New Insights into the Rangely Earthquake Control Experiment

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Abstract

The Rangely experiment was the first experiment to control the occurrence of earthquakes deliberately by varying fluid injection. It was conducted in an anticlinal oil field at Rangely, Colorado in 1970s. Due to its controlled nature and to the close correspondence between local earthquake activity and reservoir pressure, it provides a unique opportunity for studying injection induced earthquake mechanisms. Although our understanding of the mechanisms responsible for inducing earthquakes has advanced significantly since the time of the Rangely experiment in the 1970s, few attempts have been made to reanalyze the Rangely earthquakes (Byrne et al., 2020, Silva et al., 2021). This is largely attributed to the loss of original earthquake catalog. Recovery of the catalog using standard methods would be both time consuming and challenging, as all that survives are the original Develocorder microfilms. We developed an efficient machine-learning-based system for analysis of the films that efficiently processes analog seismograms at scale. We build on our reconstructed catalog to conduct a geomechanical analysis and investigate the physical mechanism inducing the Rangely earthquakes. Our results support the effective stress hypothesis as originally proposed in the Raleigh et al. (1976) study. We found that events are more continuously distributed between inside and outside the oil field than previously reported, which supports a direct fluid connection across the bounding thrust fault. The spatiotemporal distribution of seismicity and its correspondence with reservoir pressure also supports the conclusion that the earthquakes were induced by pore pressure increase rather than poroelastic effects. Additionally, we performed earthquake clustering and found that the Rangely earthquakes are characterized by short-lived sub-sequences. We inferred from the sub-sequence propagation that they are likely driven by fast stress transfer processes such as earthquake interaction, fluid diffusion or aseismic slip. These results offer new insights on the physical mechanisms of the Rangely induced earthquakes. With the Rangely example, we demonstrated that we can efficiently perform seismic analysis on analog data. This demonstrates the potential of the approach to study other important pre-digital earthquake sequences.

Reconstructing an Earthquake Catalog from the Rangely Develocorder films (DevelNet)

We reconstructed an earthquake catalog from the Develocorder film recordings by performing machine-learning image-based seismic analysis on the analog data. This allow us to recover lost spatiotemporal patterns of the Rangely induced earthquakes and their characteristics, such as focal mechanism and earthquake clustering behavior.

- Detected twice the number of events.
- Events are more persistent at later times.
- b-value 0.86
- Magnitude of completeness -0.4

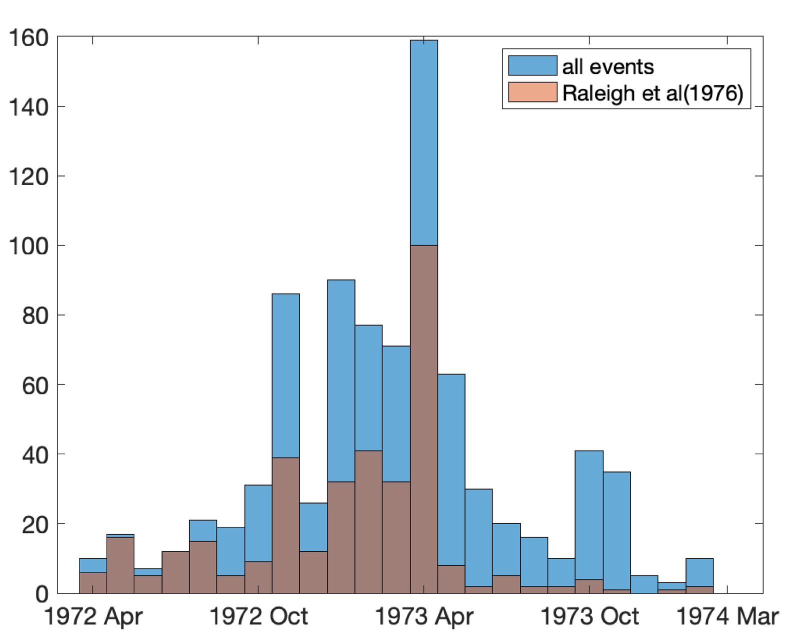

Figure 2: Histogram of monthly earthquake rate at Rangely. Red bars are monthly number of events reported by Raleigh et al. (1976). Blue bars are number of events in our reconstructed catalog.

