The spatial footprint of seismic activity and aftershock triggering in a conceptual model of fluid-induced seismicity

Omid Khajehdehi[1], Kamran Karimi[1], and Davidsen Joern[1]

[1]Complexity Science Group, Dept. of Physics and Astronomy, Univ. of Calgary, Calgary, AB, T2N 1N4, Canada.

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Abstract

Seismic hazard due to fluid invasion in hydraulic fracturing, wastewater disposal, and enhanced geothermal systems have become a concern for industry and nearby residents. Some of the challenges associated with the fluid-induced seismic hazard are the estimation of the spatial effects of these industry operations as well as the presence or absence of aftershock triggering. In some cases (e.g. Geysers, California, Hoadley gas field of Alberta), aftershocks triggering do occur, while in other cases (e.g. Soultz-sous-Forêts, France), this is not the case. First, to address the spatial effects, using several previously published high-resolution well-log data, we first show that there is a tendency that porosity within the basement resembles fractional Gaussian noise (fGn), while above the basement it resembles fractional Brownian motion (fBm). Based on this observation, we introduce a novel conceptual model of the fluid-induced seismicity in disordered porous media by integrating the notion of fluid diffusion and invasion percolation with spatially correlated permeability and porosity. We find that our model does not only capture the observed variations in frequency-magnitude distribution of seismic events but it also exhibits a much slower decay in seismic activity at large distances for fBm compared to fGn. Second, to address the presence of aftershock triggering, we also introduce nonlinear viscoelastic effects in our model to augment the failure mechanics. This allows us to test whether the presence or absence of aftershocks is coupled to the validity of a time scale separation between fluid dynamics and nonlinear viscoelastic response, for example. Our findings can be directly incorporated in the seismic hazard assessment related to fluid injections.

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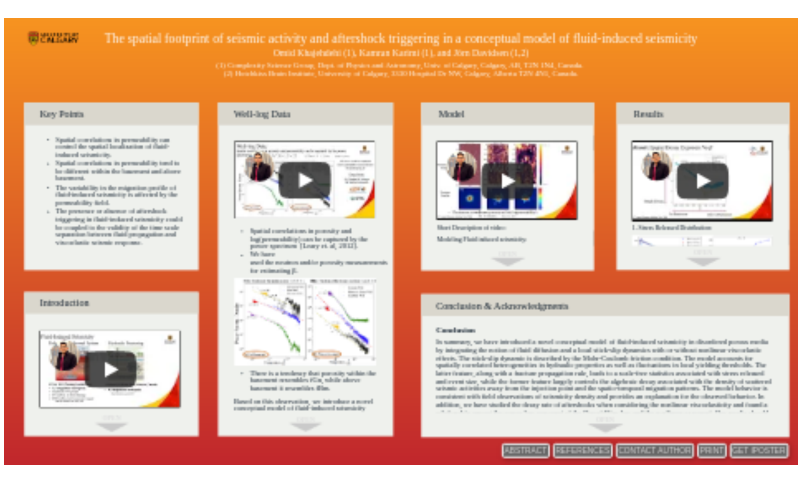
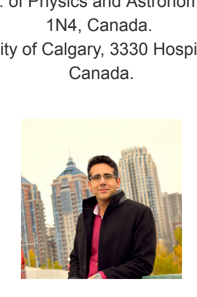


Omid Khajehdehi (1), Kamran Karimi (1), and Jörn Davidsen (1,2)

(1) Complexity Science Group, Dept. of Physics and Astronomy, Univ. of Calgary, Calgary, AB, T2N 1N4, Canada.
(2) Hotchkiss Brain Institute, University of Calgary, 3330 Hospital Dr NW, Calgary, Alberta T2N 4N1, Canada.



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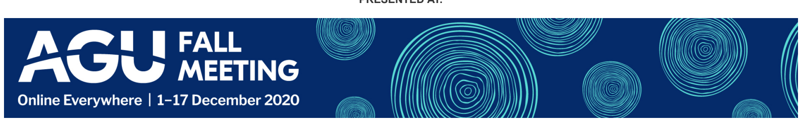


KEY POINTS

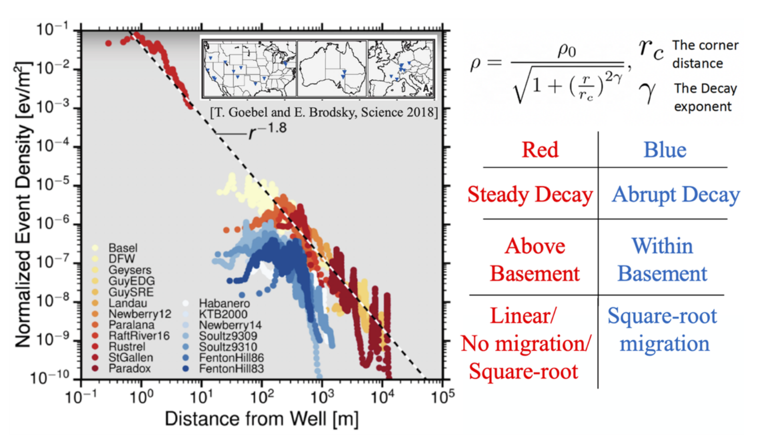
- Spatial correlations in permeability can control the spatial localization of fluid-induced seismicity.
- Spatial correlations in permeability tend to be different within the basement and above basement.
- The variability in the migration profile of fluid-induced seismicity is affected by the permeability field.
- The presence or absence of aftershock triggering in fluid-induced seismicity could be coupled to the validity of the time scale separation between fluid propagation and viscoelastic seismic response.

