thousands of cases have been identified, from multiple types of human activity [Foulger et al., 2018]. Known causes of induced seismicity include mining, reservoir impoundment, groundwater extraction, conventional petroleum production, wastewater disposal, underground storage of various gases, enhanced geothermal systems, and hydraulic fracturing. Effectively, any operation that has the potential to change stresses or forces in the subsurface also has the potential to reactivate faults to produce an earthquake [Moein et al., 2023].

Operations that inject fluids underground can cause earthquakes [Ellsworth, 2013]. As an operation injects fluids, it causes pore pressure increases in the subsurface. This pressure increase can migrate laterally, diffusing through permeable rock and potentially reaching great distances (tens of kilometers from the original injection site). Pressure increases may even travel far enough to encounter a fault. Pressure increases on a fault have the potential to reactivate them: the increase of pressure acts against the forces clamping a fault closed, effectively reducing them. This disturbs the frictional balance between clamping forces and sliding forces, moving the fault closer to sliding/slip conditions. The reactivation of a fault can be expressed as an earthquake.

Pressure increases required for reactivation can be small, since significant stresses are already stored on the fault from tectonic/geological processes. Essentially, the human activity only needs to trigger the slip process, rather than drive it, to reactivate an already stressed fault. In fact, even gravity-fed injection wells, which are relatively low-pressure, have been documented to cause earthquakes [Rubinstein & Mahani, 2015]. Faults are also surrounded by broken/damaged rock, due to their ancient histories of sliding and deformation. This ‘damage zone’ has the potential to allow vertical migration of pressure, potentially channeling fluid to the more susceptible parts of a fault [Galloway et al., 2018].

Hydraulic fracturing is an operation that injects fluids underground at pressures high enough to break nearby rock. The build-up of fluid pressure splits the rock, creating new fractures (Figure 1). This technique has been used for the extraction of hydrocarbons that are trapped in impermeable (or ‘tight’) rocks. If these growing fractures encounter a fault, then this pressurization mechanism can also reactivate a fault, potentially producing an earthquake (Figures 1 & 2).

Today, it is well-established that hydraulic fracturing for oil and gas has indeed caused earthquakes [Atkinson et al., 2016]. Hundreds to thousands of cases have been observed across disparate geological basins and tectonic settings throughout the world [Schultz et al., 2020a; Atkinson et al., 2020]. A non-exhaustive list of hydrocarbon basins where hydraulic fracturing has induced seismicity includes the Horn River Basin (Canada), Bowland Shale (UK), Duvernay Formation (Canada), Montney Formation (Canada), Utica Shale (USA), Marcellus Shale (USA), Eagle Ford Formation (USA), Delaware Basin (USA), Neuquén Basin (Argentina), and Sichuan Basin (China). There are likely more basins where hydraulic fracturing is causing earthquakes than currently recognized, since seismological monitoring is often lacking within the intra-cratonic settings where hydraulic fracturing occurs.

Research has identified some factors showing when and how often hydraulic fracturing will induce seismicity [Schultz et al., 2020a; Atkinson et al., 2020]. First, at the basin scale, only a minority (less than approximately 1%) of hydraulic fracturing wells tend to cause earthquakes, although this fraction can be larger (up to tens of percent) in earthquake prone regions. Researchers have attributed the scarcity of wells triggering earthquakes to the uniqueness in geological conditions required for fault reactivation [Schultz et al., 2018; Pawley et al., 2018]. Despite this low chance for any individual well to trigger an earthquake, however, the overall likelihood of encountering substantial earthquakes remains high for the whole basin. In a typical basin where tens of thousands of wells may be stimulated, it is common for hundreds of wells to cause earthquakes.

While many hydraulic fracturing operations do not produce earthquakes, the ones that do can experience relatively large events. For example, basins where seismic activity is linked to hydraulic fracturing have reported events up to M4 or larger. Specific to earthquakes caused by hydraulic fracturing, cases have reported felt events as small as M_L 1.5 [Edwards et al., 2021]. One of the largest published events linked to hydraulic fracturing was a M_L 5.7 earthquake in the Sichuan Basin of China on 16 December 2018 [Lei et al., 2019]. Moreover, in many seismogenic basins around the world, hydraulic fracturing-induced earthquakes have become the dominant source of seismicity.

Note that earthquake magnitude measures the relative size of an earthquake on a logarithmic scale[1]. This means that each magnitude unit increase represents an exponential—not linear—growth in shaking intensity and energy release [USGS, 2025]. For example, an M5 earthquake would generate 10 times as much ground shaking and release 32 times as much energy as an M4 event. Likewise, the same exponential relationship would apply for an M2 event as compared to an M1 event.

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[1] There are various magnitude scales, some of which are used in this opinion in reference to past seismic events. Local magnitudes (M_L) are a historical measurement that use the (distance corrected) amplitude measured on a Wood-Anderson seismometer; for practical reasons this magnitude scale persists. Moment magnitudes (M_W) are based on a logarithmic scaling of seismic moment, which is a physical parameter related to the size of the earthquake; M_W is the preferred magnitude scale. Sometimes a generic M is used when the magnitude type has not been specified.

