Which operational factors lead to seismogenic fluid-injections? observations from ten large-scale studies in North America

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Summary

We examined which operational factors are correlated with the prevalence of induced seismicity caused by hydraulic fracturing (HF) and wastewater disposal (SWD) activities in North America. We leveraged a robust hypothesis testing framework that investigates potential causal factors using the same probabilistic physics-based methodology (Grigoratos et al. 2020; 2022). This approach first hindcasts the seismicity rates after a given time on a 2D spatial grid using either actual or randomized HF and wastewater data as input, and then compares those rates against the null hypothesis of solely tectonic loading. In the end, each square cell is assigned a p-value, indicating the statistical confidence of its association with each oil and gas activity. We then labelled every SWD/HF well as seismogenic or not, employing the aforementioned confidence intervals, in conjunction with spatio-temporal well-to-earthquake association filters. Our datasets included 600,000 SWD wells, 219,000 HF stimulations and 93,000 earthquakes from Oklahoma, Kansas, Arkansas, Texas, New Mexico, Colorado, and the Western Canada Sedimentary Basin (Grigoratos & Wiemer 2023). Our methodology is described in Grigoratos et al. (2020; 2022).

Our key findings were:

SWD:

- About 90% of seismogenic wells were less than 5 km away from the closest earthquake
- median (non-zero) disposal rates above 10'000 bbls/month, total volume above 1 million bbls and proximity-to-basement are crucial parameters for seismogenic potential
- the absolute well-depth does not affect the magnitude or likelihood of triggered seismicity
- the Theis equation for large-scale diffusivity values between 0.3 and 2 m^2/s is a good and necessary first approximation for the spatio-temporal diffusion of the disposed volumes

HF:

- a very small percentage of stimulations is responsible for the reported HF-induced seismicity
- 90% of seismic clusters started developing during stimulation
- at the basin scale, there is no correlation between seismic potential and injection rate, total volume or stimulation depth
- seismic triggering due to HF seems to be a highly heterogeneous and localized process

Results for SWD

The vast majority of seismogenic SWD wells, around 90%, were within 5 km from the closest detected earthquake, while nearly all were within 10km. This implies that even though far-field effects are possible, they require a rare set of circumstances. Next, in agreement with consensus (Weingarten et al 2015), we find that the peak disposal rate is a critical operational parameter, with values exceeding 100'000 bbls/month being increasingly more likely to cause detectable seismicity. That said, we should highlight that the median disposal rate is an even better predictor, for all examined magnitude ranges (Figure 1), with 10'000 bbls/month being a key threshold. Furthermore, our analysis is the first one to clearly demonstrate that the total volume of a wastewater disposal well is a driving factor for its seismogenic potential, with values above 1 million bbls being consequential. That said, the total volume is not a good predictor of nearby earthquake magnitudes.

