

PARS: A web-based platform for probabilistic association of regional seismicity with oil and gas operations

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1 INTRODUCTION & SCOPE OF WORK

Determining whether earthquakes near oil and gas operations are induced or naturally occurring is essential for regulation, risk mitigation, hazard communication, and business planning. Yet many practical screening approaches still rely on qualitative criteria or simple proximity rules, which often lack the statistical rigor needed for defensible decisions. In this work, we present PARS (Probabilistic Association of Regional Seismicity), a web-based portal that operationalizes a peer-reviewed statistical framework for quantifying how confidently regional earthquake activity can be associated with oil and gas operations.

The current public implementation focuses on hydraulic fracturing (HF), which is the only mode presently available on the portal. The same broader framework also supports wastewater disposal (SWD) analyses, and this capability will be added to the portal very soon. The contribution presented here is therefore not a new attribution theory, but a reproducible user interface that translates an established induced-seismicity workflow into an accessible, stepwise environment for regulators, operators, consultants, and researchers.

PARS is designed to help users move from raw earthquake and injection data to interpretable, spatially distributed statistical evidence. Relevant public datasets are available within the portal, while private datasets can also be uploaded safely in structured formats. The interface is organized as a stepwise workflow in which input controls are shown on the left and spatial outputs on the right, allowing the user to define the investigation settings while simultaneously checking data coverage and, later, the resulting p-value patterns on an interactive map.

2 METHODOLOGY

The portal implements the probabilistic association framework described in Grigoratos *et al* (2020b, 2022, 2025a; Figure 1) and builds on the statistical-significance concepts discussed by McClure *et al* (2017). This robust protocol has been previously successfully applied in Oklahoma (Grigoratos *et al* 2020b; Grigoratos *et al* 2025a), West Texas (Grigoratos *et al* 2022) and in the Eagle Ford shale play (Grigoratos *et al* 2025b). Earthquake catalogs and injection records are aggregated on a two-dimensional spatial grid, producing cell-based time series of seismicity and injection. The current HF implementation uses the average daily injection rate per stimulation, the well coordinates and the stimulation dates as input. The earthquake catalog is expected to cover both natural and induced events and includes event date, location, and magnitude, and should ideally be declustered because the recurrence model simulates only mainshock occurrence. The user can choose which declustering approach fits the data best; we recommend the one followed in Grigoratos *et al* (2025a).

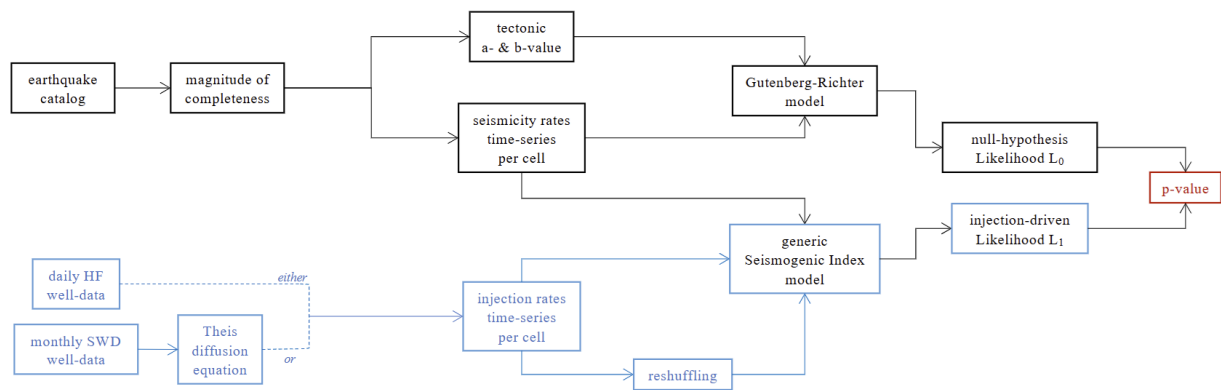


Figure 1. Schematic diagram (flowchart) of our hypothesis testing framework. Dashed lines indicate alternative paths.

