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# Chasing the ghost of fracking in the Vaca Muerta Formation: Induced seismicity in the Neuquén Basin, Argentina

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**Abstract** Earthquakes are known to be induced by a variety of anthropogenic causes, such as hydraulic fracturing. In the Neuquén Basin of Argentina, hydraulic fracturing has been used to produce hydrocarbons trapped in the shales of the Vaca Muerta Formation. Correspondingly, incidences of seismicity there have increased. We collect information on well stimulations and earthquakes to perform statistical analysis linking these two datasets together. Spatiotemporal association filters suggest that the catalogue of events is biased towards hydraulic fracturing operations. After accounting for false-positives, we estimate that ~0.5% of operations are associated with earthquakes. These associated event-operation pairs show highly correlated temporal signals (>99.99% confidence) between seismicity/injection rates. Based on this evidence, we argue that many of these earthquakes (up to M4) are induced. We support this argument by comparing the geological setting of the Neuquén Basin against conditions needed for fault reactivation in other susceptible/seismogenic basins. This recognition adds to the growing list of (hydraulic fracturing) induced seismicity.

**Non-technical summary** Earthquakes have been increasingly encountered in Argentina's Neuquén Basin, a previously seismically quiet region. Simultaneously, hydraulic fracturing operations have been targeting shales in the Vaca Muerta Formation. Hydraulic fracturing injects subsurface fluids under high enough pressure to split rocks, allowing access to the hydrocarbons within. This type of operation is known to cause earthquakes elsewhere. To determine if these earthquakes were caused by hydraulic fracturing, we performed statistical tests. To high-degrees of confidence, we find that many events tend to be clustered around hydraulic fracturing wells in time and space. Sensitivity testing suggests that these correlations almost certainly did not occur by accident. Faults, stress information, and other factors in the Neuquén Basin are comparable against other basins that have already induced earthquakes. We conclude that many of the events here were induced. We discuss how future research could better answer some of our unresolved questions.

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## 1 Introduction

Induced seismicity caused by subsurface injection operations, like wastewater disposal, has been well documented since the 1960s (Healy et al., 1968; Raleigh et al., 1976). Since 2010, earthquakes in North America have proliferated, following the advent of hydraulic fracturing for shale gas (Foulger et al., 2018). Within the United States, these earthquakes were predominantly caused by the increased disposal of frack-related produced water (Ellsworth, 2013). However, earthquakes have also been induced directly by hydraulic fracturing operations around the world (Schultz et al., 2020; Atkinson et al., 2020). For example, seismicity in the Horn River Basin (Farahbod et al., 2015), Duvernay Formation (Bao and Eaton, 2016; Schultz et al., 2017), Montney Formation (Mahani et al., 2017; Peña Castro et al., 2020), Bowland Shale (Clarke et al., 2019; Kettlety et al., 2020), Appalachian Basin (Skoumal et al., 2015; Brudzinski and Kozłowska, 2019), Delaware Basin (Skoumal et al., 2020), and Sichuan Basin (Lei et al., 2017, 2019) has been linked to hydraulic fracturing.

Typically, these earthquakes occur when the growth of stimulated fractures intersect pre-existing faults (Galloway et al., 2018), reactivating susceptible portions of the fault via a reduction in effective normal stress (Moein et al., 2023). One of the largest documented cases ($M_L$ 5.7) occurred in the Sichuan Basin of China, causing noteworthy damage and injuries (Lei et al., 2019). Many cases have encountered felt ground shaking, or events as large as M4 (Bao and Eaton, 2016;

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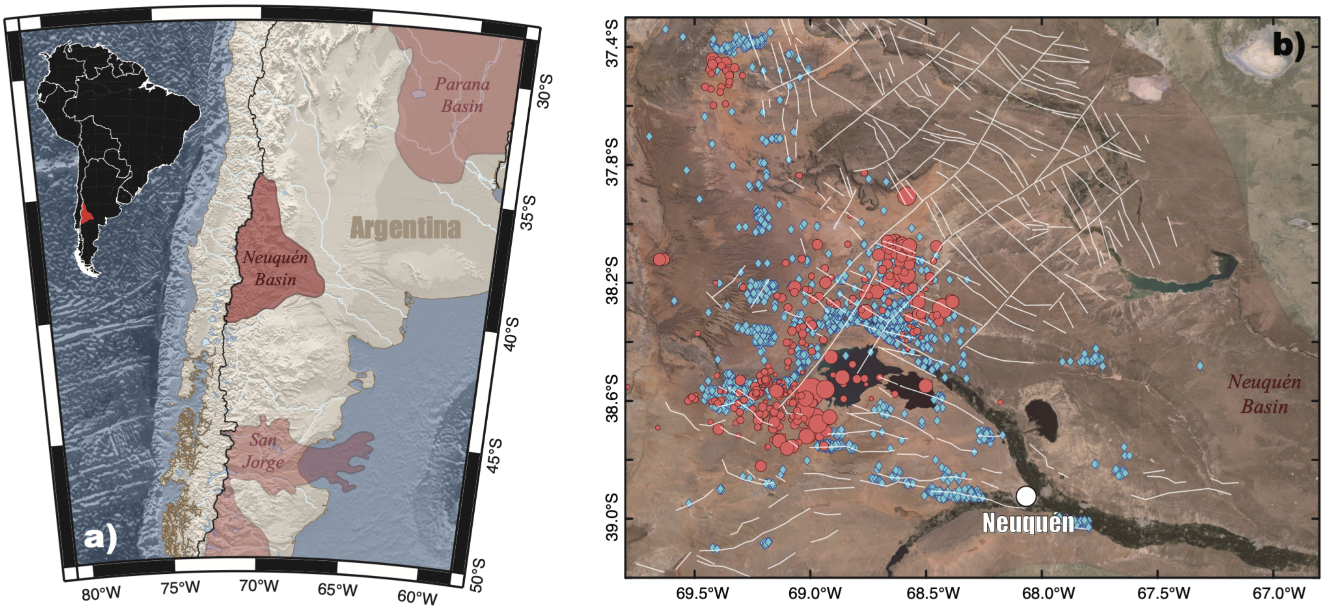


**Figure 1 Comparison between seismotectonic setting and hydraulic fracturing operations.** (a) Map showing part of Argentina, alongside boundaries of nearby shale basins (red polygons). Inset polygon shows the location of the Neuquén Basin within South America. (b) Map of the study area shows earthquakes (red circles) and hydraulic fracturing operations (blue diamonds), alongside the city of Neuquén (white circle, with text). Faults from prior studies (Silvestro and Zubiri, 2008; Cristallini et al., 2009) are also shown (white lines).