See also this link for further details: http://www.seismo.ethz.ch/en/knowledge/faq/which-types-of-magnitude-do-we-distinguish/

Those earthquakes induced by hydraulic fracturing tend to be close to the wells that cause them (within hundreds of meters), as stimulated fractures need to connect to reactivatable faults. The furthest published case is approximately 1.5 km for hydraulic fracturing [Schultz & Wang, 2020] and approximately 4.0 km for an analogous geothermal system [Schmittbuhl et al., 2021], although undocumented cases at further distances may exist.

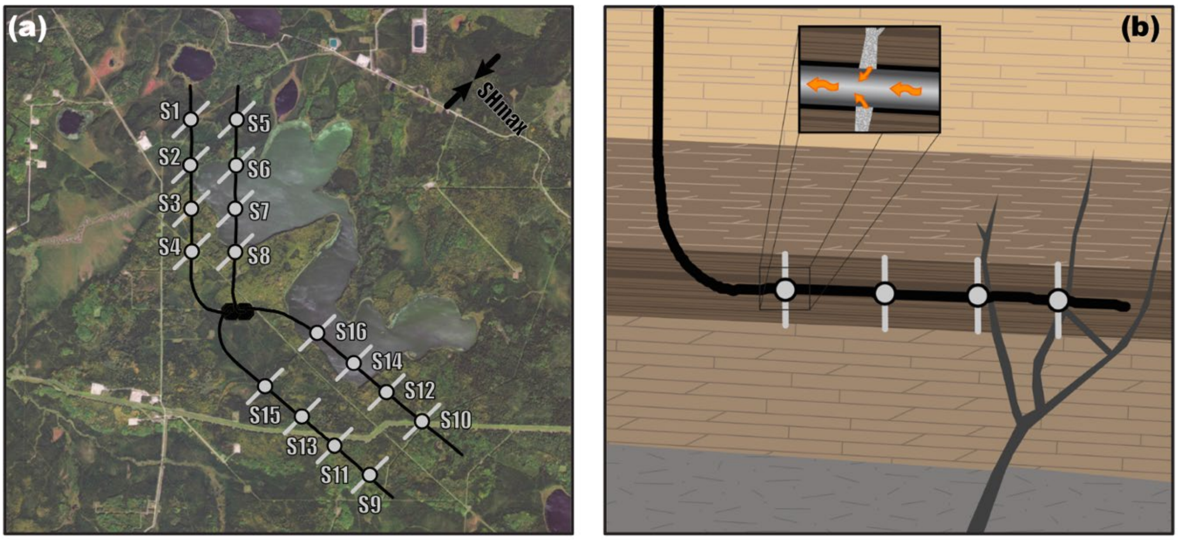

Figure 1. Schematic diagram showing a hydraulic fracturing operation that is susceptible to causing earthquakes. (a) Map view of a four-well (black lines) pad with 16 completed stages (gray lines). (b) Depth view showing a well lateral (black line) and four-stages (gray lines) that fractured the target formation (darkest brown strata); only the right-most stages are connected to a fault (dark gray lines). Inset diagram shows hydrocarbons (orange arrows) entering the wellbore (black/gray cylinder), via stimulated fractures in the target formation. Figure is from a prior study [Schultz et al., 2020a].

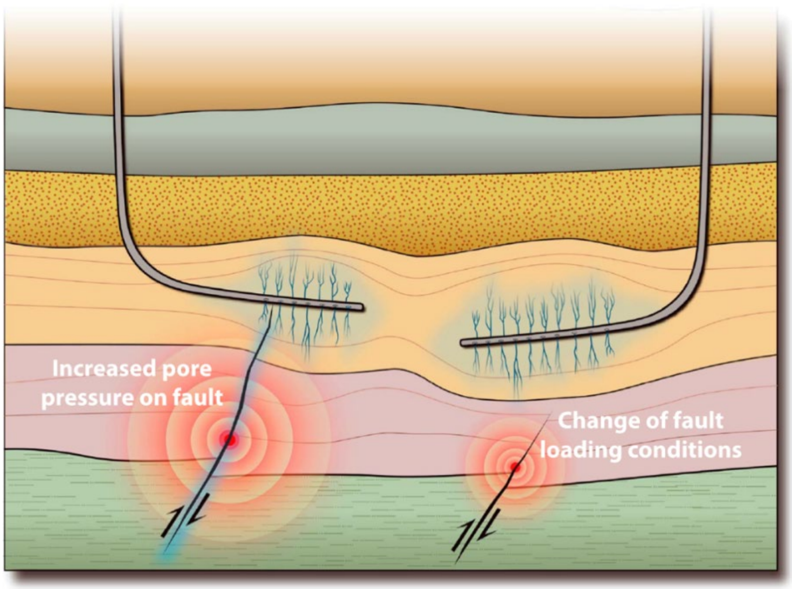

Figure 2. Conceptual diagram showing how hydraulic fracturing induces earthquakes. Stimulated fractures are connected to a critically stressed fault; when hydraulic fracturing occurs the increase of pressure opens the fault, making it more likely to slip. Figure is from a prior study [Schultz et al., 2017].