The portal workflow is organized into six steps, with reasonable and often data-driven default values provided for every parameter. In Getting started, the user selects the analysis mode, which is currently limited to HF, and loads the earthquake catalog and the injection dataset (Figure 2). The loaded tables expose the key fields used by the workflow, such as event origin date and time, local or moment magnitude, event and well coordinates, average daily HF rate, and stimulation start and end dates. The map on the right shows the geographic distribution of the uploaded datasets.

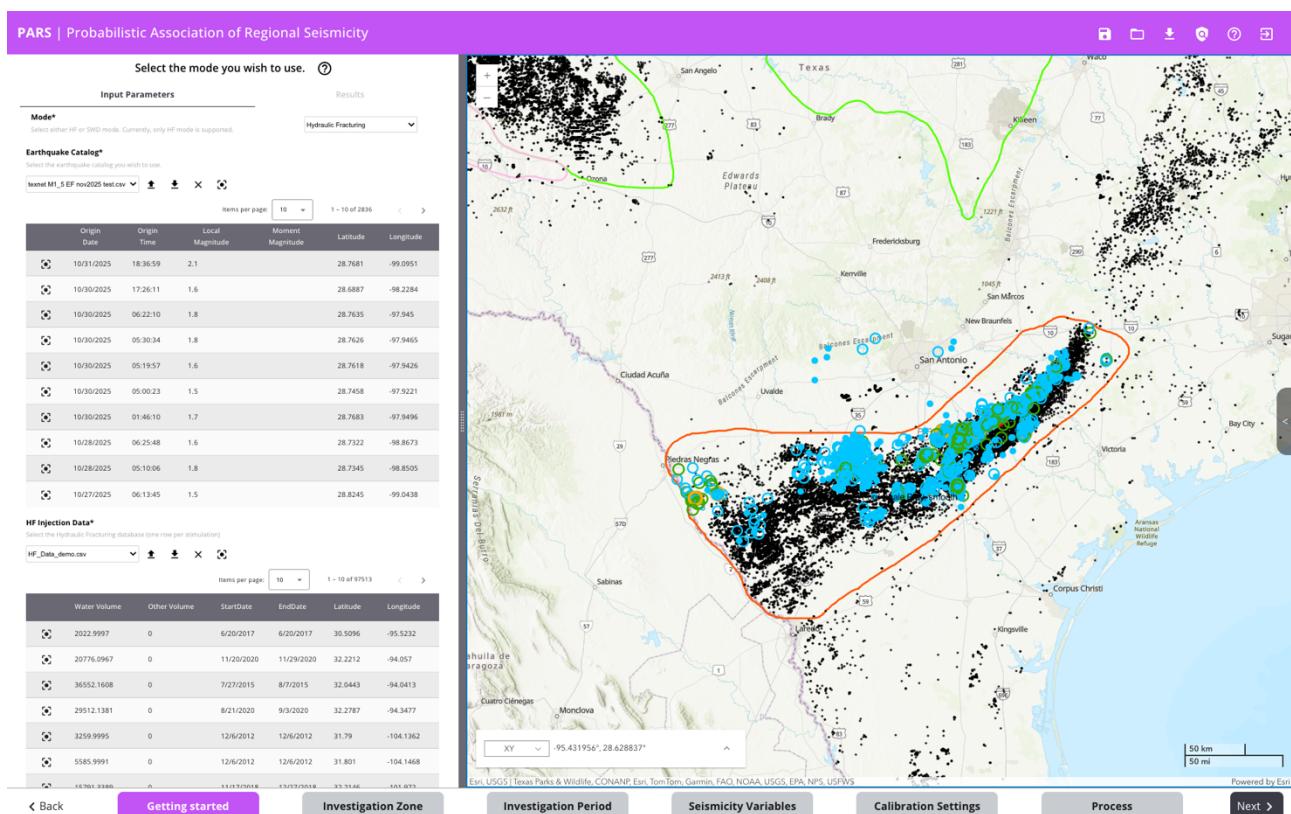


Figure 2. First step of the PARS portal. The interactive map shows the earthquake catalog (colored hollow circles sized by magnitude), the HF wells (black dots) and known basin borders. The datasets selected are only for illustration purposes.