Schultz et al., 2017; Mahani et al., 2017). In response, some jurisdictions have emplaced moratoriums on resource development because of induced earthquake concerns (Kettlety et al., 2020). Typically, these risks are managed through a traffic light protocol (Bommer et al., 2006; Häring et al., 2008; Ader et al., 2019), which designates thresholds for operations to begin mitigation (yellow-light) and a regulatory interventions (red-light). Traffic light protocols have been implemented around the world to manage hydraulic fracturing induced earthquakes, using various red-light thresholds. New approaches have begun to define these red-light thresholds using risk-based principles (Schultz et al., 2021a,b, 2023a).

Within Argentina, there are several basins which have been appraised for or targeted by hydraulic fracturing (Figure 1), the most productive of which has been the Neuquén Basin (US-EIA, 2015). The Neuquén Basin (~160,000 km$^2$) is situated in central-eastern Argentina and bounded by the Andes to the west (Urien and Zambrano, 1994; Marchal et al., 2020). For comparison, the Duvernay Formation covers an area of ~130,000 km$^2$ (US-EIA, 2013). The Neuquén Basin contains Late Triassic to Early Cenozoic strata that were deposited in a back-arc tectonic setting, including accumulated deposits of siliciclastics, carbonates, and evaporites (Howell et al., 2005). Most relevant to hydraulic fracturing development have been the Vaca Muerta Formation and the Los Molles Formation (Kugler, 1985; Ramos et al., 2020). The Vaca Muerta Formation is Late Jurassic – Early Cretaceous aged shale consisting of marls, organic shales, and lime-mudstones; in some regions, thicknesses can reach up to 520 m and depths of 3,150 m (Badessich et al., 2016; Legarreta and Villar, 2015). The deeper Los Molles Formation is Middle Jurassic aged shale consisting of organic shales and lime-mudstones (Martínez et al., 2008). The crystalline basement consists of Silurian–Devonian igneous-metamorphic rocks, intruded by magmatic arc granitoids (Cingolani et al., 2011). Initial estimates of technically recoverable natural gas were 308 Tcf and 275 Tcf for the Vaca Muerta Formation and Los Molles Formation, respectively (US-EIA, 2013). Initial estimates of technically recoverable oil were 16.2×10$^9$ bbl and 3.7×10$^9$ bbl for the Vaca Muerta Formation and Los Molles Formation, respectively (US-EIA, 2013). The Neuquén Basin is host to one of the most significant sources of unconventional hydrocarbons in the world and is an important energy source for Argentina (Minisini et al., 2020). Currently, the state-owned oil and gas company YPF holds the largest share of unconventional investments in the Neuquén Basin (Lu et al., 2024).

Like many hydraulic fracturing basins, the seismic history of the Neuquén Basin is quiescent and sparsely recorded. Past studies have understandably focused on the constraining the hazardous seismicity from the Nazca Plate subduction (Bilek, 2010). In some cases, temporary/peripheral surveys may have captured nearby seismicity (Bohm et al., 2002). Inferences from structural geology suggest a complex history, including extensional and compressional periods (Marchal et al., 2020). Recent (Cenozoic) tectonism is mostly related to compression from the Andean deformation (Cobbold and Rossello, 2003). Tectonism and faulted structures are thought to have played a role in the migration of hydrocarbons through the geological history of the Neuquén Basin (Mosquera et al., 2008). Due to concerns of induced seismicity (Cunningham, 2022;

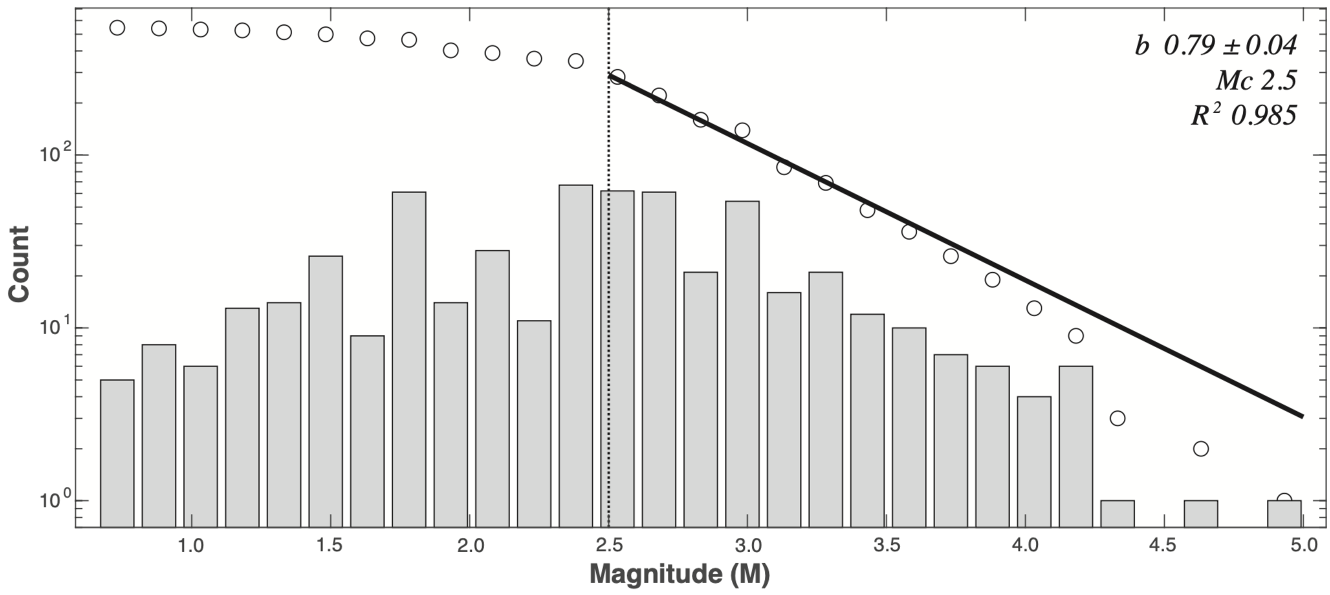


**Figure 2 Earthquake magnitude statistics.** Magnitude-frequency distribution of events in the regional catalogue: data counts are plotted as both the cumulative (circles) and non-cumulative (bars) distributions, alongside the best fit to the data (solid line) and the magnitude-of-completeness (dashed lines). Relevant parameters are reported as text.

