Geophysical Prospecting

Geophysical Prospecting

RESEARCH NOTE

Seismic Monitoring for CO_2 Sequestration—A New Advanced Strategy

Leo Eisner[1] | James P. Verdon[2] | Sherilyn C. Williams-Stroud[3] | Zuzana Jechumtálová[1] | Umair bin Waheed[4] | Thomas Finkbeiner[5]

[1]Seismik s.r.o., Prague, Czech Republic | [2]University of Bristol, Bristol, UK | [3]Texas A&M University, College Station, Texas, USA | [4]Department of Geosciences, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia | [5]Physical Science and Engineering Division, King Abdullah University of Science and Technology, Thuwal, Saudi Arabia

Correspondence: Zuzana Jechumtálová (zuzana.jechumtalova@seismik.cz)

Received: 15 April 2025 | **Accepted:** 29 May 2025

Funding: This study was sponsored by King Abdullah University of Science and Technology baseline research No. BAS/1/1421-01-01 and Texas A&M University.

ABSTRACT

Advanced seismicity monitoring is needed for CO_2 sequestration monitoring. Current regulator practices (so-called traffic light systems—TLS) are limited to mitigate public hazards and associated risks caused by induced seismicity. Such seismicity is often associated with slip on larger faults below the reservoir. We propose an advanced seismic monitoring strategy that not only accounts for felt seismicity but also targets seismicity in the seal and reservoir. This novel concept of tiered seismicity criteria for an advanced seismic monitoring strategy is governed by a storage site's specific geological properties (underburden, reservoir and seal). These observed seismicity criteria can be set by the regulator or operator to develop a corresponding and fit for purpose system that further manages induced seismicity to ensure seal integrity and storage longevity.

1 | Introduction

Induced seismicity has been well recognized as an unwanted side effect of underground injections of fluid or gas in the subsurface, especially from energy industry and wastewater disposal operations (Evans 1966; Raleigh et al. 1976; Davis and Pennington 1989; Brudzinski and Kozłowska 2019; Schultz et al. 2023). Although most of these are small (i.e., unfelt at the surface), larger earthquakes are not uncommon. Irrespective, the size and frequency of induced seismicity is of broad public concern, especially for long term, large volume injection projects such as those planned for CO_2 sequestration (Nicol et al. 2011; Zoback and Gorelick 2012). Induced seismicity may not only be felt, but it can also reach damaging levels, and so hazard assessments and mitigation may be required (e.g., Haque 2024).

A common mitigation strategy for managing induced seismicity is known as the traffic light system (TLS), which was originally introduced for enhanced geothermal systems (Bommer et al. 2016). These TLSs are based on monitoring of induced seismicity and trigger operational changes when the observed seismicity exceeds a certain preset seismicity magnitude threshold. For example, operators may reduce injection volumes when seismicity exceeds a designated magnitude threshold (amber alert) or halt operations altogether if higher thresholds are reached (red alert). TLS primarily aims to mitigate felt or potentially damaging seismicity. Although smaller induced earthquakes below TLS thresholds can inform operational adjustments, their monitoring is often left to operator discretion and is not typically enforced by regulatory agencies.

1.1 | Conventional TLS

Table 1 shows variances of currently implemented TLS thresholds for different countries in Europe and North America. Verdon

TABLE 1 | Examples of magnitude thresholds (for types of magnitudes see Section 3) for current TLS (traffic light systems) in three selected regions, which are required by regulators for energy (mostly oil and gas) operators.

Country	Yellow threshold	Red threshold
United Kingdom[a]	0.0	0.5
Ohio, USA	1.0	2.0
Oklahoma, USA	2.0	2.5
Alberta, Canada	2.0	4.0

Note: Country generally means operate as usual, yellow level implies to take action to reduce seismicity and red level implies stop of injection.
[a]Note that the UK TLS no longer applies as hydraulic fracturing for shale gas is no longer permitted.

and Bommer (2021) point out that the magnitude levels are also related to or derived from acceptable peak ground velocity or acceleration (PGV and PGA) levels at surface, although regulators generally prefer to set magnitude thresholds, as these are more sensitive to inversion assumptions rather than recorded PGV/PGA. Despite this limitation Table 1 illustrates that threshold levels vary from country to country and generally correspond to population density and sensitivity to induced seismicity rather than any physical properties of the reservoir. (*Note*: Magnitude is proportional to logarithm of released energy.) Another point to make with Table 1 is the lack of regulatory consideration of hypocentre locations. Generally, seismic events are presumed to be located in the vicinity of injection wells. Furthermore, the listed thresholds are sometimes applied to both short term (e.g., hydraulic fracturing) and long-term injections (e.g., saltwater disposal). Let us note that CO_2 sequestration is a long-term injection process (i.e., expected to last years or even decades).

