Spatiotemporal Clustering and Migration of Micro-seismicity in the Delaware Basin: Insights into the Causal Mechanisms of Induced Basement Earthquakes

Caltech GMG

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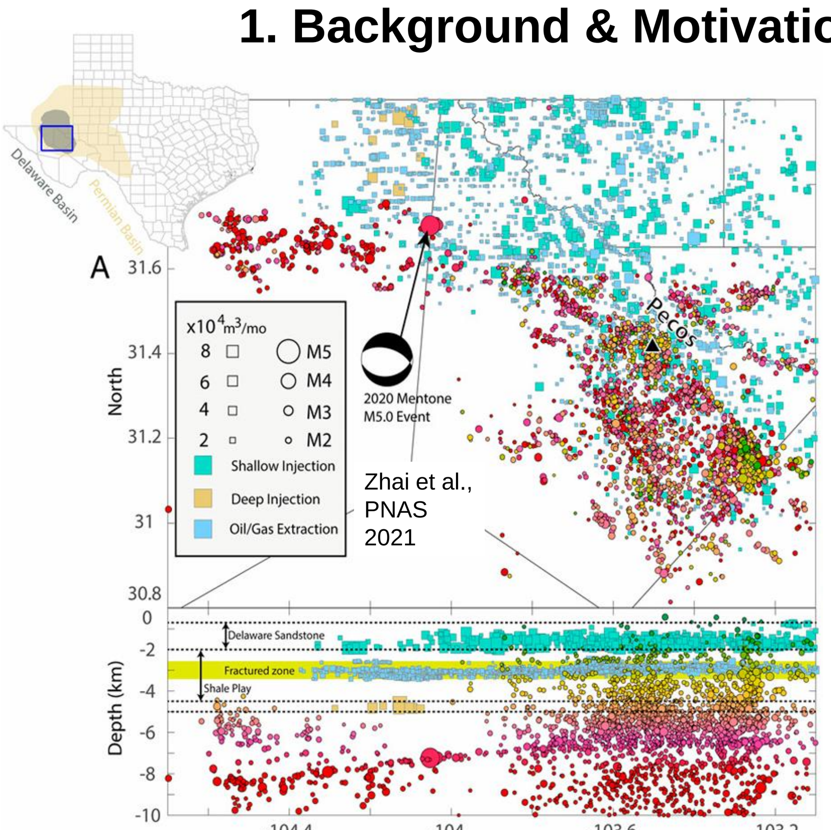
Abstract

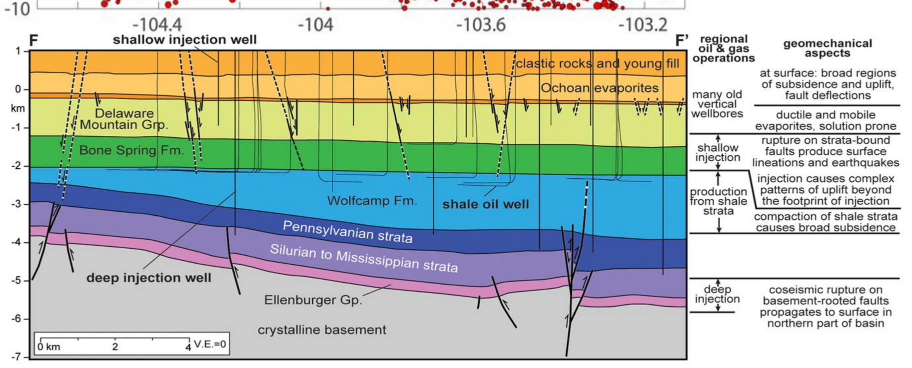
Delaware basin, located in West Texas and SE New Mexico, is one of the most productive shale basins since 2010s. Induced seismicity surged after 2014, including 7 M>5 events since 2010, with 2 occurring 2025. However, the causal mechanism is still under debate, given the various O&G operations taking place and the long-distance triggering. In this study, utilizing an enhanced seismic catalog built with dense array, we perform spatiotemporal clustering and seismic migration analysis to investigate this problem. We first applied a newly designed spatial clustering workflow based on HDBSCAN algorithm, which gives 160 clusters with >100 events. Further analysis are based on these separated clusters. Secondly, we quantified the temporal clustering degree of each cluster using Fano Factor with 1-day bins. We found that larger clusters on the NW area tend to show bursts of day-long durations: a special feature to be investigated in the future. Finally, we analyzed the migration patterns of clustered seismicity. An automatic workflow was developed to detect persistent migration over 400 days with >1 m/d expansion speed. Results show that the migrating clusters also distribute in the NE area, where continuous water injection was performed during the study period. These micro-seismicity migrations feature a dominant down-dip forefront and exhibit termination backfront that is diagnostic for fluid diffusions. Thus, the migration process and its relationship with the injection history can also provide insights into the hydraulic structure.