Surma, 2024), recent work has begun to constrain the regional seismicity of the Neuquén Basin (Curia et al., 2018; Correa-Otto et al., 2018; Correa-Otto, 2021; Correa-Otto et al., 2024). In fact, it has been suggested that seismicity in the Neuquén Basin is induced (Tamburini-Beliveau et al., 2022).

Delving deeper into the socio-environmental aspects, these recent earthquakes have impacted the region in several ways. In the rural community of Sauzal Bonito, earthquake ground shaking is regularly felt, and homes have sustained damage (Surma, 2024). Consequently, in 2022, the state committed to the construction of 56 new basic earthquake-resistant homes (12 delivered to date) which were 50% funded by one of the operating companies (LM Neuquen, 2024). Additionally, the region's cliffsides have experienced multiple landslides, resulting in fatalities and injuries (Álvarez Mullally, 2021; Nacion, 2022). Industrial operations have not been immune to the seismic activity; some operators have temporarily suspended hydraulic fracturing activities due to the associated risks of induced seismicity (Beascochea, 2020). While this socio-environmental information is limited (and primarily based on testimonies and news reports), it provides motivation for further scientific inquiry.

Within this study, we begin to the discern causal factors for seismicity in the Neuquén Basin. To do so, we compile information regarding hydraulic fracturing stimulations and regional catalogues of earthquakes. We then use spatiotemporal association filters to link candidate operations with sequences of earthquakes. Furthermore, cross-correlation reshuffling tests are used to determine the statistical confidence of well-earthquake associations. We find significant evidence (>99.99% confidence) for a correlation between hydraulic fracturing operations and many of the strongly-associated earthquakes. We then highlight the relevant geological/operational factors relevant for causing induced earthquakes, in comparison with other known cases. Last, the limitations of this analysis/dataset are also discussed – to highlight future research directions to better understand these earthquakes and further disentangle their causes.

## 2 Input Datasets

### 2.1 Earthquake catalogue

Earthquake catalogue information is compiled from multiple sources. Predominantly, these sources include the National Institute of Seismic Prevention of Argentina (Instituto Nacional de Prevención Sísmica, INPRES), a PhD project cataloguing earthquakes in the basin (Correa-Otto, 2021; Correa-Otto et al., 2024), and miscellaneous prior studies (Vásquez et al., 2020; Tamburini-Beliveau et al., 2022). The INPRES catalogue spans from 2015 onwards (predominantly starting in 2019), while the PhD project catalogue predominantly spans from 2014-2020.

The latter (PhD) catalogue was obtained by a local broadband seismological network that was established in the central-northern region of the Neuquén province (Figure S1). It comprised 11 stations covering an area of approximately 70×70 km$^2$, which consistently collected data from November 2014 to July 2016. From July 2016 until June 2020, the number of stations operational in the network was reduced to 5. Each station was outfitted with a Trillium 120PA broadband seismometer and a Taurus digital recorder (Correa-Otto, 2021). This catalogue predominantly comprises the earlier segment of our study period.

The INPRES catalogue spans from 2015 onwards and constitutes data requests from INPRES. Limited station availability hampered event detection (~10 events from

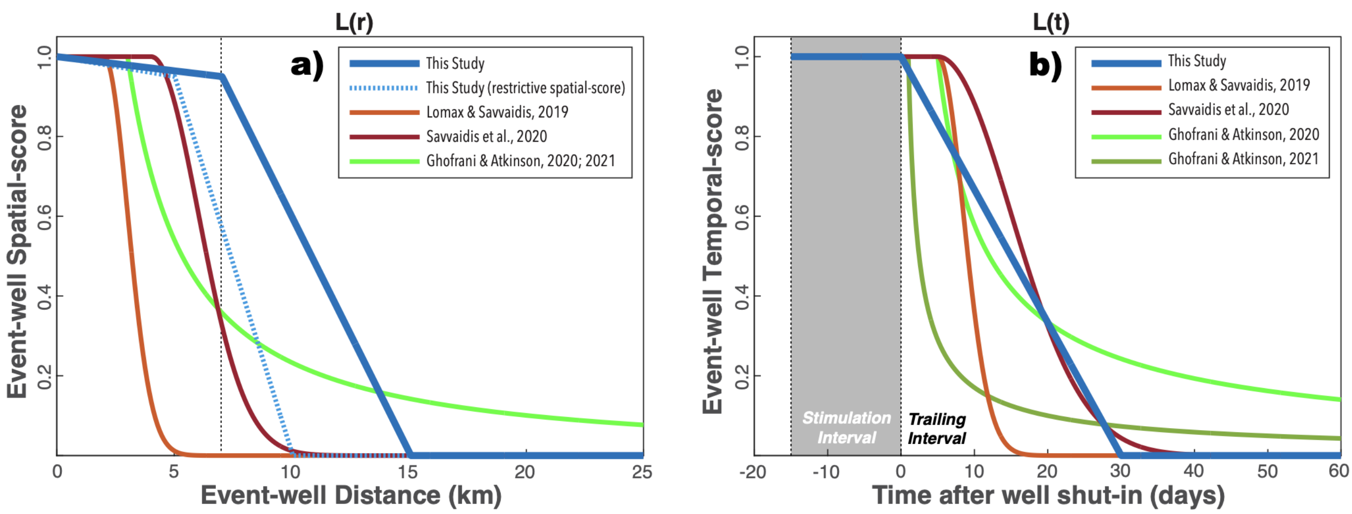


**Figure 3 Schematic diagram defining the SAF spatial/temporal-scores.** (a) The spatial-score of a single event-well pair decaying as a function of distance (lines, see legend). (b) The temporal-score of a single event-well pair decaying as a function of time (lines, see legend). Intervals separating the bi-linear pieces are denoted by vertical dashed lines.

2015-2019). Partly because of network expansion in 2019 (Figure S1), this catalogue starts detecting events more routinely (~360 events from 2019 onward). This catalogue predominantly comprises the later segment of our study period.