3.1. Fully accepted scientific evidence shows that induced earthquakes have the potential to cause nuisance, damage to buildings, injuries, and fatalities

In general, ground shaking from earthquakes has the potential for catastrophic consequences, including damage to buildings, injuries, and fatalities. The severity of these consequences depends on multiple factors, the most important of which are earthquake magnitude and distance from the earthquake [Atkinson, 2015]. Other factors that can influence the severity of ground shaking include basin effects, near site geology, and local site effects. The severity of risks and consequences can further vary based on the amount of assets exposed to the hazard and how fragile those exposed assets are [Bommer, 2022]. More plainly, earthquakes with similar ground shaking hazards can generate different risks depending on location – for example, the consequences will be radically different in a case where an earthquake occurs in a remote desert or, in contrast, directly underneath an unprepared city. While large magnitude events are more destructive, moderately sized earthquakes (as small as M4) have been associated with damage to buildings [Nievas et al., 2020]. Important, albeit somewhat less consequential, nuisance impacts (*e.g.*, felt ground shaking) can result from events as small as M1-2, in favourable settings. For example, earthquakes caused by hydraulic fracturing have resulted in felt events as small as M_L 1.5 [Edwards et al., 2021].

Hazards and risks from induced seismicity can be similar to those resulting from comparable tectonic earthquakes. Damage to buildings from induced events in the Netherlands from gas extraction (up to M_L 3.6) resulted in the company NAM (an operation of Shell and ExxonMobil) being liable for hundreds of millions of euros of compensation to affected homeowners and businesses [van der Voort, 2015]. In another example, earthquakes induced by hydraulic fracturing for geothermal energy in Pohang, South Korea resulted in a M_W 5.5 earthquake [Grigoli et al., 2018]; consequences there included at least ~$75M USD in damages, 1,124 displaced residents, 82 injuries, and 15 hospitalizations [Ellsworth et al., 2019]. However, research has also shown that moderately sized induced earthquakes in more remote settings, such as one M_L 5.6 event near Peace River in Canada, may also result in no reported building damages, likely because there are fewer nearby people and structures to affect [Schultz et al., 2023]. Specific to earthquakes caused by hydraulic fracturing for oil and gas, the 16 December 2018 earthquake (M_L 5.7) in the Sichuan Basin of China resulted in 17 injuries and up to ~$7M USD in direct economic losses, and triggered landslides and rock collapses [Lei et al., 2019]. In many cases, subsurface projects have been terminated due to earthquake risks encountered during the operation [Foulger et al., 2018].

4. Frameworks to manage the risks of hydraulic fracturing induced seismicity

Proper risk management plans are needed for any basin in which hydraulic fracturing creates a likely risk of induced seismicity, to ensure that earthquake risks are either avoided or effectively mitigated.

While there is no 'silver bullet' to entirely prevent earthquakes, there are 'good practice' guidelines for management. These guidelines are based on state-of-the-art science that governments should implement in regions encountering induced earthquakes [Majer et al., 2013; National Research Council, 2013; Zhou et al., 2024]. For hydraulic fracturing-induced seismicity, the two core elements are: (1) the implementation of a traffic light protocol (TLP); and (2) the deployment of a robust and transparent monitoring system.

It's important to highlight that these good practices are necessary because a failure to properly manage induced seismicity can lead to a build-up of public tensions against hydraulic fracturing, spurring a loss of 'social license,' and creating the potential for extreme countermeasures. For example, gas production in the Groningen Field of the Netherlands has caused decades worth of induced earthquakes, the largest being the M_L 3.6 Huizinge event on 16 August 2012 [Muntendam-Bos et al., 2022]. Social unrest over these events eventually spurred the decision to abandon this field [van der Voort, 2015], stranding ~800 billion m^3 of gas in place [Muntendam-Bos et al., 2022]. An official inquiry into the induced earthquakes at the Groningen gas field found that the safety of citizens appeared to have no influence over decision-making, operators/regulators failed to apply uncertainty reduction as a guiding principle for their actions, and operators/regulators did not transparently communicate relevant information to impacted stakeholders [Dutch Safety Board, 2015; Tweede Kamer der Staten-Generaal, 2023]. These failures contributed to the growth of earthquakes in the Groningen, social tensions around the events, and ultimately the decision to abandon gas production.

In another example, development of hydraulic fracturing in the UK is currently banned because of induced seismicity [Baptie et al., 2022]. Three operations have been attempted, with a contentious history of seismicity and social unrest. The third operation resulted in a M_L 2.9 earthquake on 26 August 2019 [Kettlety et al., 2021], which triggered the development moratorium.

There are several relevant parties for induced seismicity management: the operator(s), regulator, independent expert groups, interested stakeholders, and impacted public. Good practice guidelines for induced seismicity outline the roles for these groups [Majer et al., 2013; National Research Council, 2013; Zhou et al., 2024]. The operator is responsible for the safe execution of their operation, while complying with all regulations. The regulator is responsible for creating the guidelines that operators will follow, while also ensuring compliance with regulations. Independent expert groups provide input for guiding decision-making or risk-reduction strategies, while also providing new research insights. Vendors will often be hired by the operators to fill professional needs, such as earthquake monitoring services. Overall, transparency is key to fostering trust amongst these groups.

There are useful examples of detailed risk-reduction plans for induced seismicity that adhere to these good practices. One such operational plan was developed for a geothermal hydraulic fracturing experiment at Utah FORGE [Pankow et al., 2023]. Geothermal hydraulic fracturing is analogous to hydraulic fracturing for oil and gas, and this example can therefore serve as a comprehensive template for oil and gas hydraulic fracturing operations to follow. A detailed regulatory plan that covers most good practices for hydraulic fracturing induced seismicity management is also available for comparison from the Northern Territory of Australia [Northern Territory Government, 2025].