1. Background & Motivation



Various O&G operations:

- **Shallow water injection**: into the DMG sandstones
- **Deep water injection**: into Silurian–Devonian carbonates
- **Hydraulic fracturing** (HF) and **oil production** within the Wolfcamp and Bone Spring Formations



Hennings et al., STE 2023

Reference	Method	Conclusion
Skoumal et al., JGR 2020	Spatiotemporal correlation between seismicity rate and HF stimulations to distinguish HF-induced seismicity	~5% HF-induced ~95% WD
Grigoratos et al., SRL 2022	Statistical hypothesis testing to evaluate the likelihood of seismicity induced by HF, shallow or deep WD	~18% HF ~43% Shallow WD ~12% Deep WD
Savvaidis et al. BSSA 2020	Use space-time clustering and probabilistic association to attribute seismicity to HF or WD	HF+SWD, with spatially varying dominance
Zhai, Shirzaei, & Manga, PNAS 2021	Poroelastic stress modeling with waste water injection and hydrocarbon extraction	Poroelastic effect explains long-distance triggering

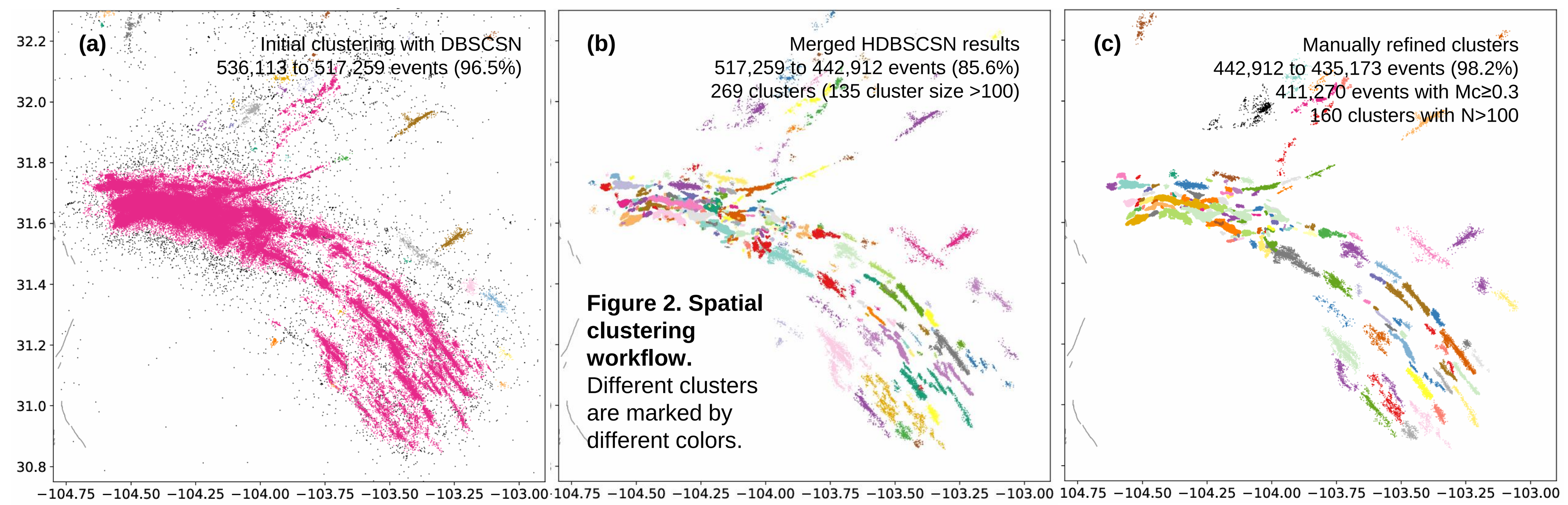
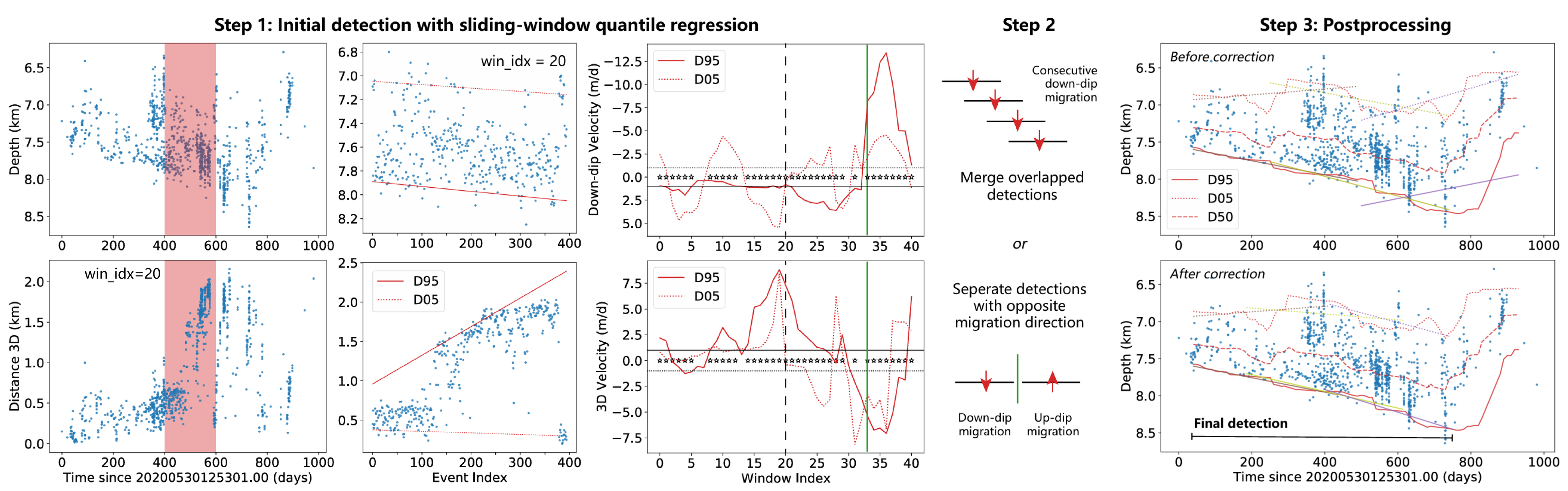


Figure 2. Spatial clustering workflow. Different clusters are marked by different colors.