We collated these catalogues together into a single combined catalogue for this study. To ensure the uniqueness of events, we identify those which are contemporaneous and then merge them. The preferred origin is selected as the one from the PhD project catalogue. The limited overlap between catalogues means very few events are flagged as identical. Our combined catalogue starts in November 2014 and spans until March 2024 (Figure S2). There are 545 events in this catalogue. Event depths range from the surface to 66 km; with a mean value of ~7 km and a standard deviation of ~6 km. The largest event in our catalogue compilation is M 5.0 and occurred on 7 March 2019. There have been more than 10 M4+ events documented during the recording interval. A simple fit to the magnitude-frequency distribution indicates a *b*-value of 0.79±0.04 (Figure 2). The magnitude-of-completeness appears at M ~2.5, which is the value asserted by INPRES.

## 2.2 Hydraulic fracturing information

The data for wells location, injection and other characteristics were downloaded in plain text format from the official public databases from the Argentina Energy Secretariat and the Neuquén province's Ministry for Energy and Natural Resources. The databases were combined and cleaned to avoid duplicated registries and other inconsistencies (Figure S3). Data on hydraulic fracturing includes surface well locations, stimulation start/end times, total fluid injected, number of stages, and other information less relevant for this study. Unfortunately, the start/end times of 16% of hydraulic fracturing wells (Figure S4) are missing in the original source files. We are unable to assert if or how many wells are enitrely missing from this database. These missing cases will evade scrutiny in our subsequent analysis, since both spatial and temporal information are needed.

The economic potential of the Vaca Muerta Formation, as a hydraulic fracturing target, was first recognized in 2010 by Repsol-YPF. During this early phase (2010-2012), wells tended to inject modest amounts of fluid during stimulation programs ($10^1$-$10^3$ $m^3$). However, similar to other hydraulic fracturing basins, the scale, complexity, and frequency of operations increased with time. By 2019, the vast majority of operations are injecting $10^4$-$10^5$ $m^3$, per well. To date, there have been more than 4,000 unconventional wells stimulated in the Neuquén Basin.

# 3 Methods & Results

## 3.1 Screening for wells via a spatiotemporal association filter (SAF)

The first step in determining the propensity for induced earthquakes is to screen for events that are close to operations in time and space. This rationale is based on standard criteria for identifying a causal induced seismicity relationship, which prioritizes the examination of relationships in time-and-space (Davis and Frohlich, 1993; Verdon et al., 2019; Foulger et al., 2023). In this study, we use a spatiotemporal association filter (SAF) to screen for induced events. Comparable approaches have been used for identifying induced seismicity caused by hydraulic fracturing (at the basin-scale) in the past (Atkinson et al., 2016; Schultz et al., 2018; Lomax and Savvaidis, 2019; Savvaidis et al., 2020; Ghofrani and Atkinson, 2020, 2021).

To quantify the linkage between earthquakes and operations, we start by defining a simple bi-linear decay function: $L(\mathbf{X}; X_1,\ X_2,\ P_1)$. Over the interval 0-$X_1$ function scores decline from 1-$P_1$, and over the interval $X_1$-$X_2$ function scores decline from $P_1$-0. For any candidate event-well pair $(i, j)$, the spatial-score $L_{i,j}(\mathbf{r};\ r_1,\ r_2,\ P_1)$ and a temporal-score