4.1. The design and implementation of a risk-based traffic light protocol (TLP)

Traffic light protocols (TLPs) are the most common framework used to mitigate induced seismicity caused by hydraulic fracturing [Schultz et al., 2020a]. Typically, the TLP establishes three thresholds labelled as red-, yellow-, and green-lights, based on the current level of seismic activity in a region of hydraulic fracturing activity. Usually, these three thresholds are pre-defined magnitude values. While within the green-light, an operator is allowed to proceed uninhibited. If an operation triggers the yellow-light threshold, the operator must execute mitigation strategies to reduce the frequency and magnitude of induced earthquakes, for example, by limiting injected fluid or pausing operations within a set time period. The red-light threshold is the last possible stopping-point before exceeding an intolerable amount of risk. Operators triggering the red-light threshold are subject to regulatory intervention; often, requiring the operator to abandon any further fracturing in a given area.

The first TLP was designed to manage earthquakes caused by geothermal operations in the Berlín geothermal field in El Salvador [Bommer et al., 2006]. To date, many jurisdictions have implemented TLPs for a variety of induced seismicity causes. For hydraulic fracturing, TLPs have been implemented in Alberta (Canada), British Columbia (Canada), Ohio (US), Oklahoma (US), and the UK [Schultz et al., 2020b]. Red-light thresholds have varied between 0.5-4.0 M_L, depending on the jurisdiction.

The separation of roles between regulator and operator for defining, implementing, and executing a TLP are vital to ensuring conflicts of interest are avoided. Thus, it is important that the regulator explicitly define what is an intolerable level of risk and subsequently set the red- and yellow-light thresholds that follow. These choices should fall within the mandate of a regulator to enforce safe and responsible development. Regulators should also ensure compliance via a mandatory system of industry reporting, verification, and audits. The responsibility of executing an operation within the TLP bounds lies first with the operator. Often, the operator is also responsible for detailing yellow-light mitigation strategies, since they are most knowledgeable about the particulars of their operation and the local subsurface.

While there are different ways to decide on TLP thresholds, a growing body of research is showing the benefits of grounding TLP designs in seismic risk principles. Under these principles, regulators should first explicitly define acceptable tolerances to risks of nuisance, damage to buildings, or human losses before operations begin (Figure 3). Then, seismic risk modelling can be used to define magnitude-based red-light thresholds [Schultz et al., 2021a], relying on information on ground shaking estimation, site amplification, hazard exposure, and asset vulnerability to appraise and model seismic hazards and risks [Bommer, 2022]. Crucial to this process is adequately capturing the potential for trailing seismicity: aftershock-like earthquakes that continue to occur after an operation has stopped [Verdon & Bommer, 2021; Schultz et al., 2022]. To account for the effects of trailing seismicity, operators will need to stop before encountering an intolerable risk. Models used to estimate red-light thresholds from risk tolerances will need to be updated as new information is acquired. It is noteworthy to highlight that many TLPs have also included supplementary red-light metrics (*e.g.*, ground shaking intensity, rates of seismicity, spatial orientations of earthquakes) to better assess risk potential and alleviate weaknesses in the model [Zhou et al., 2024].

The choice of the yellow-light threshold can then be set based on the red-light threshold (Figure 3). The intention of the yellow-light threshold is to serve as a buffer to ultimately avoid encountering a red-light event. In this sense, the yellow-light threshold needs to be far back enough from the red-light threshold to avoid large 'jumps' in magnitude that go straight from green to red. One of the key considerations in developing these thresholds is the natural variability in magnitudes that arises because of their statistical distribution [Gutenberg & Richter, 1944]. This can be used to quantify the expected range of jumps in magnitude. Studies have measured this variability in magnitude jumps for induced seismicity cases [Verdon & Bommer, 2021], and then integrated it into models for further use with TLPs [Schultz et al., 2022]. Typically, TLPs for hydraulic fracturing have differences of 1.0-2.0 M_L between red/yellow-light thresholds to account for these jumps [Schultz et al., 2021b]. It is noteworthy that jumps in magnitude greater than 2.0 M_L have been observed for hydraulic fracturing induced seismicity before [Schultz & Wang, 2020].

The yellow-light provides the opportunity for an operator to enact their mitigation strategies, to avoid encountering a red-light while still conducting injection activities. Typical mitigation strategies entail defining a new injection plan that reduces injection rates and/or pressures, ensuring that changes to the injection rate are made gradually rather than quickly, operational pauses, reorganizing the stage schedule, changing injection designs, allowing for flowback between stages, reducing total injection volume, skipping problematic stages, or ultimately pad/well abandonment [CAPP, 2019]. Other strategies to reduce the harm (or perceived harm) of induced seismicity have included public outreach, relocation of infrastructure/personnel, building retrofitting, or financial compensation schemes.