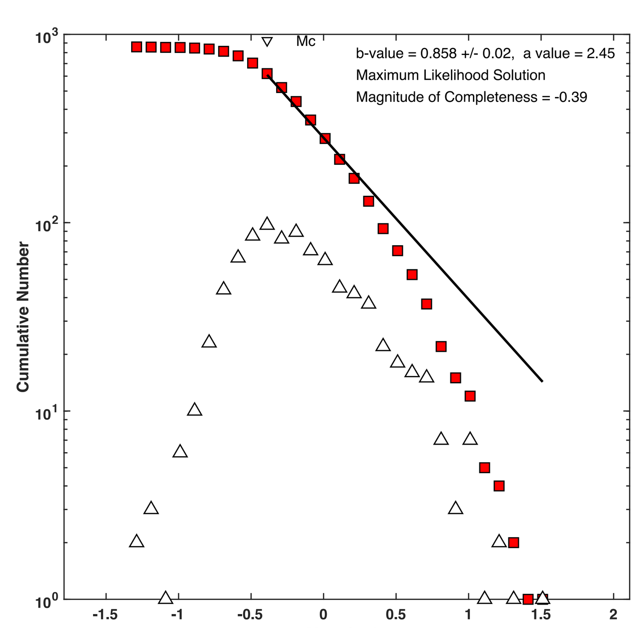

Figure 3: Coda magnitude distribution of the Rangely events. Red squares are cumulative number of magnitude distribution. Black line shows the b-value fit.

Contact me if you are interested in DevelNet!
(earthquake detection on Develocorder films)

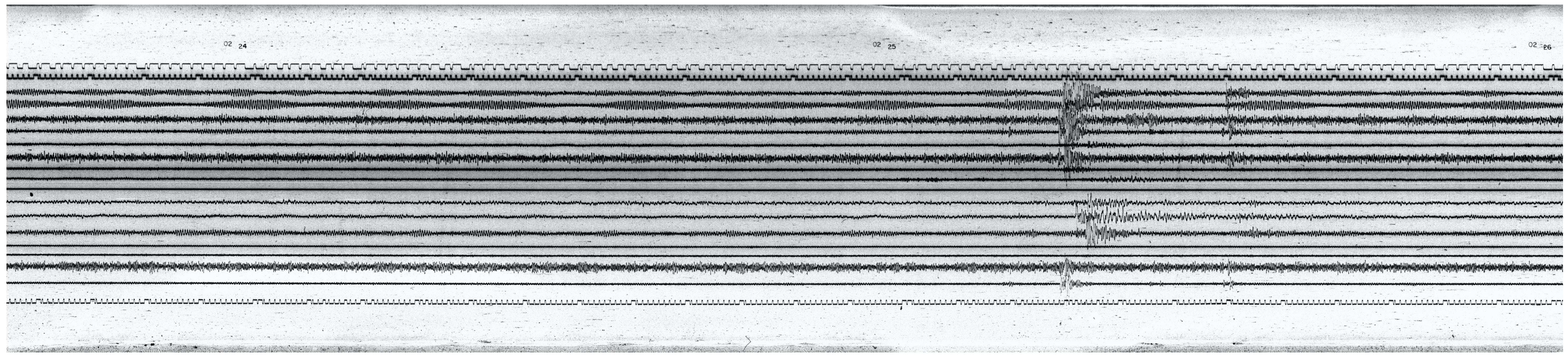

Figure 1: An example of the Rangely Develocorder film scan.

Rangely Fault geometry

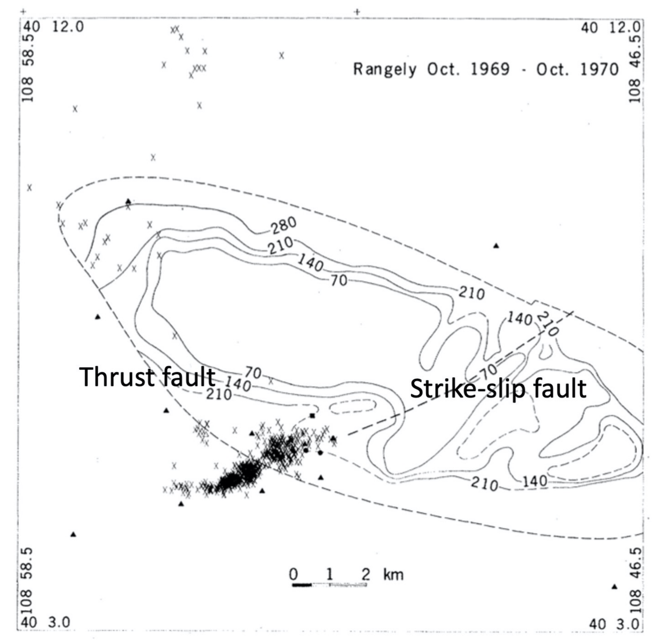

Figure 4: Adapted from Raleigh et al. (1976). The Rangely induced earthquake locations in the original catalog. The dashed line plots the inferred subsurface strike-slip fault, and the thrust fault is near the boundary of the oil field.