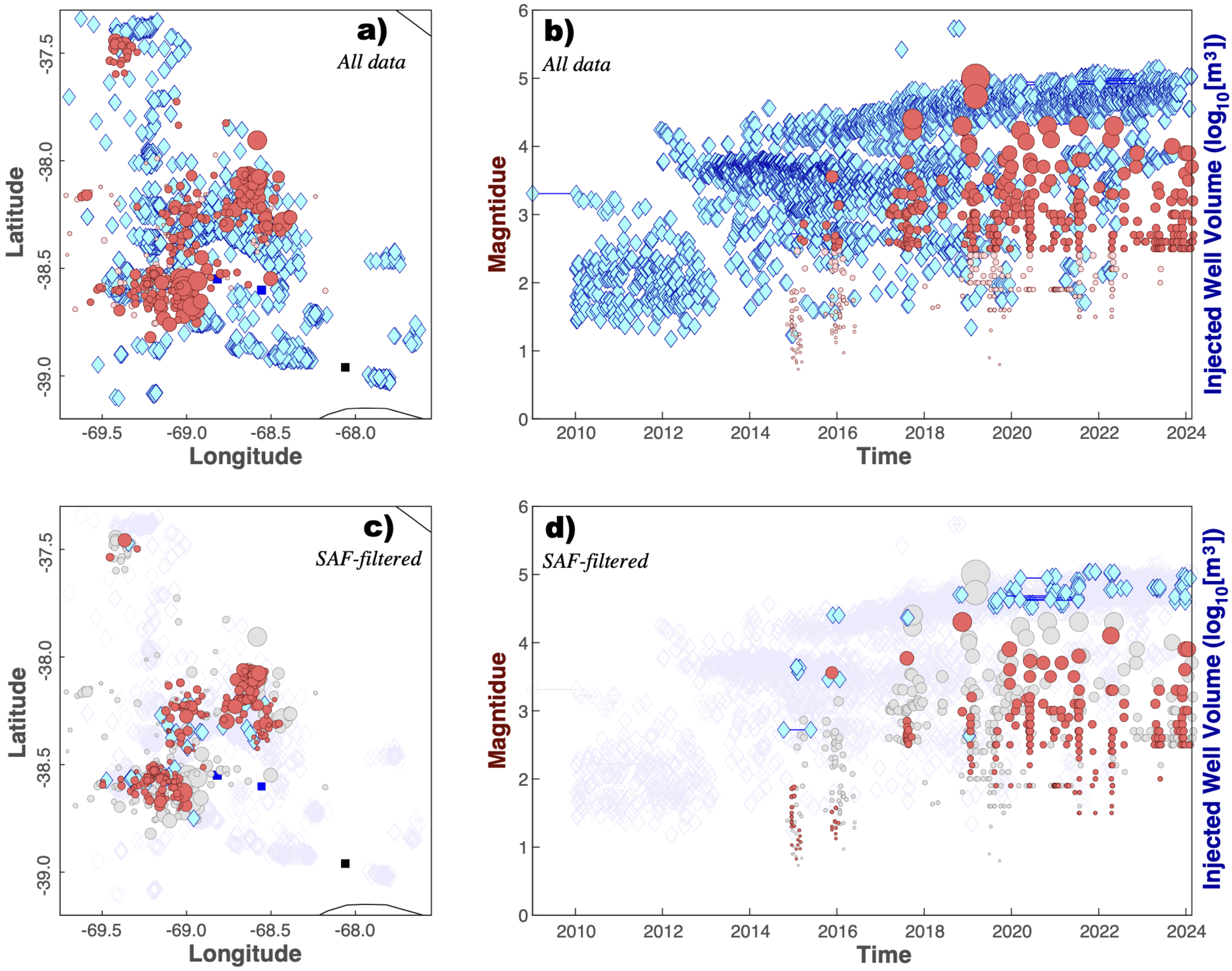


**Figure 4 Spatiotemporal association filtering.** (a & c) Maps with locations of earthquakes (circles) and hydraulic fracturing operations (diamonds). (b & d) Temporal timings of hydraulic fracturing operations (two diamonds linked with a blue line) and earthquake magnitudes (circles). Comparisons are made between the full (top row) and filtered (bottom row) datasets. Unassociated operations/earthquakes have faded colors.

$L_{i,j}(\mathbf{t};\ t_1,\ t_2,\ P_1)$ are assigned using this bi-linear function, with unique window intervals ($r_1$-$r_2$, $t_1$-$t_2$) and score cut-off point ($P_1$). Next, temporal and spatial score components are combined into a single event-well SAF-score by multiplication: *i.e.*, $L_{i,j}{=}L_{i,j}\left(\mathbf{r}\right)\times L_{i,j}\left(\mathbf{t}\right)$. For a given operation $j$, SAF-scores are computed for all events and the total SAF-score is a summation of all single-event scores $SAF_j = \sum_i L_{i,j}$. Note that we also apply a uniqueness condition, so that any individual event $i$ can only be associated with a single (highest-scoring) operation $j$, to avoid double-counting events.

In applying this approach to the Neuquén Basin, we use our compiled catalogue of earthquakes and hydraulic fracturing database (Section 2). For the spatial component of SAF-scores $L_{i,j}(\mathbf{r})$, earthquakes that are within 7 km of an operation are scored between 1.00-0.95, with earthquakes between 7–15 kms scoring 0.95-0.00. We feel that the choice of 7–15 km interval for the spatial-score is justified, based on the reported spatial resolution of catalogued earthquakes. In cases of poorer spatial resolution, SAF spatial intervals ($r_1$-$r_2$) should match this resolution, to avoid discarding true associations because of this variance. If a high-resolution catalogue was available instead, intervals of 1–3 km would be more appropriate, since the furthest documented case of induced seismicity from a hydraulic fracturing well was ~1.5 km (Schultz and Wang, 2020) – although this would require also having information on the horizontal trajectory of wells, which is also unavailable to us. For the temporal-scores $L_{i,j}(\mathbf{t})$, any earthquakes that occurs during well stimulation period are assigned a score of 1.0; anything that occurs post completion decays linearly to 0.0 by 30 days afterwards. This 30-day interval is justified, based on decays of trailing seismicity typically following hydraulic fracturing in other basins (Schultz et al., 2022, 2023b). For clarity, we also provide a visual definition of how we individually assign spatial-scores $L_{i,j}(\mathbf{r})$ and temporal-scores $L_{i,j}(\mathbf{t})$ (Figure 3). Our SAF processing choices are comparable to those used in previous studies (Lomax and Savvaidis, 2019; Savvaidis et al., 2020; Ghofrani and Atkinson, 2020, 2021).

The application of the SAF begins to identify potential induced seismicity cases (Figure 4). We consider only wells with summed SAF-scores greater than 1.0, which identifies 46 potential cases for further consideration. The case with the highest SAF-score is ~12. The two largest earthquakes associated with an operation are the M 4.3 event on 16 November 2018 and the M 4.1 event on 13 April 2022. Associated cases predominantly occur after 2019, in the region surrounding the Cerros Colorados Complex (*i.e.,* the Los Barreales and Mari Menuco Reservoirs). Although, we do note associated cases as early as late-2014. Likely, this temporal skew has been influenced by monitoring improvements alongside increases in fracking intensity. Of the total database of unconventional wells, ~1.6% operations were associated with earthquakes and ~42% of the earthquakes were associated with hydraulic fracturing operations. However, this analysis has the potential for false-positives – spurious associations between earthquakes and operations.

We ensure the robustness of our results through bootstrap resampling. To do so, we take the catalogue of events and randomly reshuffle their origin times. This process destroys any meaningful earthquake-operation correlations. Said another way, the reshuffling process is used to estimate the rate of false-positives, given our SAF design choices. Considering the potential for false-positives is especially important here, given the previously described unknowns/uncertainties of our input datasets (Section 2). We then take this randomly reshuffled catalogue and perform the exact same SAF processing. This is repeated 500 times, to query the variability of (false-positive) SAF scores as a statistical distribution (Figure 5). After reshuffling, the SAF processing is no longer able to produce similarly high percentages of association, suggesting an average false-positive association of ~1.1% (Figure 5a). This means there is only a 1/500 chance of producing an association as high as the 'regular' value by accident. If we next examine the distribution of SAF-scores (Figure 5b), we see that the two variants are visually distinct. We estimate that the maximum (false-positive) SAF-score is ~5.5 on average, which is much lower than the regularly observed value. Furthermore, we perform the Kolmogorov-Smirnov test (Berger and Zhou, 2014) to statistically quantify differences between the regular/reshuffled distributions of SAF-scores (Figures 5b & S5). To ~99.8% confidence, the distribution of these two SAF-score variants are significantly different.

We further assess the robustness of our results through a perturbation analysis. In this test, we modify the parameters and functional form of the spatial/temporal-sores during SAF processing, to examine the influence these subjective choices have on our results. Here, we consider five alternative SAF processing approaches. In the first alternative, the same $L_{i,j}(\mathbf{r})$ and $L_{i,j}(\mathbf{t})$ bilinear functions are used, just with more restrictive spatial-score cutoffs (*i.e.,* 5-10 km for $r_1$-$r_2$). In the four remaining alternatives, we consider spatial/temporal-scores and functions/parameters previously used for identifying seismicity induced by hydraulic fracturing (Lomax and Savvaidis, 2019; Savvaidis et al., 2020; Ghofrani and Atkinson, 2020, 2021). Then, the SAF processing and bootstrapping is repeated for all these alternative formulations (Table 1 & Figures S6-S15). Despite the differences between the SAF alternatives, the results consistently suggest a statistically meaningful association between hydraulic fracturing and earthquakes. Overall, the results of this section are indicative of some physical process biasing the triggering of earthquakes in the Neuquén Basin.