This study proposes to refine current criteria for seismicity monitoring of CO_2 sequestration to account both for the location of induced seismicity as well as its relevance to ensure seal integrity and storage longevity. The proposed advanced seismic monitoring strategy should be used mainly during the injection of CO_2 when alternative actions can be taken (e.g., injection into alternative depth horizons as in Decatur site). We wish to emphasize that induced seismicity in the seal or reservoir does not imply breach of the reservoir and associated CO_2 leakage. Detected seismicity implies actions may need to be taken (e.g., switch injection into another part of the reservoir).

1.2 | Monitoring of Induced Seismicity

In the context of CO_2 sequestration, operational concerns extend beyond felt or damaging induced seismicity and extend into the issue of potential activation of faults within the reservoir or/and in the sealing caprock, which may be associated with leakage. These additional risks make permitting and monitoring processes more complex. Thus, permits nowadays often require caprock integrity monitoring in addition to strategies for avoiding felt or damaging induced seismicity.

A TLS designed induced to mitigate felt seismicity is not the same as the monitoring of cap rock integrity. Felt or damaging seismicity typically arises from the reactivation of large faults in deeper formations (often in the underlying crystalline basement) below the reservoir, as observed in wastewater disposal operations in Oklahoma and Texas (e.g., Walsh and Zoback 2015; Kao, Hyndman, et al. 2018; Kao, Visser, et al. 2018; Smye et al. 2024). Thus, TLS regulations for damaging/felt seismicity mandate a monitoring network capable of detecting increases in seismicity rates and event magnitudes that typically correlate with injection rates. Furthermore, these TLS regulations must consider the possibility of stronger events occurring after the end of injection, a phenomenon widely reported. Verdon and Bommer (2021) provide an overview and discussion of these thresholds, including magnitude prediction for this type of induced seismicity.

The TLS threshold for felt or damaging earthquakes is influenced by the vulnerability of surface structures, proximity to population centres, and the potential hazard posed by known faults in the region of interest. As the induced seismicity in the Basel geothermal project (Häring et al. 2008), TLSs have been extensively adopted to manage induced seismicity associated with fluid injection. The overarching goal of TLS in these operations, whether explicitly stated or not, is to mitigate the seismic risk linked to nuisance or damage from induced earthquakes.

Criteria for TLS thresholds for induced seismicity are relatively well established—they should be defined on the basis of the potential for public nuisance or damage to buildings and (near-)surface infrastructure from induced events. However, consideration needs to be given for the criteria on which decision-making should be based when it comes to using microseismic observations to assess caprock integrity. Ideally, such criteria should be conceptually simple, easy to explain to non-expert stakeholders and the general public, and relatively immune to model-based assumptions or parameterization (Verdon and Bommer 2021). However, recognizing the complex nature of different caprock leakage mechanisms, such criteria will not be as simple as TLSs defined for induced seismicity management. Moreover, higher quality and resolution of data may be needed to perform such evaluations, relative to the monitoring requirements for induced seismicity management.

2 | Criteria for Containment Risk Management Using Passive Seismic Observations

The above discussion outlines the need for advanced monitoring systems that have sufficient capability to monitor seal integrity in addition to managing the risks posed by felt/damaging seismicity. It is obvious that the monitoring criteria required to perform these tasks will be constrained by the depth intervals of interest; that is, the seismic monitoring network should be designed to detect events with magnitudes significant to the seal formation, as well as meet the felt/damaging earthquake criteria for formations below the reservoir (often bedrock) and to differentiate between these types of events. Thus, the question arises as to what these different monitoring performances should be?