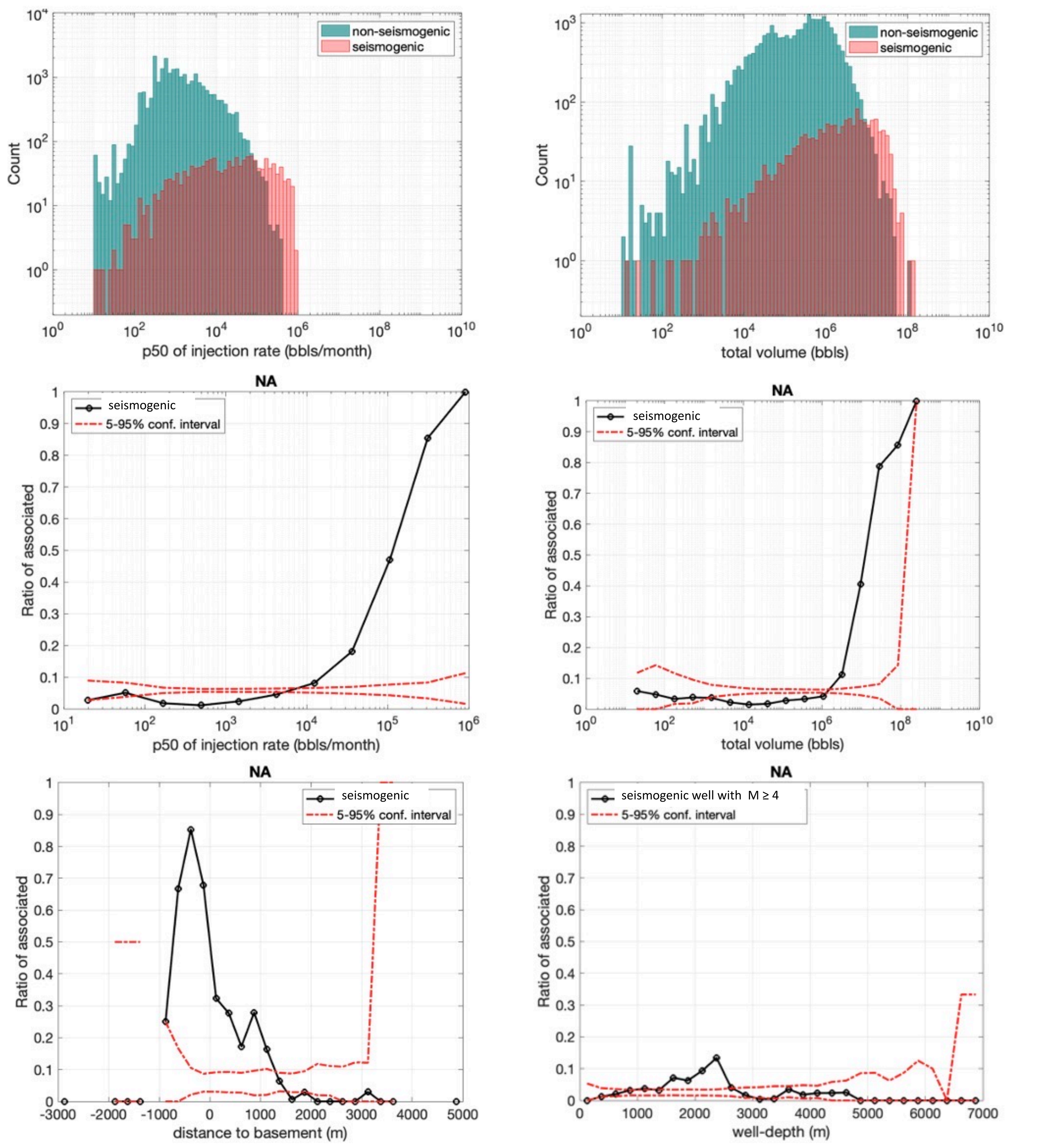

Figure 1. Histograms of seismogenic and non-seismogenic SWD wells (from all regions combined) for M ≥ Mc as a function of (a) median monthly disposal rate, (b) cumulative disposed volume. In (c) – (f), we plot the ratio of seismogenic versus non-seismogenic SWD wells in each bin as a function of (c) median monthly rate for $M \geq M_c$, (d) cumulative disposed volume for $M \geq M_c$, (e) proximity to basement for $M \geq M_c$, (f) true vertical depth for M ≥ 4. Only OK data were available in (d). The median disposal rates are computed excluding zeros. The two dashed red lines represent the upper (95%) and lower (5%) confidence bounds in each bin generated by 10,000 bootstrap resamples and following the assumption that the rate of association is random.

Results for HF

Even in areas where HF seismicity was prevalent, only a very small percentage of stimulations was confidently associated with the recorded seismicity. The exact number was 1% in OK-KN, 5% in Delaware basin, 3% in EF, 1% in Alberta, 11% in BC, and 5% in Arkansas. This might imply that the control over the seismic hazard lies more in the hands of operators than regulators. Furthermore, on aggregate, 90% of detectable earthquake clusters started during stimulation, thus we advise against long temporal association windows.

Figure 2 shows that neither the injection rate nor the total injected volume is a good proxy for the seismogenic potential of a HF stimulation, in contrast to SWD. Geomechanical factors dominate operational ones across basins. The volume and the rate have predictive value for the seismicity within local (sub km) scales, once the overall triggering sensitivity of the site has been accounted for.

The stimulation depth is also not a good proxy for the seismic potential of a HF stimulation, regardless of the examined magnitude range. The nucleation process appears to be highly heterogeneous, and perhaps dominated by fault proximity and orientation at the local level.