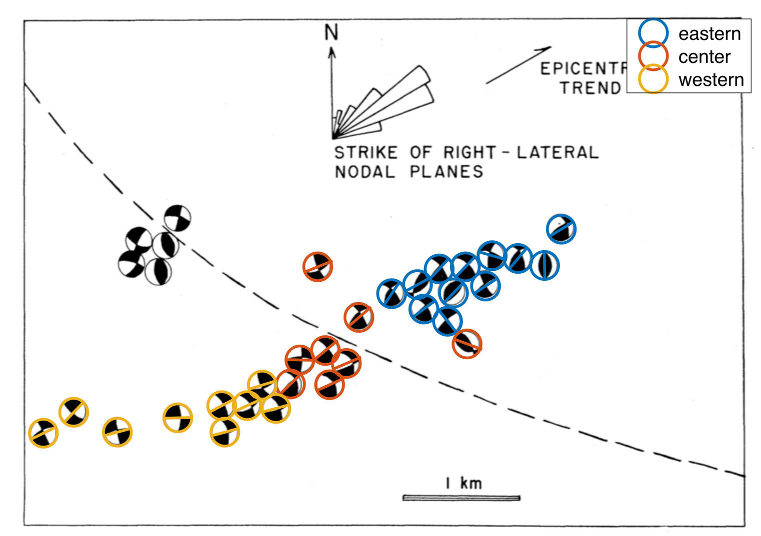

Figure 5: Preferred nodal planes for the focal mechanism solutions in the original study under local stress field on the strike-slip fault. Figure modified from Raleigh et al. (1976).

From seismicity:
- Strike N44°E and dips 76°

From focal mechanism:
- Strike N45°E and dips 75°

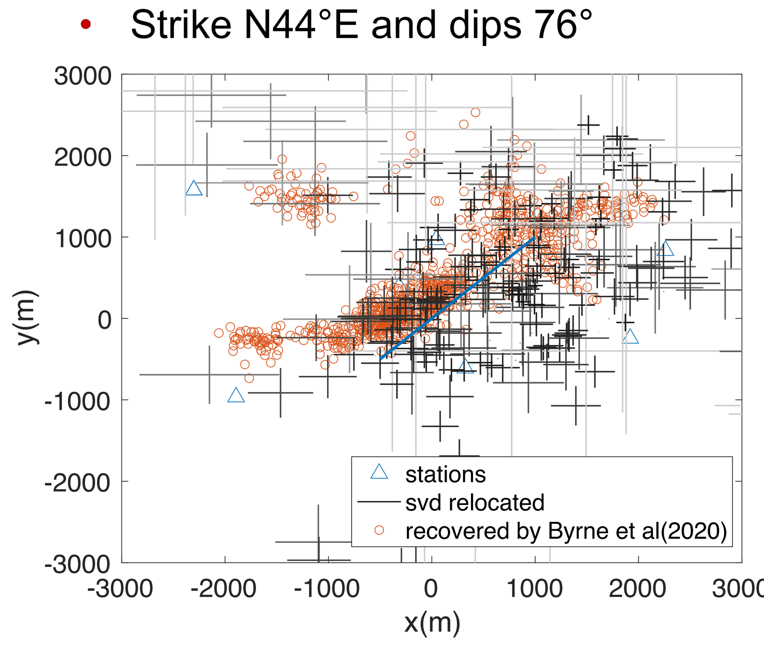

Figure 6: Earthquake locations (solved using automatic picks) with 1σ error bars from our reconstructed catalog (04/1972 to 03/1974). The locations in the Raleigh et. al. catalog (10/1969 to 05/1974) are plotted as circles for reference.