### 3.2 Quantifying the strength of associations through the cross-correlation reshuffling test

To further investigate the source of this biased earthquake triggering, we next consider the cross-correlation reshuffling test (Oprsal and Eisner, 2014; Schultz and Telesca, 2018). In this test, rates of seismicity are compared with hydraulic fracturing injection rates using cross-correlations. The cross-correlation quantifies the strength of time-lagged correlations between these two signals. The statistical significance of this time-lagged correlation can be discerned via a reshuffling of the input timeseries' spectral phase information (Schultz and Telesca, 2018).

In applying this approach to the Neuquén Basin, we first filter our earthquake catalogue above the magnitude-of-completeness (Figure 2) to account for temporally changing detection thresholds. We consider the correlation between the top ten SAF-screened operations (Section 3.1) and their associated earthquakes (Figure 6a), to ensure that only adequately identified cases are considered. Due to limited data availability, we simply consider an effective injection rate timeseries, which is the total amount of volume injected at a well divided by the total duration of stimulation start/stop times. Catalogue information is binned into a timeseries of daily earthquake rates. Reshuffled cross-correlation tests place very high confidence (>99.99%) on these two timeseries being associated with each other (Figure 6b). Similarly, tests performed on the top SAF-scoring operations as individual sequences, also shows strong (up to ~99.7%) indications of an association (Figures S26-S31). Unfortunately, these tests are unable to meaningfully discern lag times between start of operations and responding seismicity, because of the low temporal resolution of the well database. Discrete timings of individual stage stimulations (and better catalogue detections) would be needed to improve the results here. These results are further suggestive of hydraulic fracturing playing a role in triggering some of the events in the Neuquén Basin.

## 4 Discussion

### 4.1 Comparison against known cases of hydraulic fracturing induced seismicity

Much of the Neuquén Basin seismicity is likely induced, with hydraulic fracturing being a strong candidate for the anthropogenic source. This is based on statistical testing that indicated biased spatiotemporal associations (Section 3.1; Figures 4 & 5) and statistically significant correlations (Section 3.2; Figure 6) with ongo-

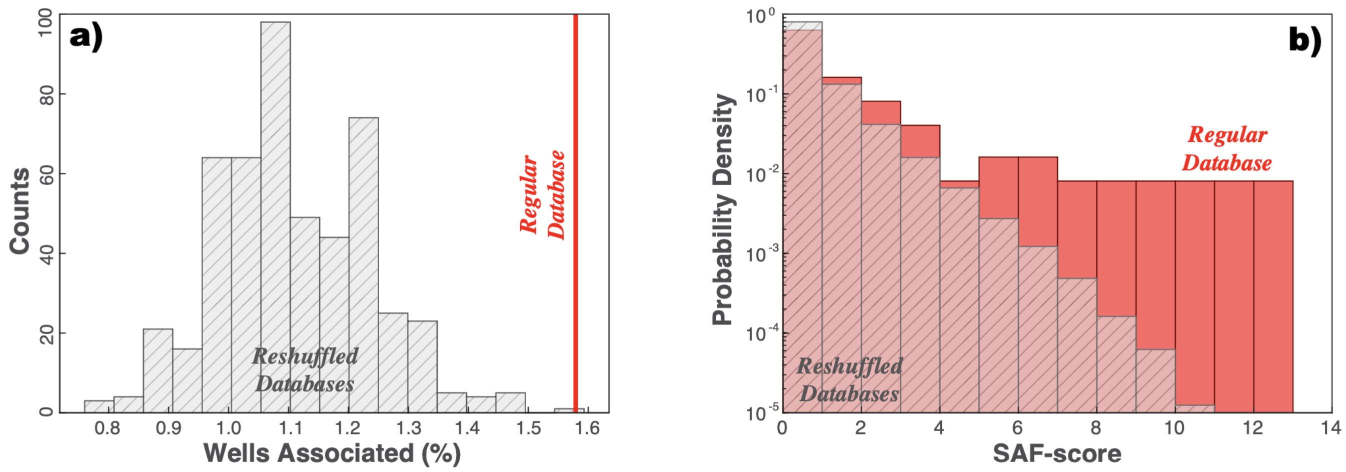


**Figure 5** **Bootstrapped SAF results.** (a) The basin-scale percentage of wells associated with earthquakes via SAF (red-line), in comparison to the association percentages when reshuffling catalogues (grey bars). (b) The distribution of SAF-scores for the regular dataset (red bars), in comparison with reshuffled data (grey bars).

| Study | % Association | (FP) % Assoc | Association chance | Max SAF | (FP) Max SAF | KS-test |
|---|---|---|---|---|---|---|
| This study | 1.58 | 1.11±0.13 | ~ 1/500 | 12.40 | 5.47±1.22 | 99.79% |
| This study (w/ restrictive spatial-score) | 1.13 | 0.55±0.10 | ≪1/500 | 12.02 | 3.69±0.93 | 99.98% |
| Lomax and Savvaidis (2019) | 0.65 | 0.11±0.05 | ≪1/500 | 9.09 | 2.08±0.61 | 97.89% |
| Savvaidis et al. (2020) | 1.03 | 0.50±0.10 | < 1/500 | 12.36 | 3.43±0.87 | 99.96% |
| Ghofrani and Atkinson (2020) | 1.20 | 0.72±0.10 | ≪1/500 | 10.42 | 3.85±0.80 | 99.25% |
| Ghofrani and Atkinson (2021) | 1.13 | 0.66±0.09 | ≪1/500 | 9.21 | 3.78±0.75 | 95.39% |

**Table 1** Summary of alternative SAF processing. Results for SAF-scores and bootstrapping results are summarized for five SAF processing alternatives. See Figure 3 for a visualization of spatial/temporal-scoring functions. FP is an abbreviation for false-positive here.

ing operations. These spatiotemporal indicators are key criteria for declaring a sequence of events as induced (Davis and Frohlich, 1993; Verdon et al., 2019; Foulger et al., 2023).