Unfortunately, the efficacy of these mitigation strategies is still poorly understood. No empirical studies quantifying or ranking the effectiveness of these measures exist. Thus, no models to estimate their effectiveness exist either, despite the obvious importance for risk management. Nonetheless, the implementation of some kind of mitigation strategy, with adequate supervision by the regulator, is far better than requiring no mitigation strategy at all. Ultimately, this deficiency highlights the need for open and transparent datasets – and the importance of interaction between industry, regulators, and academics. For example, future studies (facilitated by open data sharing) could quantify the effectiveness of mitigation strategies. These results can guide future best practices, which inform future regulation and industry practices.

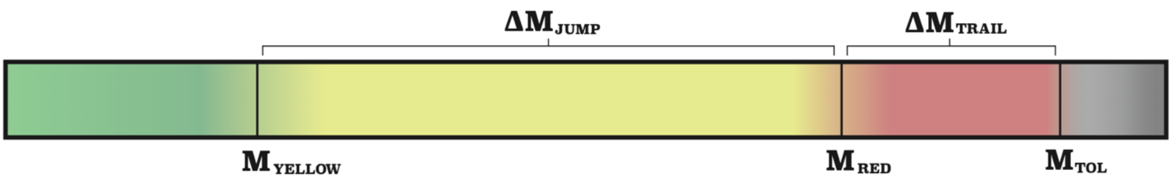

Figure 3. Schematic framework for a risk-based TLP design, using magnitude thresholds. Risk-based principles are first used to define the magnitude M_{TOL} that will exceed a predefined intolerable level of risk. Then the red-light threshold (M_{RED}) can be defined by setting far back enough from M_{TOL} to compensate for trailing seismicity. Finally, the yellow-light threshold ($M_{YELLLOW}$) can be defined by setting it far back enough from M_{RED} to compensate for magnitude jumps. Figure is from a prior study [Zhou et al., 2024].

4.2. Effective earthquake monitoring for ensuring compliance

Effective earthquake monitoring is vital to ensuring safe and responsible operations, properly executing a TLP, reducing subsurface uncertainties, reporting to authorities, enforcing compliance, and building trust amongst the impacted community. For example, executing a TLP crucially depends on a feedback process: operators and regulators monitor for earthquakes during injection and then react to incoming earthquake information, relative to the TLP thresholds. Proper reporting and enforcement also need well-calibrated and verified catalogues of earthquakes that perform at least well enough to execute the TLP.

At a minimum, the regulator must have access to a 'backbone' monitoring network. Backbone monitoring provides coarse, basin-scale monitoring of earthquakes. This backbone monitoring network should be used to establish a baseline of natural seismicity before any hydraulic fracturing operations commence. After operations commence, this monitoring system serves the dual purpose of identifying new regions of induced seismicity and for the regulator to independently ensure industry compliance. Thus, this backbone monitoring system must be sensitive enough to detect all yellow-light events while also be precise enough to unambiguously attribute them to the correct source [Zhou et al., 2024]. Prior documents outline an example of this type of monitoring [Ward et al., 2020]. Accomplishing this attribution task requires a complete and fine-scale database of subsurface operations to cross-reference against earthquake catalogues. Specific to hydraulic fracturing, required operational data includes the well locations and their subsurface trajectories, alongside locations of individual stages and corresponding timings of injection rates/volumes. All of this information should be immediately and openly accessible to the public.

In regions of induced seismicity, operators are responsible for the deployment and maintenance of a 'local' seismic monitoring network. This local network is in addition to and independent from the backbone. Operators typically contract vendors to provide this service, with either multiple operators pooling funds to receive this service collectively, or individual operators developing one-on-one contracts with these seismic contractors. Data collected from the local network is used to create a real-time catalogue of earthquakes. This real-time catalogue is sufficiently fine scale to inform the operator of how they must change their operations to stay within the definitions of the TLP. This includes the implementation of yellow-light mitigation strategies, and shut-in procedures if a red-light event occurs. In many cases, this requires attribution of earthquakes to individual stages and the delineation of faults [CAPP, 2019; Zhou et al., 2024]. Because of these increased requirements, the local network typically requires greater sensitivity and resolution than the regional backbone network. Data from the local network should also be accessible to the public.

Broad participation from independent expert groups, interested stakeholders, and the impacted public help ensure the effectiveness of monitoring. Good practice guidelines for induced seismicity detail broad overarching roles for these groups [Majer et al., 2013; National Research Council, 2013; Zhou et al., 2024]. For example, independent expert groups provide input for guiding decision-making or risk-reduction strategies, while also providing new research insights. Depending on the jurisdiction, operators and regulators may not have in-house expertise for earthquake monitoring. In this case, independent groups or vendors may be consulted. For example, regulators have often reached out to independent expert groups like geological surveys, national monitoring agencies, or research institutions for their monitoring needs. Meanwhile, as noted above, operators commonly employ professional seismological vendors to develop and manage the local networks.

Transparency is key to fostering trust amongst these different actors. Transparent communication is also required with the impacted public, so that they can make informed decisions about ongoing operations. Importantly, the open and transparent sharing of information is required because many unanswered questions around the physical process and risk management of induced seismicity still linger. Neither regulator nor industry (typically) have the in-house expertise to resolve these questions. Ensuring data is transparently shared allows independent expert groups to examine past cases, providing both independent verification of past interpretations and new methods to improve risk management of induced seismicity. This cross-examination from independent groups also helps to foster trust.