In Investigation Zone, the user defines the rectangular study area and the spatial discretization through grid-cell size; the interface also reports the resulting width and height of

the selected domain (Figure 3a). In Investigation Period, the temporal window for aggregation and calibration is set (Figure 3b).

(a)

PARS | Probabilistic Association of Regional Seismicity

Enter parameters of the investigation zone. ?

Input Parameters	Results
Investigation Zone Extent* Geographic extent (in latitude and longitude) of the investigation zone.	
Longitude Min. -100.5675936172483 Latitude Max. 29.620806464501523	Longitude Max. -96.81713585357663 Latitude Min. 27.945806057095993
Width: 366.18 km Height: 185.64 km	
Grid Cell Size (km)* Grid cell resolution of the spatial grid.	5
Block Cell Size (km)* Size of blocks - Must be double the cell size.	10
Minimum Distance (km)* Minimum distance between the reshuffled blocks. Should be at least 2x block size.	5

(b)

PARS | Probabilistic Association of Regional Seismicity

Enter parameters of the investigation period. ?

Input Parameters	Results
Starting Period* Beginning month and year for the data and calibration	
Month and Year 02/2017 📅	
Ending Period* Ending month and year for the data and calibration	
Month and Year 10/2025 📅	

Figure 3. Second (a; Investigation Zone) and third (b; Investigation Period) steps of the PARS portal. Only the settings side is shown here; the interactive map is omitted. The values selected are only for illustration purposes.

In Seismicity Variables, the user specifies the magnitude of completeness of the earthquake catalog and some optional advanced parameters, such as the minimum number of earthquakes for a block to be analyzed, the Gutenberg-Richter b-value and the tectonic activity rate (Figure 4a). For user convenience, the latter is auto-filled, for the given investigation zone, based on the calculations in Bird *et al* (2015). In the user interface of the portal, the map on the right gets progressively automatically filtered for the investigation zone, investigation period, and magnitude of completeness.

In Calibration Settings, the user chooses the number of resamples for the reshuffling process, the number of shifted spatial grids used for oversampling, the maximum constant time-lag, and the admissible Seismogenic Index (Σ) range (Figure 4b). For user convenience, the latter is auto-filled, based on limits defined by processing the filtered datasets in use. Finally, in step Process, the portal computes and displays the results (Figure 5).

At the core of the method are two competing block-specific seismicity models (Figure 1). The null hypothesis assumes that observed rates are explained by tectonic loading alone, whereas the alternative hypothesis allows the seismicity rate to be driven by injection (Grigoratos *et al* 2020a). At each block, the null hypothesis assumes that all earthquakes can be modelled using the classic Gutenberg–Richter (G-R) relationship. The injection-driven model adopts a physics-based earthquake recurrence model that is an extension of the Seismogenic Index model (Shapiro *et al* 2010), which predicts that the number of induced earthquakes is proportional to the pore pressure change, which can be approximated by the injected volume. The modifications of Grigoratos *et al* (2022; 2025a) took into account the background tectonic rate and the stressing-rate dependency of the time lag between injection and seismicity rate changes.

For each block, the corresponding model parameters (Seismogenic Index, time-lag) are calibrated and the likelihood of the observations under each hypothesis is computed. Likelihood ratios are then converted to p-values through reshuffling tests, in which injection data are randomized in space and time to quantify the frequency of coincidental correlations (Grigoratos *et al* 2022). The resulting p-value is therefore a measure of confidence for rejecting the null hypothesis in favor of the injection-driven explanation (McClure *et al* 2017; Grigoratos *et al*

2020b). The workflow is intended for large-scale investigations, assumes that injection operations are not strongly altered by seismicity-mitigation responses, and evaluates one external triggering factor at a time within each analysis.

For each block, PARS compares the likelihood of the observed seismicity under the tectonic and injection-driven hypotheses. It then reshuffles gridded injection data in space and time to build a reference distribution for coincidental correlations. The resulting p-value measures how unusual the observed likelihood gain of the injection-driven model is relative to randomized injection histories.