To continue building a case for causality, we also consider a comparison against known cases of hydraulic fracturing induced seismicity. Typically, these induced earthquakes are observed close to their causal operations (Eaton et al., 2018; Fasola et al., 2019; Wang et al., 2020), occurring predominantly during stimulation (Schultz et al., 2017, 2022; Clarke et al., 2019), and preferentially associated with stimulation of deep/basal shales (Skoumal et al., 2018). Of the best identified cases, we see a similar correspondence (Figures S16-S25): all earthquakes are clustered nearby to their operations with earthquakes occurring frequently during stimulation intervals and fewer trailing events.

Often this proximity is interpreted as related to the causal mechanisms: stimulated fractures need to encounter pre-existing faults that allow for hydraulic communication to susceptible portions of the fault (Galloway et al., 2018). In this sense, nearby basement-rooted faults cross-cutting the targeted shale are an important indicator for seismogenic operations (Corlett et al., 2018). Within the Neuquén Basin, the complex tectonic history has left a series of such faults, including transtensional and transpressional flower structures (Marchal et al., 2020), which are often associated with induced earthquakes in other basins. Furthermore, these faulted structures have been implicated in fluid-flow events of the geological past (Mosquera et al., 2008), providing a plausible means for reservoir-basement pore pressure communication. Interestingly, hydrocarbon maturation has contributed to overpressure reservoir conditions for much of the Vaca Muerta Formation (Varela et al., 2020). In other basins, overpressure has been another indicator of earthquake susceptible regions (Eaton and Schultz, 2018). Overall, the geological conditions needed to encounter hydraulic fracturing induced seismicity seem to be intact for the Neuquén Basin (and consistent with other cases).

In highly susceptible sub-basin regions, the activation rate of operations can be large (up to tens of percent) (Schultz et al., 2018); however, this can vary considerably over a few kms, with only a paucity of wells inducing events at the basin-scale (Atkinson et al., 2016; Brudzinski and Kozłowska, 2019). This is often interpreted as due to the rarity of encountering all susceptibility conditions simultaneously, due to subsurface heterogeneities (Pawley et al., 2018; Hicks et al., 2021). These factors are likely relevant for the Neuquén Basin, given the strong clustering of cases within the opera-

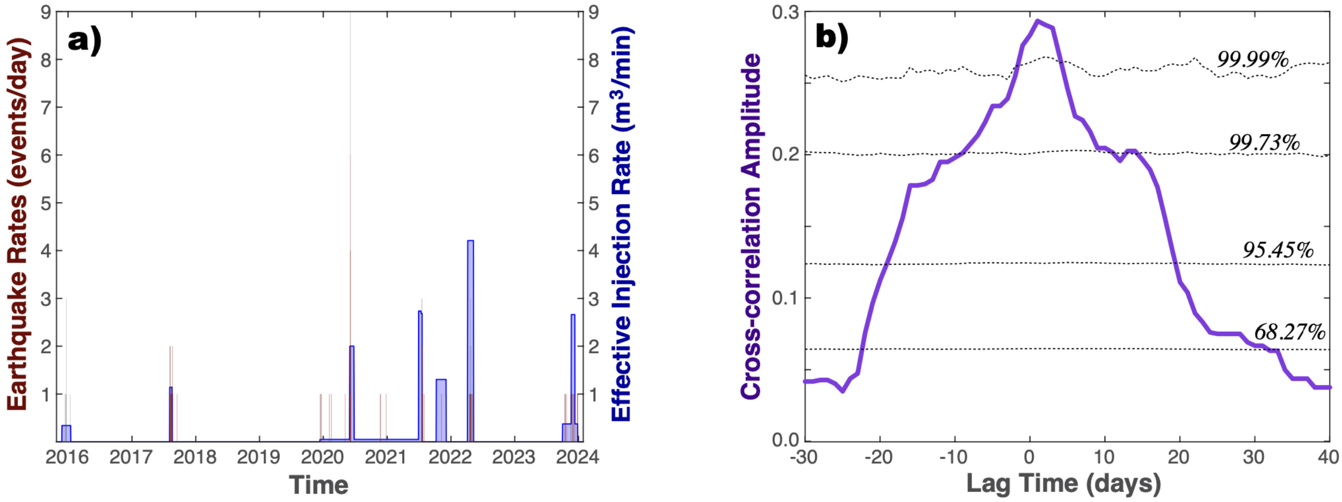


**Figure 6 Cross-correlation reshuffling tests.** (a) Timeseries data of earthquake rates above the magnitude-of-completeness (red bars), earthquake rates for the full catalogue (grey bars), and effective injection rates (blue lines), for the top ten SAF-scoring operations. (b) cross-correlation of timeseries data (purple line) alongside confidence intervals (black lines) from reshuffling tests.

tional footprint (Figure 4). Despite these complexities, constraining this activation rate can be important for hazard analysis (Ghofrani and Atkinson, 2020, 2021; Verdon and Bommer, 2021). Our raw rate of activation in the Neuquén Basin (*i.e.*, ~1.6%) likely overestimates the true rate, due to the potential for false-positives during SAF processing (Section 3.1). If we simply subtract off the false-positive rates, all our SAF alternative processing agree on a corrected rate of ~0.5% ± 0.1%. We note that this value is on the same order-of-magnitude as other basins around the world (Schultz et al., 2020). On the other hand, our analysis has neglected to account for potential false-negatives – true cases of hydraulic fracturing induced seismicity that were misidentified by SAF processing. Accounting for these types of errors is nebulous, so our estimate should be considered as a lower bound. Certainly, monitoring improvements can demonstrably influence the estimation of this parameter (Ghofrani and Atkinson, 2020). Higher resolution databases would be needed to provide further interpretation.

## 4.2 Limitations of our analysis

While it appears clear that some of the earthquakes in the Neuquén Basin are induced by hydraulic fracturing, there still remains ambiguous events: for example, the largest earthquake within our catalogue, the M5 event on 7 March 2019. Similarly, the majority of the M4 events were not associated with an operation (Figure 4). In fact, only 42% of the catalogued earthquakes were linked with operations via our SAF. Considering these observations, we discuss the potential deficiencies and limitations of our analysis.