Analogously to setting TLS criteria for felt or damaging seismicity, monitoring criteria for seal and reservoir rock formations should be driven by the level of known hazard. We propose to follow these general guidelines, where the potential risk to CO_2 contain-

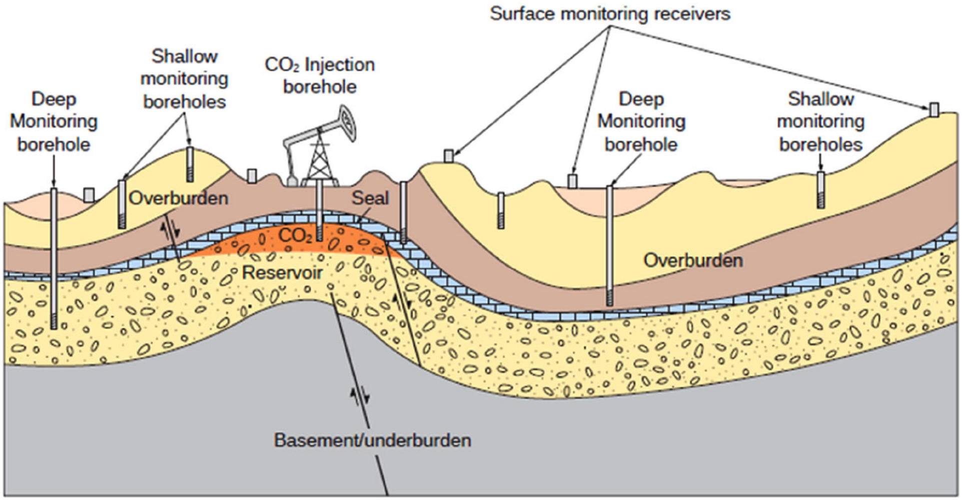

FIGURE 1 | Conceptual illustration for monitoring a hypothetical CO_2 sequestration site.

ment may also be influenced by the size of the fault that ruptures in an induced event as illustrated in Figure 1:

- The seal—To assess containment, it is critical to record seismicity that has a potential to compromise seal integrity. Fault activation should signal that pressure perturbations and stress changes are affecting seal capacity. But how significant should these slipping faults be before concern is warranted? A reasonable criterion might be that if the slipping fault size is comparable to seal thickness, stress changes in the seal layer may increase the fault's conductivity, and remedial action may be necessary. Although such seismicity does not necessarily indicate that the seal has been compromised or that a leakage pathway has formed, it should trigger an alert and a reassessment of the injection strategy. Conversely, it should be noted that leakage is also possible without inducing micro- or felt seismicity (i.e., leakage can occur aseismically), and so an absence of seismicity cannot be taken as an absence of leakage, and other monitoring techniques are required (however, discussing these is outside the scope of this study).
- The reservoir—Analogously to the seal, we need to be concerned. If induced seismicity indicates that the length of (re-)activated faults exceed reservoir thickness, the potential to breach the overlying seal or for felt seismicity in to occur in underlying formations increases. Such extended faults may intersect existing pathways for fluid migration, potentially resulting in leakage that compromises the integrity of the sequestration site. Therefore, monitoring networks should aim to detect fault activation that exceeds the reservoir boundaries, prompting early intervention and adjustments to injection practices.
- The basement/underburden—Prevention of induced felt and damaging seismicity is largely driven by our ability to predict size of the induced seismicity occurring after the change of injection activities, as discussed in Verdon and Eisner (2024), and this type of monitoring is generally covered by current TLS systems and what we are addressing is the need to augment these by monitoring for smaller magnitude induced seismicity in the reservoir and seal. We emphasize that location accuracy greatly helps to assess if the detected seismicity is aligned along a major fault. Hence, the monitoring network should be designed to be capable to determine accurate epicentral locations of the detected seismicity.

It is important to consider that a seismic monitoring network capable of capturing very weak seismicity from deep monitoring boreholes is in most cases very expensive. Additionally, designing a network with deep monitoring boreholes raises the carbon footprint of the monitoring process resulting from the required drilling, and the deep boreholes introduce potential leakage points through the seal and heighten the leakage risk from the reservoir.