3. Temporal Clustering

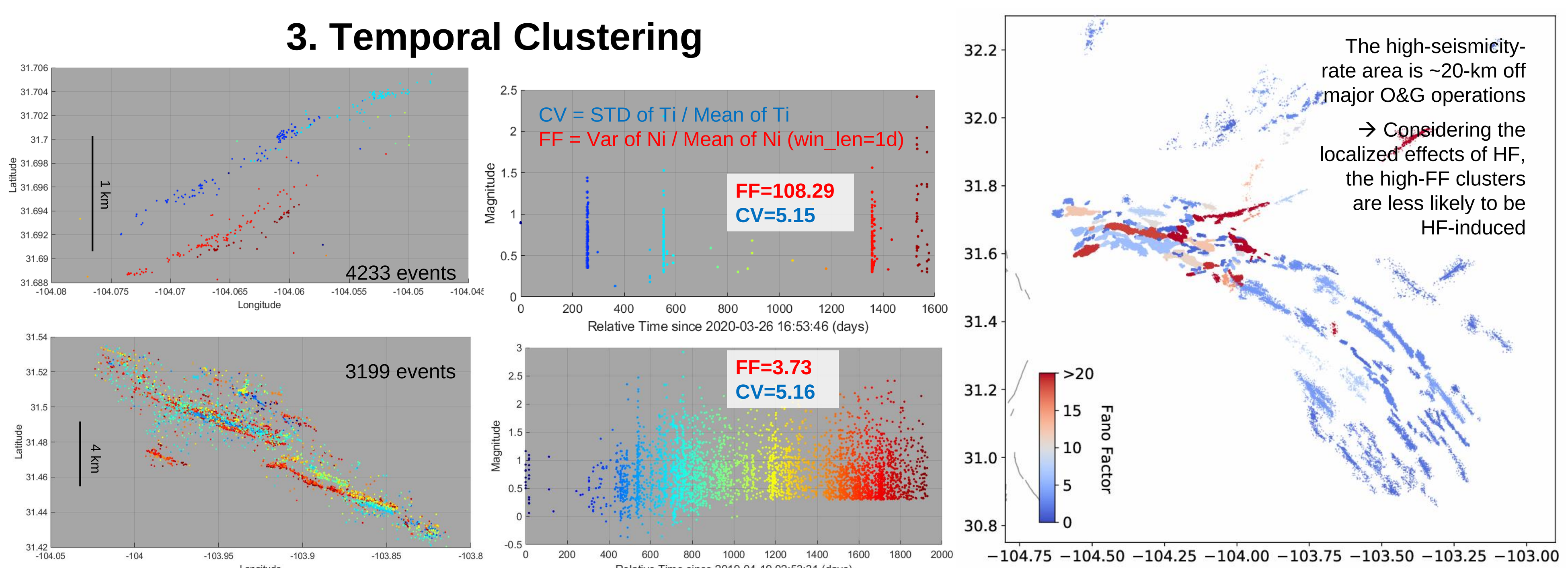


Figure 3. End-member examples of temporal clustering patterns. The upper and lower panels show the map-view distribution and magnitude-time plot of two seismicity clusters. Events are color-coded by the origin time. Both clusters have similar Coefficient of Variance (CV), but contrast in Fano Factor (FF). The high FF value for the first cluster indicate its high degree of burstiness.