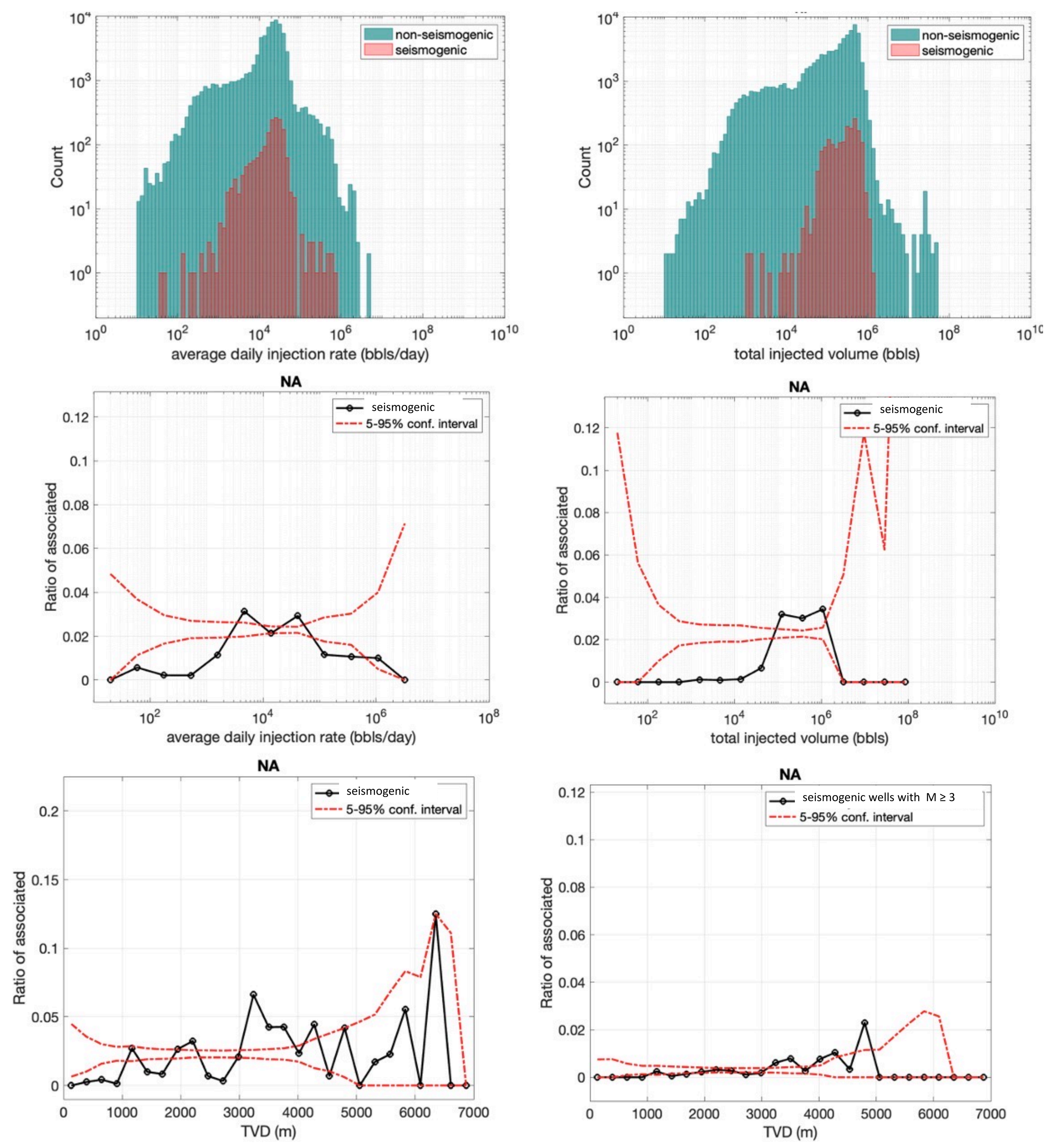

Figure 2. Histograms of seismogenic and non-seismogenic HF stimulations as a function of (a) average daily injection rate, (b) total injected volume, and of the true vertical depth for $M \geq M_c$ (c) and for M ≥ 3 (d). Next, the ratio of seismogenic versus non-seismogenic stimulations in each bin is plotted as a function of (b) average daily injection rate, (c) total injected volume. The two dashed red lines represent the upper (95%) and lower (5%) confidence bounds in each bin generated by 10,000 bootstrap resamples and following the assumption that the rate of association is random.

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