To ensure transparency, all monitoring networks and data should be shared openly using FAIR (Findability, Accessibility, Interoperability, and Reusability) principles [Wilkinson et al., 2016]. These principles require that data are permanently stored in a repository that can be easily found and then shared in an automated and readily accessible fashion (*i.e.*, without the need for human interaction or data requests).

To exemplify how split responsibilities and transparency work in reality, we can look to Alberta, Canada, where the regulator and operators have followed these practices to both manage and learn from induced seismicity caused by hydraulic fracturing. The Alberta Geological Survey performs regional backbone seismic monitoring, as an expert group in support of the Alberta Energy Regulator. Alberta's provincial seismic network (RAVEN: https://doi.org/10.7914/SN/RV) spans the entire province, in order to identify new cases of induced seismicity and to independently ensure that operators are complying with regulations [Schultz & Stern, 2015; Schultz et al., 2015]. All data from RAVEN is immediately made publicly available, via online access portals that are standard practice in seismology. For finer-scale monitoring, operators subscribe to data from 'local' networks managed by private vendors. As part of the regulator's commitment to transparency, all local seismological data required for regulatory compliance must be openly shared: immediately with the regulator and after one year with the public. To facilitate this, a seismological network (SCISMN: https://doi.org/10.7914/eeh3-2y80) was created to house the data; there, anyone can access this information [Schultz et al., 2020c].

4.3. Summary of key requirements for the effective management of induced seismicity caused by hydraulic fracturing

This section summarizes the key requirements for effective management of induced seismicity caused by hydraulic fracturing, namely, a risk-based TLP partnered with robust and transparent earthquake monitoring. This summary primarily adopts recommendations provided in prior good practice guidelines [Majer et al., 2013; CAPP, 2019; Zhou et al., 2024].

- A risk-based TLP
    - A TLP should provide regulatory definitions of when an operation should change (yellow-light threshold) and ultimately stop (red-light threshold) in reaction to earthquakes.
    - The intolerable level of risk should be explicitly defined by the regulator, before operations commence. This information should be publicly accessible.
    - Red-light thresholds should be designed in consideration of risks of nuisance, damage to buildings, and fatality – to ensure that intolerable risks are avoided, even if 'trailing' seismicity occurs after injection has stopped.
    - Yellow-light thresholds should be designed to ensure operators have enough 'space' to enact mitigation strategies that avoid triggering a red-light.
    - Operators should develop their yellow-light mitigation strategies and red-light procedures for halting operations (shut-in); these plans should be submitted for regulatory approval, before starting operations.

- Robust and transparent earthquake monitoring
    - An independent, public agency should maintain a regional 'backbone' monitoring system. This system provides coarse, basin-scale monitoring of earthquakes that the regulator can rely on to independently ensure industry compliance with the TLP and to identify new regions of induced seismicity.
    - Backbone monitoring should be of sufficient resolution to identify all earthquakes that surpass both the yellow-light and red-light thresholds, and to determine their cause without ambiguity.
    - In addition, operators should be responsible for 'local' monitoring of their sites, to properly implement mitigation strategies during the yellow-light of the TLP.
    - Local monitoring efforts should be of a resolution sufficient to effectively execute the TLP and planned mitigation strategies, to adequately reduce induced seismicity risks.
    - All data should be shared openly and transparently, using FAIR (Findability, Accessibility, Interoperability, and Reusability) principles.
    - Open data is important for ensuring compliance and enabling research from independent expert groups that can improve risk management.
    - Operational data also needs to be shared transparently, to identify the specific operations that induce earthquakes.

5. Induced seismicity considerations for South Africa

Intraplate seismicity is a relatively common occurrence in South Africa [Manzunzu et al., 2019]. The largest recorded earthquake (M_W 6.3) occurred in Ceres–Tulbagh region of Cape Province and was recorded on 29 September 1969 [Krüger & Scherbaum, 2014]. This event was accompanied by casualties, damage, and aftershocks up to M_W 5.7. In fact, this event spurred the initial deployment of the South African National Seismograph Network (SANSN) [Saunders et al., 2008]. Paleoseismic studies indicate that even larger events occurred along the Kango Fault, before instrumental records existed [Goedhart et al., 2016]. These observations demonstrate that South Africa can host significantly sized earthquakes.

Induced seismicity has a historical precedent in South Africa. Induced earthquakes were first recognized in 1894, following ground shaking felt in Johannesburg, which researchers later linked to gold production near Witwatersrand [McGarr et al., 2002]. These events have continued for decades. One notable mining-induced event (M_L 5.3) occurred on 9 March 2005, causing serious damage to buildings and minor injuries to people in the nearby town of Stilfontein [Durrheim et al., 2006]. These observations indicate that South Africa can also host impactful induced earthquakes.