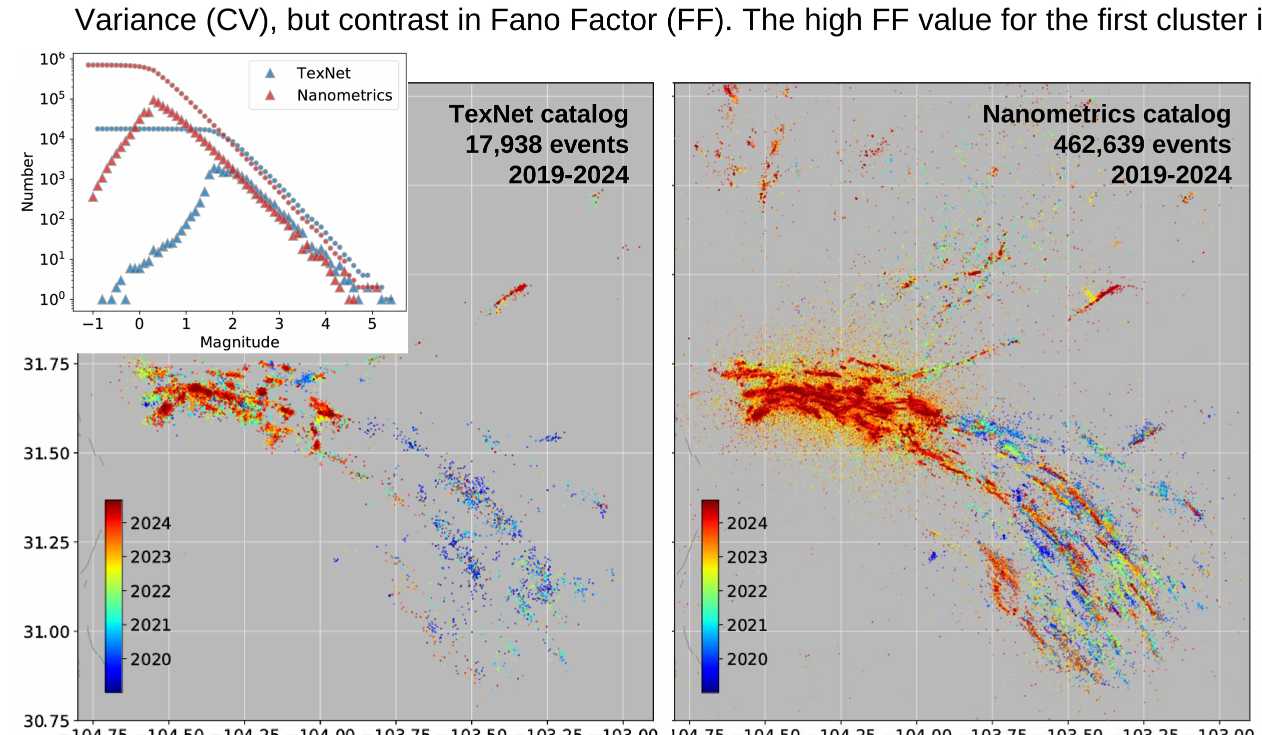


Figure 1. Comparison of seismic catalogs. The left and right panels plot the TexNet catalog and the Nanometrics catalog, with events color-coded by the origin time. The inset plot frequency-magnitude distribution, with triangles and dots