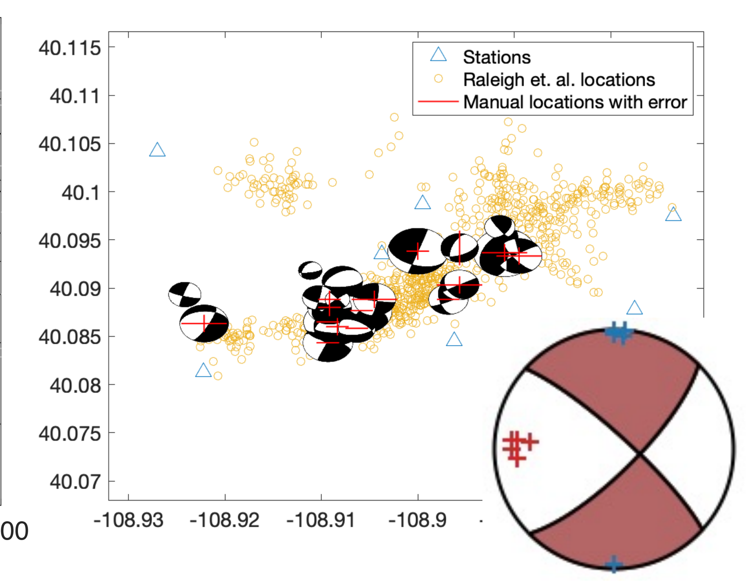

Figure 7: Focal mechanism solutions for the Rangely earthquakes (between April 1972 and March 1974) calculated for events greater than M 0.6 on the strike-slip fault. Locations solved using manual P&S picks. Lower right shows the composite mechanism for these events.

We couldn't document any thrust event at reported locations, which suggests unmapped strike slip faults might be another possibility.

Stress state of the Rangely faults

30° discrepancy in SHmax orientation among estimates from different studies, likely caused by uncertainty in the stress measurements.

N70°E S_{Hmax} following Raleigh et al. (1976). N100°E S_{Hmax} following Zoback and Healy (1984).

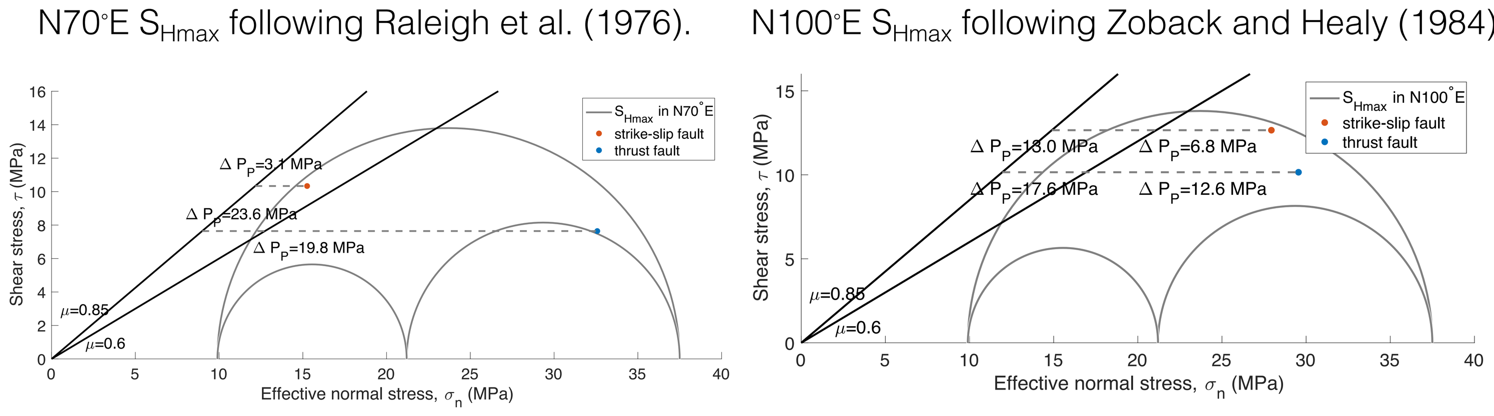

Figure 8: Stress state on the strike-slip and thrust fault at Rangely. The required pore pressure perturbation for fault activation is marked on the side for each case.

Earthquake clustering characteristics

- Background mode dominant, similar to other induced earthquake sequences
- Cluster mode at small rescaled times, indicating short-lived sub-sequences (~day) driven by fast stress transfer.