The vulnerability of surrounding areas influences TLS threshold levels, which can vary widely—from very low (magnitude 0 in the United Kingdom) to more moderate (magnitude 2.0 in Canada). To convert the above limits of the fault sizes to magnitude criteria, we can use empirical relationships between earthquake magnitude and fault size (with uncertainty of stress drop as illustrated in Figure 2), as published by Tomic et al. (2009) and Zoback and Gorelick (2012). For example, if a seal formation had a thickness of 100 m, an event with magnitude between 1.0 and 2.3 would (if located in the centre of this layer) represent a rupture running though the entirety of this seal. These values were determined from Figure 2 using the relationship between magnitude and event radius. Note that this determination accounts for uncertainty associated with the stress drop values of induced seismicity. Similarly, if a reservoir had a thickness of 500 m, an event with magnitude between 2.3 and 3.8 would (if located in the centre of this layer) represent rupture across the entire reservoir thickness. Hence, for illustration purposes, assuming such a reservoir-seal pair, we would recommend to design a seismic monitoring network that is capable of detecting induced seismicity with a criterium of magnitude of 1.0 in the seal and 2.3 in the reservoir. The limit in the underburden (basement) is driven by population density and may range anywhere from magnitude 0 in England to magnitude 2 or even 4 in (Western) Canada. We note that the suggested criteria for seal and reservoir detectability are not criteria for stopping CO_2 sequestration; they are criteria above which operator should be aware of induced seismicity and take further action. Furthermore, any proposed,

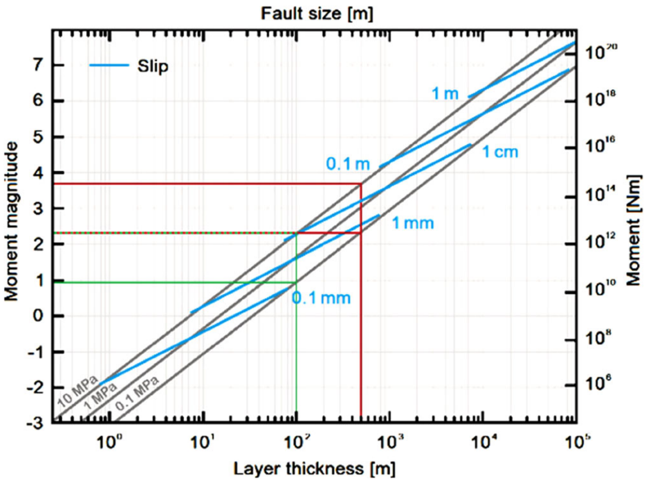

FIGURE 2 | Moment magnitude criteria for seismic monitoring during CO_2 sequestration as a function of caprock (or reservoir) thickness. The diagonal lines represent the bounds on possible stress drop values of induced seismicity, representing the uncertainty in the stress drop (or magnitude-fault dimension) values. The green and red lines illustrate the method of determination of magnitude levels for layer thickness of 100 m (green line) and 500 m (red line). *Source:* Modified from Zoback and Gorelick (2012).

region-specific seismicity criteria inform and enable the regulator to develop a corresponding and fit for purpose traffic light monitoring system adapted to and calibrated by a given operator for the area in question.

3 | Discussion

Given the potentially large dimensions of the expected CO_2 plumes (ranging from several kilometres to tens of kilometres) within the reservoir, the seismic monitoring network should be designed to meet the above criteria over a wide area. In principle we have three ways of monitoring array design: surface stations with limited detection of events in deeper parts of the reservoir, shallow borehole arrays with improved detectability but higher cost and deep borehole monitoring arrays with excellent detectability in the vicinity of the monitoring borehole but rapidly decaying away from borehole. Choice between these three methods and their design need to be modelled and then compared with required performance. General advantages and drawbacks of each type of the monitoring array are known but need to be adapted to the local conditions (e.g., layer thicknesses). Note that the network must be capable of distinguishing event depths to determine whether detected seismicity originates from the seal, reservoir or underburden. This requires an accurate velocity model, a non-trivial challenge. Developing an advanced monitoring systems for differentiated seismic monitoring that provides information to allow decisions for preventing the development of leakage and felt seismicity would enhance storage security for the large volumes of CO_2 injection needed to reach greenhouse gas emission goals.

The proposed strategy is not a risk or hazard assessment but meant to guide the development of a site-specific advanced hazard mitigation system. The novel aspect is to account not only for induced seismicity felt/damaging on surface but also account for lower magnitude seismicity, which indicates risk for seal failure. This would then put in question the main purpose of the CO_2 sequestration process itself. Last but not least, the proposed methodology involves assessing the underlying physical processes for setting site-specific criteria. In this context, it may then reduce the rather subjective sensitivity of local population. Finally, let us point out that the criterium for felt seismicity remain as criteria for the underburden area of interest, and these criteria do not influence the seal or reservoir area unless they are very low.