denote non-cumulative and cumulative distributions, respectively.

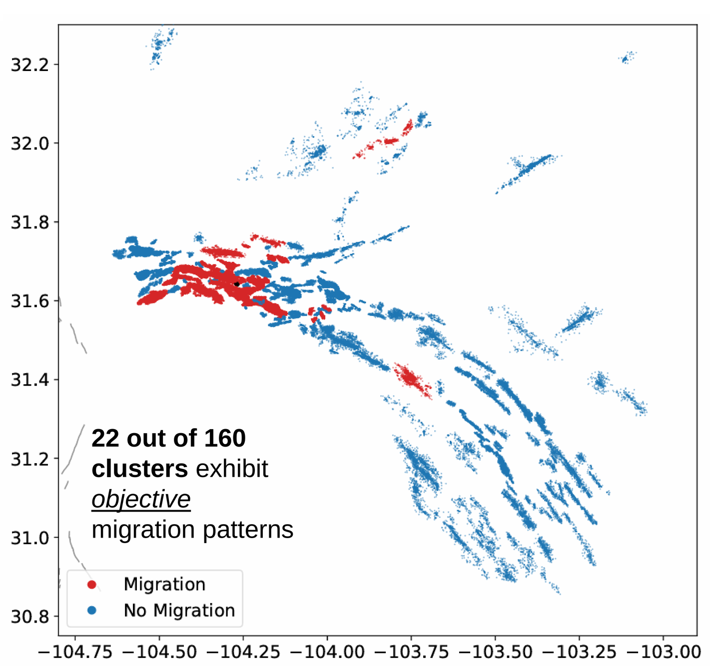


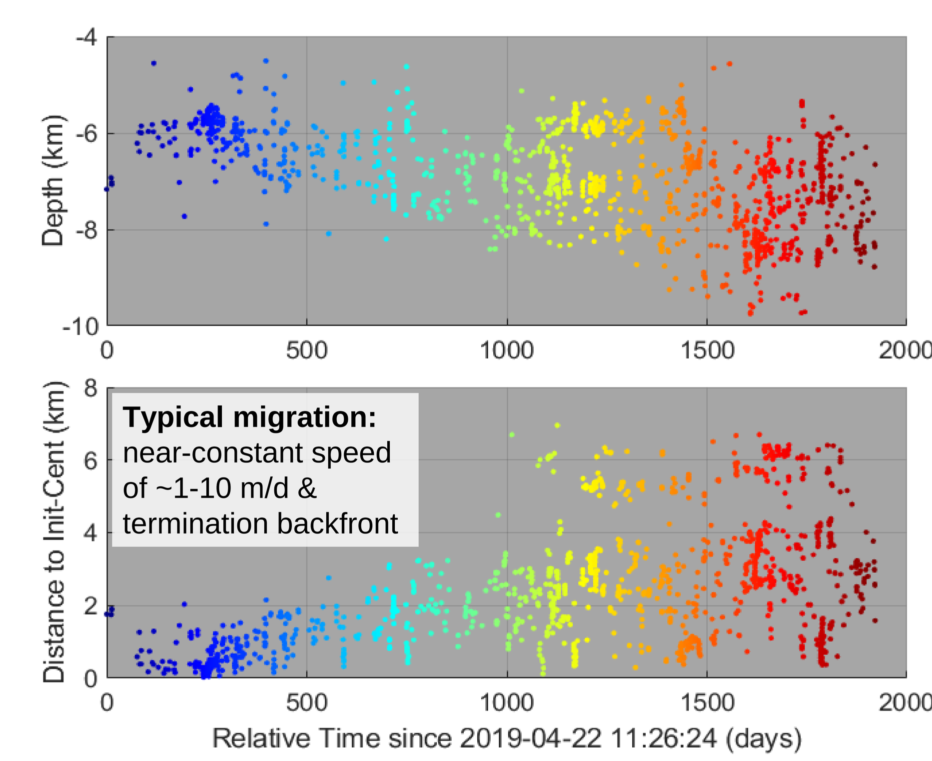
Figure 4. Distribution of migrating clusters. Red and blue dots denote clusters with and without objective seismicity migrations.