5.1. The potential for induced seismicity in the Karoo Basin

The hydraulic fracturing prospects primarily target the Karoo Basin at present, making a review of the present state of seismicity in this basin particularly important [Scheiber-Enslin et al., 2016]. For example, a swarm of earthquakes occurred near Leeu Gamka from 2007-2022; the largest event was M_L 4.8 [Whitehead et al., 2026]. The earthquakes tend to be concentrated within the Beattie magnetic anomaly, which runs along the entire southern portion of South Africa [Scheiber-Enslin et al., 2014]. These earthquakes are hosted along a subvertical WNW-ESE strike-slip fault from, with depths from 2.4-12.1 km which is within the Karoo Supergroup sediments to the shallow crystalline basement [Whitehead et al., 2026]. These observations show that the Karoo Basin has pre-existing faults, some of those faults are connected to the hydraulic fracturing development intervals, these faults are implicated in subsurface fluid flow, and they can host earthquake swarms – all the conditions needed to cause induced seismicity. This also means that special care will need to be taken during monitoring, to distinguish natural events from induced ones.

Taken together, there is no credible reason to expect that hydraulic fracturing induced seismicity would not occur in the Karoo Basin. To the contrary, this basin exhibits more susceptibility indicators than other basins that have already encountered induced earthquakes. Thus, regulations should be designed with the expectation that these earthquakes will occur, rather than reacting if or when they do.

6. Critique of the proposed hydraulic fracturing induced seismicity regulations and measures for addressing them

I reviewed three of the proposed regulations ("Consultation Documents") for governing hydraulic fracturing in South Africa published in the Government Gazette in 2025 [DoFFE, 2025a; 2025b; 2025c] to understand whether the proposals rely on best available science and would minimize risks from induced seismicity. In the subsections that follow, I first explain why the science that the Consultation Documents depend on for the regulations on induced seismicity is outdated, and second highlight the gaps between the regulatory proposals and the good practice for managing seismicity risks.

I conclude based upon this review that the management of induced seismicity proposed in the Consultation Documents suffers from an underestimation of the risks of induced seismicity, stemming from a reliance on outdated science. As a result, the regulatory proposal fails to take this risk seriously, leaving out essential requirements for effective management of induced seismicity. For example, the proposal seems to suggest that operator-led efforts, like local monitoring and periodic reports will be sufficient for managing seismicity. Cases from around the world show that such minimal regulation of induced seismicity can result an erosion of the social license to operate; the regulator needs to take an active role in monitoring, communication, and enforcement. As a result, I encourage DoFFE to reframe and rebuild the requirements for addressing induced seismicity in the Consultation Documents, by grounding their regulations in the current understanding of science and good practice. The subsections that follow reflect key changes that should be part of this rebuilding process.

6.1. Corrections to the scientific understanding of induced seismicity in the proposed regulations

In this section, I provide some critiques of statements regarding the scientific understanding of induced seismicity caused by hydraulic fracturing, as described by the Consultation Documents [DoFFE, 2025a; 2025b; 2025c]. Many statements within the documents stand in contrast with the state-of-the-art understanding. My critiques focus predominantly around the section that most comprehensively describes how the regulations would reduce induced seismicity risk namely, Section 2.14 of the Minimum Information Requirements Consultation Document (starting on Page 139) [DoFFE, 2025b].

- <u>Claim</u>: *Induced seismicity is most often associated with wastewater injection projects.*
  <u>Correction</u>: This statement stems from initial observations (and statements from the United States Geological Survey); it is specific to induced seismicity in Oklahoma and restricted to observations up to ~2015. Since then, this perspective has been challenged by the facts in several basins. For example, hydraulic fracturing for oil and gas has also been shown to cause earthquakes of similar size to wastewater disposal events [Schultz et al., 2020]. Furthermore, in the Western Canada Sedimentary Basin, hydraulic fracturing is the predominant source of seismic activity, as compared against other sources like wastewater disposal. Which type

of operation tends to produce more impactful earthquakes appears to be basin-specific.

- <u>Claim</u>: *Noting that few seismic events of notable impact have taken place in South Africa historically …*
  <u>Correction</u>: Seismic events causing damage, injury, and loss of human life have already occurred in South Africa, both from natural and induced earthquakes. Examples include the M_W 6.3 Ceres–Tulbagh tectonic event in 1969 [Krüger & Scherbaum, 2014] and the M_L 5.3 mining induced event in 2005 [Durrheim et al., 2006]. Furthermore, mining induced earthquakes as small as M ~4 have already caused injury and fatality in South Africa [Nievas et al., 2020].
- <u>Claim</u>: *… noting that no re-injection of waste into wells is [to] be allowed, it is unlikely that the use of fracturing technology will induce seismic events larger in magnitude than what was observed historically.*
  <u>Correction</u>: There is no reason to expect that earthquakes induced by hydraulic fracturing will be equal to or smaller in magnitude than the historical observations. To the contrary, other basins around the world that have encountered hydraulic fracturing induced seismicity have already experienced events larger than those within their instrumental records [Schultz et al., 2020]. Generally speaking, historical records are incomplete (especially in poorly instrumented intra-cratonic settings), as the seismic cycle occurs on geological timeframes outside of human record. Furthermore, events of M_L 4.8 have already been experienced during the Leeu Gamka swarm, which is inside of the Karoo Basin development area [Whitehead et al., 2026]; earthquakes of this magnitude have the potential for damage, injury, or fatality [Nievas et al., 2020]. Thus, earthquakes of M_L 4.8 could still have severe consequences that should not be dismissed lightly.

6.2. Gaps in the proposed regulation of induced seismicity in the Karoo Basin.

The Consultation Documents describe the minimum reporting requirements and minimum monitoring requirements for the operators, or the creation of the operator's 'local' network.