To address the question whether our proposed strategy is satisfactory or too strict would require an actual example of seal breach with observed microseismicity from an operating CO_2 sequestration site. Such example, to the best of our best knowledge, does not exist—at least not in the published literature (e.g., Jechumtálová et al. 2024). Alternatively, modelling may be used to prove the concept. However, we do not find such modelling meaningful because in the absence of known seal properties, the modelling does not prove or disprove the conceptual model. That said, this proposed methodology accounts for specific uncertainty of unknown induced seismicity stress drop as illustrated in

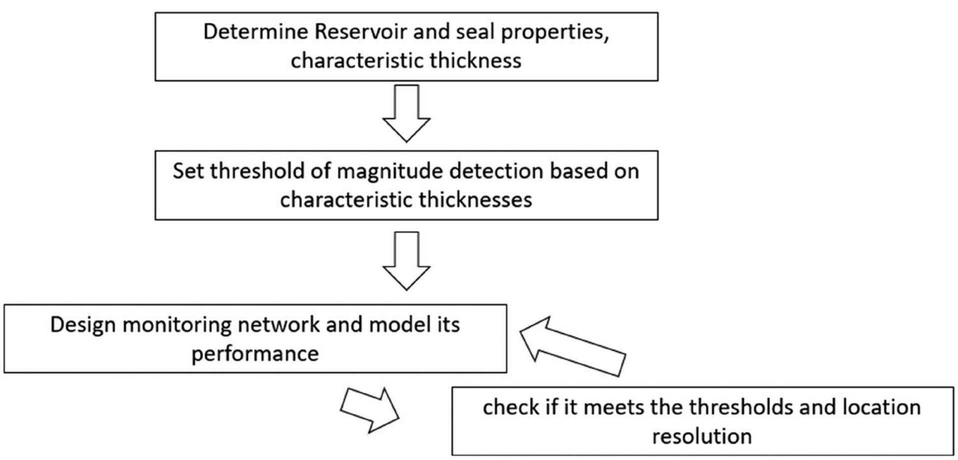

FIGURE 3 | Flow chart proposed for the design of a fit for purpose CO_2 sequestration monitoring network.

Figure 2. The unknown value assumes the lower magnitude limit corresponding to the mapped or interpreted thickness of a given layer (seal or reservoir). We further point out that our proposed mitigation strategy is not specifying what actions should be taken if the criteria are exceeded. We envision that this requires further expert investigations possibly ranging from modelling of CO_2 storage, active seismic imaging through gravity, elevation changes for onshore systems, monitoring of downhole pressure during shut-in injection wells, and surface geochemistry measuring the presence of CO_2—just to name a few measures. An example of such complementary plan is discussed in Furre et al. (2019), who also point out need to considering reservoir specific plan for such reaction suitable for specific conditions.

Figure 3 summarizes the steps that should be taken to develop seismic monitoring network on the basis of our proposed methodology. Note that the seismicity monitoring design require creation of a model of at least reservoir and seal rock, which are then used as input data for network design parametrization. This is principal difference to previous seismic monitoring designs, which mostly were mostly dependent on population sensitivity and preset thresholds.

4 | Conclusions

We propose a novel advanced seismic monitoring strategy where a fit for purpose monitoring network is designed to detect seismic events of different magnitudes in different layers across the monitoring area. The implication of this concept is that this network needs to be able to locate seismic event with sufficient accuracy (mainly depth) to differentiate between seal, reservoir and underburden events. In addition, it is designed to detect event sizes corresponding to site-specific layer thicknesses for the seal and reservoir.

Acknowledgements

Authors are grateful to King Abdullah University of Science and Technology for sponsoring this study under research grant ORA-CRG2021-4671.

Data Availability Statement

The authors have nothing to report.

References

Bommer, J. J., B. Dost, B. Edwards, et al. 2016. "Developing an Application-Specific Ground-Motion Model for Induced Seismicity." *Bulletin of the Seismological Society of America* 106, no. 1: 158–173. https://doi.org/10.1785/0120150184.

Brudzinski, M. R., and M. Kozłowska. 2019. "Seismicity Induced by Hydraulic Fracturing and Wastewater Disposal in the Appalachian Basin, USA: A Review." *Acta Geophysica* 67: 351–364. https://doi.org/10.1007/s11600-019-00249-7.

Davis, S., and W. Pennington. 1989. "Induced Seismic Deformation in the Cogdell Oil Field of West Texas." *Bulletin of the Seismological Society of America* 79: 1477–1495. https://doi.org/10.1785/BSSA0790051477.