2. Spatial Clustering

- **(1) Initial denoising with DBSCAN (*eps*=2 km)**
  - Some obvious noise may bias visual inspections and potentially the HDBSCSN clustering process
- **(2) HDBSCAN with multiple sets of parameters**
  - *min_cluster_size=20~100; min_samples=10 or nan*
  - Different parameters focus on clusters of various properties
  - Distinct clusters rarely merges under different parameters, and no single parameter setting captures all of them
- **(3) Manual post-proc. for under-clustered cases**
  - Only separate visually distinct clusters, while keeping most of the inner geometrical complexities

4. Seismicity Migration

- **(1) Initial detection with quantile regression**
  - Sliding 200-d windows with 20-d steps to estimate D05 & D95 expansion speed for both Depth and 3D Distance
  - Quantile regression on event index plot for slope estimation
- **(2) Merge all detections and separate reversed periods**
  - Merge as long as two sliding frames overlap
  - For migrations of reversed direction, separate into two segments
- **(3) Tune start & end time and check evolution proc.**
  - The early/middle/late stage need to show consistent migration speed and direction with the overall behavior



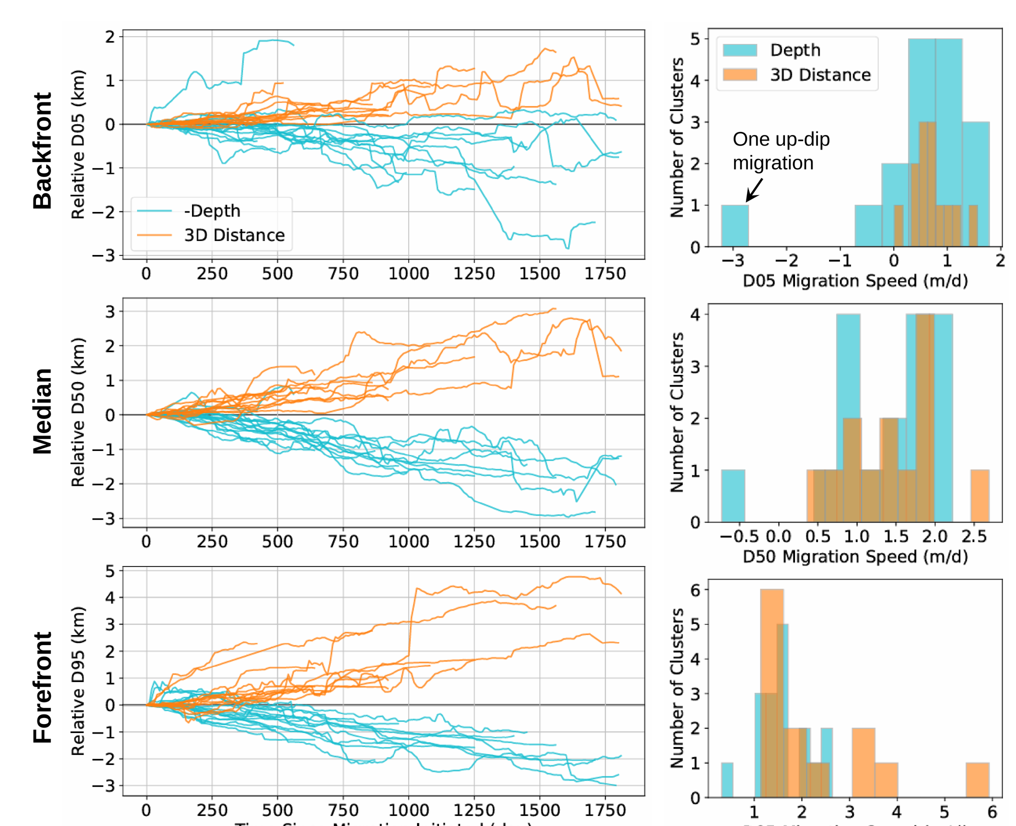
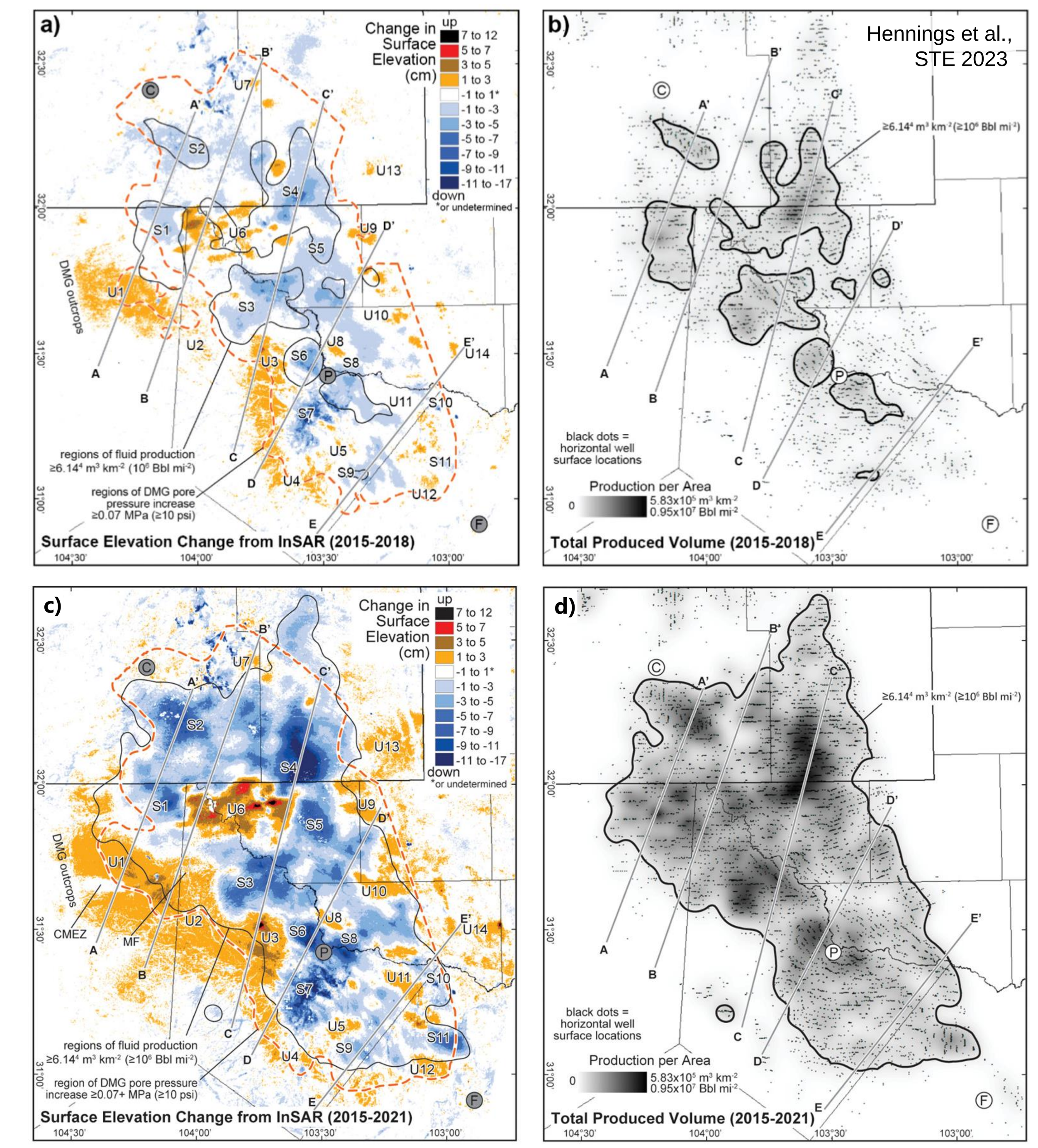


Figure 5. Migration contours and distribution of migration speed. Cyan and orange markers denote the migration along Depth and 3D Distance, respectively.