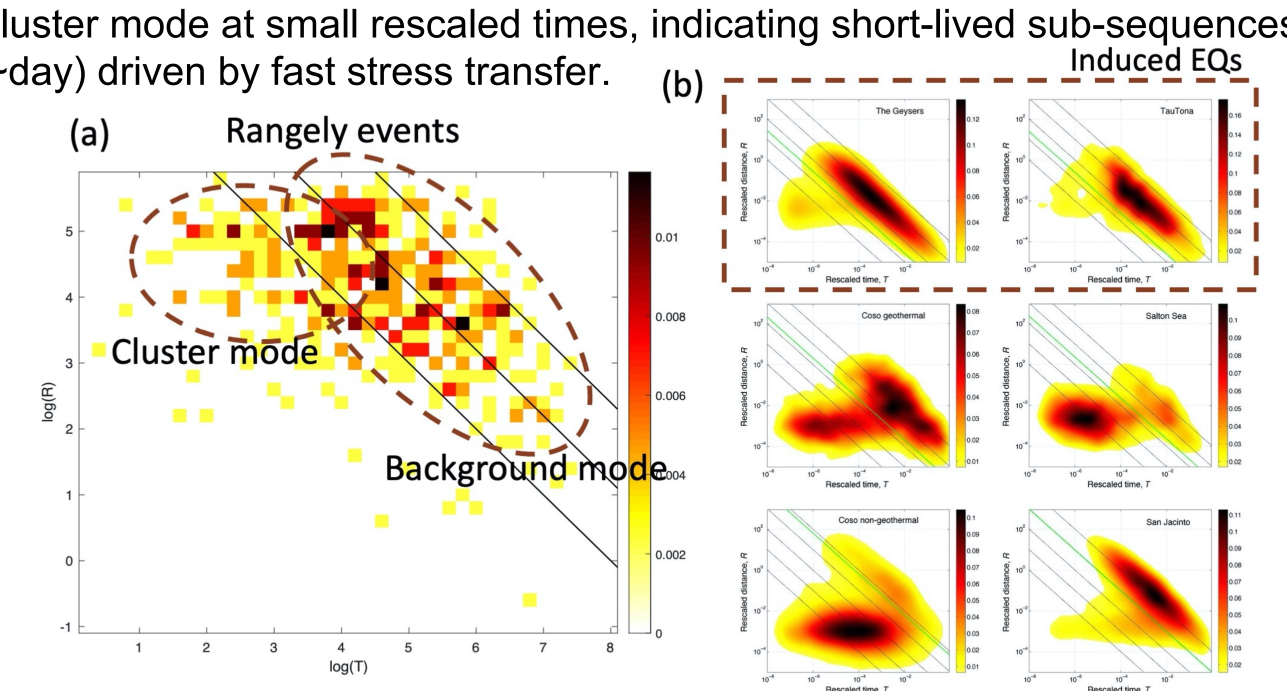

Figure 9: Characteristics of earthquake clustering. (a) Clustering style of Rangely earthquakes, (b) Clustering style of seismicity in six regions (Zaliapin and Ben-Zion, 2016).

- Linear migration velocity range from 0.02 to 1 km/hr, which is consistent with the migration velocity of tectonic tremors.
- Apparent diffusivity(bulk diffusivity) range from 3 to 100 m2/s, agree with the observation from the Guy-Greenbrier.

Mechanism of the events outside the oil field

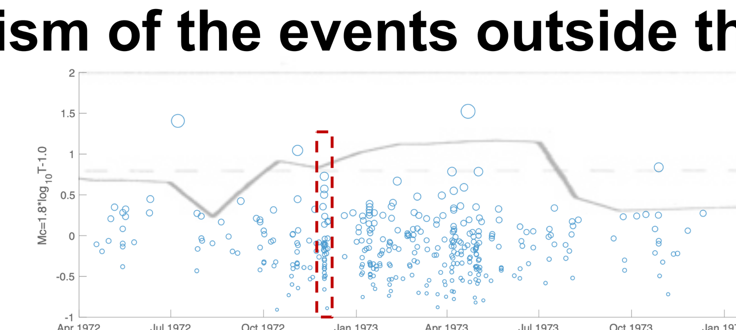

Figure 10: Magnitude-time plot of the Rangely earthquakes with reservoir pressure.

- Active period of the western cluster correspond to peak reservoir pressure, just the opposite of the prediction by poroelastic stress change.
- Direct pore pressure connection rather than poroelasticity induced the Rangely earthquakes.

Conclusion

- Seismicity induced during the Rangely experiment has been reconstructed from the original Develocorder films using machine learning image-based methods. We detected twice the number of events with M_C -0.4.
- Our results support that the Rangely earthquakes were induced by pore pressure increase through direct pressure connection rather than poroelastic effect.
- Clustering characteristics show short-lived sub-sequences (~day) driven by fast stress transfer, likely aseismic slip, fluid diffusion, or earthquake interaction.

References

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Acknowledgements

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