(a)

PARS | Probabilistic Association of Regional Seismicity

Enter parameters related to the level of seismicity ?

Input Parameters	Results
Magnitude of Completeness* Magnitude threshold above which all earthquakes are considered in the catalog.	1.5 ⓘ
Advanced Options ^	
Annual tectonic events >= M3* Annual number of M3+ events in the region	0.3128 ⓘ
Tectonic b-value* Slope of log-normal magnitude-frequency distribution.	1
Minimum #EQs per block* Minimum number of earthquakes above the magnitude of completeness	3
Calculate seismogenic index* Calculate seismogenic index	☒

(b)

PARS | Probabilistic Association of Regional Seismicity

Enter calibration settings ?

Input Parameters	
Number of resamples* Requested number of samples for reshuffling. (Recommend 100)	20
Spatial Grids* Number of spatial grids. Recommended: 5	1 v
Maximum Constant Time-lag* Measured in days.	1
Σ Range* Range of Seismogenic Index values. Lower and upper bounds. Dimensionless.	Minimum: -5.1005 Maximum: -0.4303 ⓘ
Advanced Options ^	
Maximum Number of Resamples* Maximum allowed iterations to reach requested number of resamples.	20
Time-lag* Constant or time-dependent time-lag	Constant v
Σ Step* Interval step between min and max Σ values. Must always be positive.	0.1
Minimum Injection Rate* Minimum injection rate per well, measured in BBLs/day.	1
HF Fluid Type* Fluid type used in the stimulation.	Any v

Figure 4. Fourth (a; Seismicity Variables) and fifth (b; Calibration Settings) steps of the PARS portal. Only the settings side is shown here; the interactive map is omitted. The values selected are only for illustration purposes.

3 RESEARCH OUTCOMES

The user interface hosted on the web portal converts a statistically rigorous induced-seismicity attribution framework into a guided workflow that can be used to indirectly run the underlying MATLAB codebase (hosted on university servers). The user interface exposes the key methodological choices in a transparent way: the user selects the data, defines the study domain, calibrates the model parameters, and receives block-by-block p-values together with the relevant spatial context.

The results page illustrates the practical form of the output. Each analyzed block is assigned a p-value and summarized in a table that includes its coordinates together with supporting quantities such as the number of earthquakes above the magnitude threshold, the maximum observed magnitude, cumulative injected volume, median fitted Seismogenic Index, and median fitted constant time-lag (Figure 5). The same information is shown spatially on the interactive map, where blocks are color-coded by p-value and displayed together with the earthquake catalog. The table can be exported as a CSV file, allowing downstream reporting and further analysis.

The interpretation follows the logic already embedded in the portal documentation. P-values below 0.05 indicate that the investigated activity is a key triggering factor for the seismicity in that block. Values between 0.05 and 0.10 suggest that some induced seismicity may be present, values between 0.10 and 0.20 are inconclusive, and values above 0.20, especially above 0.50, suggest little to no triggering by the analyzed activity.