However, this regulatory proposal leaves unaddressed gaps that are important for effective risk management, including those associated with establishing a risk-based TLP, and clear delineation of monitoring standards. The most numerous absences in the Consultation Documents fall under the responsibilities of the regulator: in most cases, these core components for effective risk management are entirely absent, including active monitoring, participation, communication, and enforcement by the regulator. There are also places where key responsibilities are not clearly assigned, such as deployment of a backbone monitoring network. While less numerous, the Consultation Documents also leave out core responsibilities of the operator. For example, the proposed minimum reporting requirements also fall short of the standards for transparent reporting, sharing, and publication of data, while opportunities for public participation are also absent.

The subsection that follows details what additional requirements the Consultation Documents need to effectively fill these gaps. I note that many of my critiques echo concerns raised a decade ago around the initial prospecting of the Karoo Basin [Kijko et al., 2016].

6.3. Recommendations for managing induced seismicity risks within the proposed regulations.

Given that the present regulatory proposal fails to meet the good practice requirements (§ 4), I highlight my recommendations to fill these risk management gaps in the following list:

1. Pre-design a TLP for any hydraulic fracturing development areas (*e.g.*, the Karoo Basin), in part to serve as a guideline for monitoring performance metrics; the TLP must be immediately implemented in any regions that become seismogenic. Presently, there is no provision requiring a TLP in the Consultation Documents. Development of an effective TLP would include the following steps:
    a. Determine the regulatory authority responsible for enforcing the TLP
    b. Require the regulator to provide clear thresholds (*i.e.*, yellow- and red-lights) for when operators need to change and halt operations.
        i. Red-light thresholds should be informed by risk-based principles; the regulator should explicitly define acceptable and unacceptable risk tolerances that the red-light threshold can be derived from.
        ii. Yellow-light thresholds should be informed by best practices and account for 'magnitude jumps' (*i.e.*, sudden increases in the largest event).
    c. Define exclusion zones around critical infrastructure.
    d. Require operators to develop and submit to the regulator their binding response plan for when yellow- and red-light thresholds are reached.
        i. The regulator should assess the proposed response plans to ensure they will meet the goals of the TLP, prior to the start of operations.
        ii. The regulator should enforce operator compliance with the pre-approved response plan, if a yellow-light or red-light threshold is triggered. Penalties should be incurred for failing to execute the response plan.

2. Create an effective monitoring network to detect seismic events. The present description of the seismic monitoring required in the Consultation Documents [DoFEE, 2025b; 2025c] omits key details for making this monitoring effective. The documents must clarify the following points:
    a. The regulator should establish clear monitoring performance metrics, in terms of both detectability and spatial resolution.
    b. These performance metrics should be informed by the TLP, to ensure its effectiveness for risk reduction.
    c. The monitoring system should be able to detect seismic events at or lower than the yellow-light threshold.

   d. The network's spatial resolution should be able to unambiguously attribute yellow- and red-light earthquakes to their source; this includes distinguishing induced events from natural events.
   e. The regulator should be responsible for ensuring these monitoring performance standards are met for the backbone network, adjusting the existing network as necessary.
      i. Likely this will require additional station deployments in the South African National Seismograph Network [CG South Africa, 2005; Saunders et al., 2007] and a partnership with the Council for Geoscience (https://www.geoscience.org.za/project/seismic-monitoring-and-maintenance/) to perform routine monitoring and catalogue building.
   f. The regulator should use its monitoring network to independently verify that operators are complying with the TLP and identify new regions of induced seismicity.
   g. Operators should be responsible for maintaining these monitoring performance standards for local networks during the following periods: prior to the initiation of injection, during injection, and for a reasonable period afterwards (*i.e.*, at least until seismicity returns to background rates).
   h. Mechanisms should be in place to independently verify that these monitoring performance metrics are being met, and to independently verify the attribution of an event as induced or natural.

3. Create transparent and open sharing mechanisms for all scientific data from the existing monitoring network. A pre-operation and post-operation report from the operators that describes these details, as presently proposed in the exploration and production MIR [Section 2.14.2; DoFFE, 2025b] would be insufficient for this purpose. Instead, these mechanisms would:
   a. Share all raw waveform data from seismometers, as well as derived products (*e.g.*, catalogues).
   b. Data sharing should follow FAIR (Findability, Accessibility, Interoperability, and Reusability) principles.

4. Create public reporting and participation mechanisms for transmitting information to the public and receiving complaints. There are presently no such mechanisms mandated in the Consultation Documents [DoFFE, 2025a; 2025b; 2025c]. These must include the following elements:
   a. Clear, publicly available, and easily accessible reporting mechanisms for when yellow- and red-light events occur.
   b. Clear and simple mechanisms for the impacted public to report nuisance, damage to buildings, or personal harm.

Current monitoring efforts in South Africa [CG South Africa, 2005; Saunders et al., 2007] and the proposed regulations [DoFFE, 2025a; 2025b; 2025c] provide a start to the management of induced seismicity. Nevertheless, a fundamental shift in the way the Consultation Documents considers induced seismicity risk is still warranted. The improvements proposed in this document are my recommendations of some of the most important changes still needed, based on experiences with induced seismicity around the world. These changes would help make development of hydraulic fracturing for oil and gas in South Africa safer and transparent.

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