Evans, D. 1966. "The Denver Area Earthquakes and the Rocky Mountain." *Mountain Geologist* 1, no. 1: 23–36. https://doi.org/10.1130/Eng-Case-8.25.

Furre A.-K., R. Meneguolo, P. Ringrose, and S. Kassold. 2019. "Building Confidence in CCS: From Sleipner to the Northern Lights Project." *First Break* 37: 81–87. https://doi.org/10.3997/1365-2397.n0038.

Haque F. 2024. "Predicting Seismic Sustainability for a Complex CHESST Interaction by AHP Using LWST." *Journal of Safety and Sustainability* 1, no. 3: 181–188. https://doi.org/10.1016/j.jsasus.2024.07.001.

Häring, M., U. Schanz, F. Ladner, and B. Dyer. 2008. "Characterisation of the Basel 1 Enhanced Geothermal System." *Geothermics* 37, no. 5: 469–495. https://doi.org/10.1016/j.geothermics.2008.06.002.

Jechumtálová, Z., L. Eisner, and T. Finkbeiner. 2024. "How large should microseismic monitoring networks be for CO_2 injection? Case study review." *First Break* 42, no. 4: 49–54. https://doi.org/10.3997/1365-2397.fb2024031.

Kao, H., R. Hyndman, Y. Jiang, et al. 2018. "Induced Seismicity in Western Canada Linked to Tectonic Strain Rate: Implications for Regional Seismic Hazard." *Geophysical Research Letters* 45, no. 20: 11104–11115. https://doi.org/10.1029/2018GL079288.

Kao, H., R. Visser, B. Smith, and S. Venables. 2018. "Performance Assessment of the Induced Seismicity Traffic Light Protocol for Northeastern British Columbia and Western Alberta." *Leading Edge* 37, no. 2: 117–126. https://doi.org/10.1190/tle37020117.1.

Nicol, A., R. Carne, M. Gerstenberger, and A. Christophersen. 2011. "Induced Seismicity and Its Implications for CO_2 Storage Risk." *Energy Procedia* 4: 3699–3706. https://doi.org/10.1016/J.EGYPRO.2011.02.302.

Raleigh, C., J. Healy, and J. Bredehoeft. 1976. "An Experiment in Earthquake Control at Rangely, Colorado." *Science* 191: 1230–1237. https://doi.org/10.1126/science.191.4233.1230.

Schultz, R., J.-U. Woo, K. Pepin, et al. 2023. "Disposal From In Situ Bitumen Recovery Induced the ML 5.6 Peace River Earthquake." *Geophysical Research Letters* 50, no. 6: e2023GL102940. https://doi.org/10.1029/2023GL102940.

Smye, K. M., J. Ge, A. Calle, et al. 2024. "Role of Deep Fluid Injection in Induced Seismicity in the Delaware Basin, West Texas and Southeast New Mexico." *Geochemistry, Geophysics, Geosystems* 25, no. 6: e2023GC011260. https://doi.org/10.1029/2023GC011260.

Tomic, J., R. Abercrombie, and A. do Nascimento. 2009. "Source Parameters and Rupture Velocity of Small $M \leq 2.1$ Reservoir Induced Earthquakes." *Geophysical Journal International* 179, no. 2: 1013–1023. https://doi.org/10.1111/j.1365-246X.2009.04233.x.

Verdon, J. P., and J. J. Bommer. 2021. "Green, Yellow, Red, or Out of the Blue? An Assessment of Traffic Light Schemes to Mitigate the Impact of Hydraulic Fracturing-Induced Seismicity." *Journal of Seismology* 25: 301–326. https://doi.org/10.1007/s10950-020-09966-9.

Verdon, J. P., and L. Eisner. 2024. "An Empirically Constrained Forecasting Strategy for Induced Earthquake Magnitudes Using Extreme Value Theory." *Seismological Research Letters* 95, no. 6: 3278–3294. https://doi.org/10.1785/0220240061.

Walsh, R., and M. D. Zoback. 2015. "Oklahoma's Recent Earthquakes and Saltwater Disposal." *Science Advances* 1, no. 5: e1500195. https://doi.org/10.1126/sciadv.1500195.

Zoback, M. D., and S. M. Gorelick. 2012. "Earthquake Triggering and Large-Scale Geologic Storage of Carbon Dioxide." *Proceedings of the National Academy of Sciences of the United States of America* 109, no. 26: 10164–10168. https://doi.org/10.1073/pnas.1508533112.