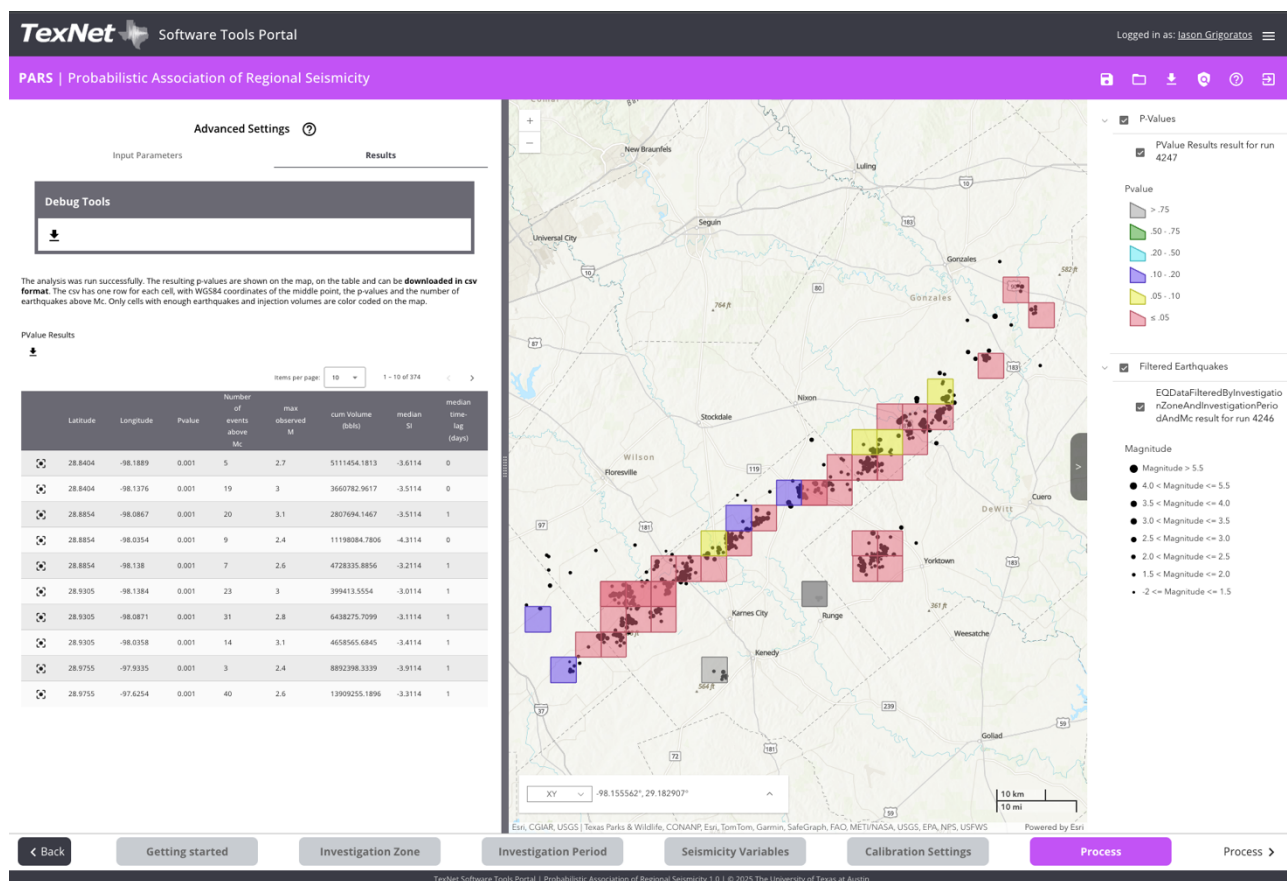


Figure 5. Illustrative results view, showing block-level HF p-values, relevant variables, and the mapped spatial distribution of statistical confidence.

From a policy and risk-governance perspective, a framework such as PARS is useful because it moves the discussion of whether seismicity is natural or operationally induced from qualitative judgment to a transparent, reproducible, and spatially resolved statistical basis. By quantifying the confidence with which earthquake activity can be associated with nearby oil and gas operations, the method can help regulators prioritize scrutiny, design proportionate mitigation measures, and support more defensible operational decisions in areas of elevated concern. The same output is also relevant to the insurance sector, where probabilistic association metrics can provide an objective evidentiary basis for claims assessment, portfolio screening, and underwriting in regions affected by induced seismicity, including whether reported damage may plausibly be linked to anthropogenic activity rather than background tectonics.

In summary, PARS provides a transparent bridge between peer-reviewed induced-seismicity science and practical decision support. The current HF release is ready for regional probabilistic assessments of hydraulic-fracturing-related seismicity, while the forthcoming SWD release will extend the same interface philosophy to wastewater-disposal investigations.

FUNDING

This material is based upon work supported by the U.S. Geological Survey under Grant No. G22AP00243 (FY2022) of the call G22AS00006. The Texas Seismological Network and Seismology Research (TexNet) and the State of Texas provided financial support under the University of Texas at Austin Award Number 201503664.

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