5. Future Works

- **(1) Understand the surface deformation pattern**
  - Widespread subsidence spatially correlate with the production zones
  - Uplift occur in areas peripheral to subsidence, indicating a fluid diffusion process
  - Localized uplift patches (e.g. U6) potentially imply heterogeneous fluid flow barriers



- **(2) Understand the diverging seismicity evolution in different regions**
  - The SE seismicity (mostly shallow events) peaked in ~2017-2019, after which the rate declined sharply, even though shallow injection volumes stayed high
  - Seismicity in the NW region surged after 2019 and continue through 2024. These events were deeper, often below the basement
- *Given the similar injection history, why induced seismicity in the two regions (SE vs. NW) exhibit diverging patterns?*
  - SE shallow seismicity decreased because of fault saturation?
  - NW deep seismicity showcased delayed response to deep injection?

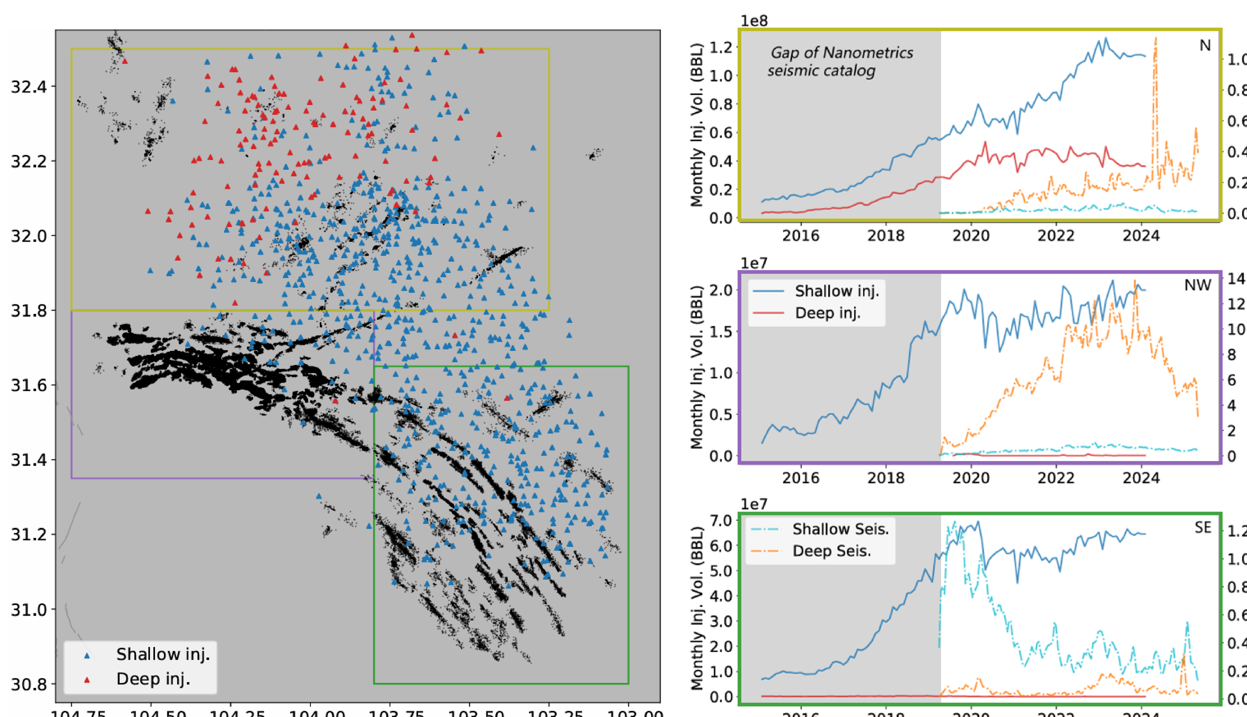


Figure 6. Evolution of seismicity and injection history for different regions. The whole Delaware Basin is divided into North, Northwest, and Southeast subregions. The temporal evolution of deep (below basement) and shallow seismicity are plotted as orange and cyan dashed lines, respectively. The deep and shallow injection history are plotted in the same panels with solid red and blue lines, respectively.