Part of this can be alleviated slightly through SAF optimization. For example, the M 4.2 event on 25 September 2017 occurring just outside the range of our temporal window (Figure S16). However, we suspect that this is a relatively minor factor, given the relative agreement between all SAF processing alternatives. Another issue confounding our analysis (and potentially causing an underreporting of cases) is the incompleteness of input datasets (Figure S4). Of the reported ~4000 well locations, roughly 16% are missing data critical for our analysis. Similarly, the M5 event (7 March 2019) happens one day before the reported start time of a nearby well (*i.e.*, ~2.5 km southwest from '*YPF.Nq.LLLO.x-2(h)*'). It is possible that many events could still be associated with hydraulic fracturing operations that were only poorly or coarsely documented.

On the other hand, there is the potential that these residual events could also be associated with other anthropogenic operations. Globally, induced seismicity has been observed in correspondence with numerous operation types (Foulger et al., 2018). Operations relevant for the Neuquén Basin include reservoir impoundment (Gupta, 2002), hydrocarbon production (Muntendam-Bos et al., 2022), or wastewater disposal (Ellsworth, 2013). Even some component of natural/baseline seismicity could play a role here, given the propensity for regions of seismic activity outside of the Neuquén Basin (Correa-Otto et al., 2018, 2024). The observation of multiple anthropogenic sources can complicate the identification of the true triggering mechanism (Zhai et al., 2021).

**Regarding reservoir impoundment** The Cerros Colorados Complex is a series of four embankment dams and a hydroelectric facility with a capacity of 462 MW (Dalmati et al., 2018), related to the Los Barreales and Mari Menuco Reservoirs along the Neuquén River (Figures 1 & 4). These two reservoirs have mean depths of ~67 m and ~80 m, respectively, and constitute a large water body covering more than 587 km$^2$. These facilities have been in operation for decades, with the facility beginning operation in 1972 and construction officially completed on 31 October 1980. To our knowledge, no reports of induced seismicity have been linked to the impoundment of these reservoirs (or any of the other nearby Argentinian reservoirs).

**Regarding hydrocarbon production** Unconventional production in the Neuquén Basin is the dominant source of hydrocarbons for Argentina. Since the start of unconventional exploitation in the Neuquén Basin, rates of oil and gas production have steadily risen. By 2017, oil/gas production rates were ~$2\times10^6$ $m^3$/year and ~$3\times10^9$ $m^3$/year, respectively; cumulative amounts were ~$8\times10^6$ $m^3$ and ~$7\times10^{12}$ $m^3$, respectively (Rosa and D'Odorico, 2019). To date, no studies have linked induced seismicity with hydrocarbon production following hydraulic fracturing anywhere throughout the world; although, this could change with time given that induced seismicity has been associated with conventional hydrocarbon production (Wetmiller, 1986; Jacquemond et al., 2024; Muntendam-Bos et al., 2022).

**Regarding wastewater disposal** Generally, the proper management of water is a significant concern for the Neuquén Basin (Forni et al., 2018, 2021). During unconventional oil production, roughly one third of the produced fluid is wastewater, which is then disposed of via subsurface injection (only a 5% recycling fraction is reported) (Rosa and D'Odorico, 2019). Basin-scale disposal rates are negligible prior to 2012, but quickly rises to ~$10^6$ $m^3$/year by 2014 (Rosa and D'Odorico, 2019); by the end of 2020, there had been ~$5\times10^6$ $m^3$ of wastewater disposed of in the Neuquén Basin (Tamburini-Beliveau et al., 2022). Better understanding the potential for disposal earthquakes will likely be important here; especially considering the prevalence of earthquakes caused by comparable wastewater disposal of elsewhere (Horton, 2012; Ellsworth, 2013; Frohlich et al., 2016; Zhai et al., 2021; Schultz et al., 2023c).

Ultimately, these kinds of limitations are best addressed by an improvement of the input dataset quality, focusing on detectability, completeness, and finer resolution. First and foremost, increased monitoring densification over the footprint of seismically active regions (Correa-Otto et al., 2018) will be critical for catalogue improvement. In many cases, events in the Neuquén Basin were only recorded by a handful of stations, impacting the detection completeness and spatial resolution of the input catalogue. Substantial improvements can also be realized through the deployment of advanced processing methodologies, such as phase picking via machine learning (Mousavi and Beroza, 2022) or template-matching (Skoumal et al., 2014). Both techniques have shown significant promise for improving catalogue sizes by up to an order-of-magnitude. Deeper catalogues will enable the use of advanced methods that can disentangle competing causal factors (Petrillo et al., 2024; Grigoratos et al., 2022). That said, ensuring that these datasets are open, transparent, and complete will be a key consideration (Schultz et al., 2020). Overall, improving dataset quality will be important for the future of earthquake risk management in the Neuquén Basin (Zhou et al., 2024).

## 5 Conclusions

In conclusion, we find that many of the earthquakes recorded in the Neuquén Basin are likely induced by hydraulic fracturing. This assertion is based on strong statistical evidence (>99.99% confidence) linking the timings and locations of earthquakes to operations. The lower bound estimate of wells that induced earthquakes is ~0.5%, with maximum magnitudes reaching M4. We further infer causation based on a similarity comparison against known hydraulic fracturing cases around the world. While these analyses indicate events that were induced (~42%), there remains others without clear associations. Whether these events are truly induced by hydraulic fracturing (but lacking an association due to incomplete data), induced by other anthropogenic operations, or part of the natural/tectonic background seismicity is unclear. This lack of clarity could be resolved with additional data (and then further study).

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## Data and code availability

The data and codes used to produce the results and figures of this study are available online for download at GitHub (https://github.com/RyanJamesSchultz/VM-ID). These resources are also available online at Zenodo (https://doi.org/10.5281/zenodo.14065345). The earthquake catalogue can also be found online at http://contenidos.inpres.gob.ar/buscar_sismo. Well information were derived from the Argentina Energy Secretariat (https://datos.gob.ar/dataset/energia-produccion-petroleo-gas-por-pozo-capitulo-iv/archivo/energia_0abd7bf1-c184-4940-b8cf-5f37961a2ba8) and the Ministry for Energy and Natural Resources of the Neuquén Province (http://hidrocarburos.energianeuquen.gov.ar/gis).

## Competing interests

The authors declare no competing interests.

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