INTRODUCTION

[VIDEO] https://www.youtube.com/embed/AHyggYkJTvY?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Research questions:

1. Can We Model Spatial Footprint of Fluid-induced Seismicity?



(Goebel and Brodsky, 2018) examined the spatial distribution of induced earthquakes from injection wells. They found that one can group the different field data into two classes: The first group exhibits mostly near-well seismicity with an abrupt decay at larger distances, while the second group displays longer-ranged seismic activity with a much slower decay at larger distances. The observed behavior correlated well with distance to basement, with the first group largely corresponding to injections within the crystalline basement, while the second group largely corresponded to injections above basement. Here, we show that the spatial properties of the underlying porosity and permeability fields, which guide the propagation of the injected fluids, can explain this behavior.

2. What controls the presence or absence of aftershocks triggering in the context of fluid-induced seismicity?

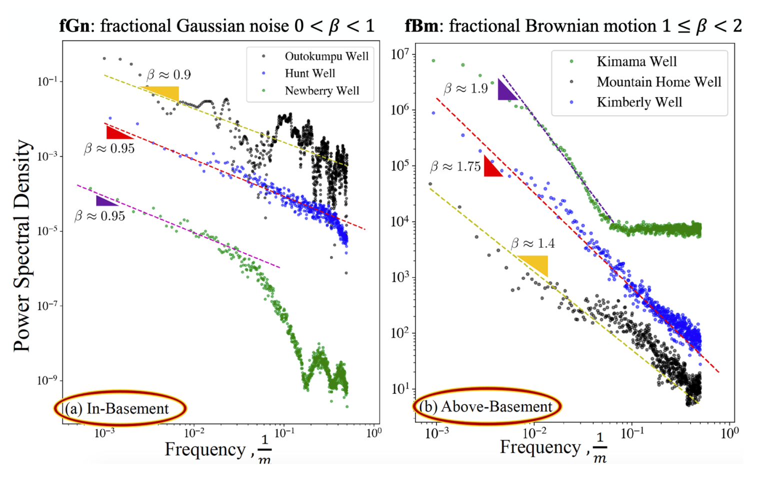
The presence of interevent triggering is well established in tectonic earthquakes [Gu et al., 2013]. But, in context of Fluid-induced Seismicity, in some cases (e.g. Salton Sea of California, Hoadley gas field of Alberta) aftershocks do occur] [Martnez-Garzon et al., 2018] [Maghsoudi et al., 2018], and in other cases (e.g. Soultz-sous-Forets, France) aftershocks do not occur [Langenbruch et al., 2011].

(X. Zhang and Shcherbakov, 2016) and (Baro and Davidsen, 2018) showed that nonlinear viscoelasticity can play a critical role in the gen-eration of aftershocks. Thus, we introduce the nonlinear viscoelastic effects in our model to augment the failure mechanics that give rise to realistic aftershock behavior in earthquakes.

WELL-LOG DATA

[VIDEO] https://www.youtube.com/embed/qeroOKXKgK8?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

- Spatial correlations in porosity and log(permeability) can be captured by the power spectrum [Leary et. al, 2012].
- We have used the neutron and/or porosity measurements for estimating β.



- There is a tendency that porosity within the basement resembles fGn, while above basement it resembles fBm.

Based on this observation, we introduce a novel conceptual model of fluid-induced seismicity with spatially correlated permeability. We find that our model not only captures the observed frequency-magnitude distribution of seismic events but it also exhibits a much slower decay in seismic activity at large distances for fBm compared to fGn. In particular, it can quantitatively explain the different spatial decay exponents observed in real-world fluid-induced seismic catalogs.

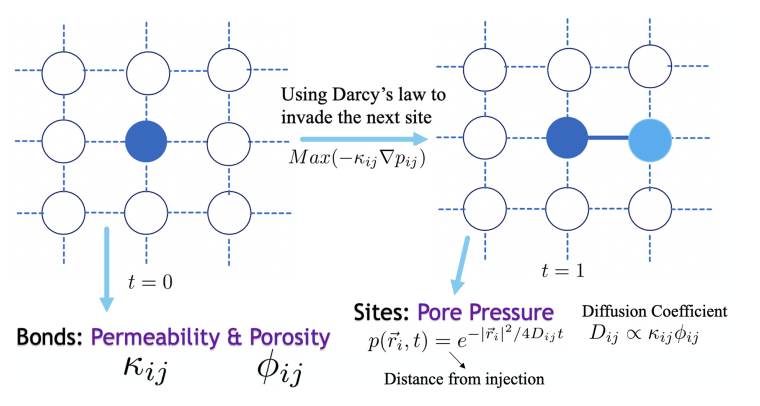
MODEL

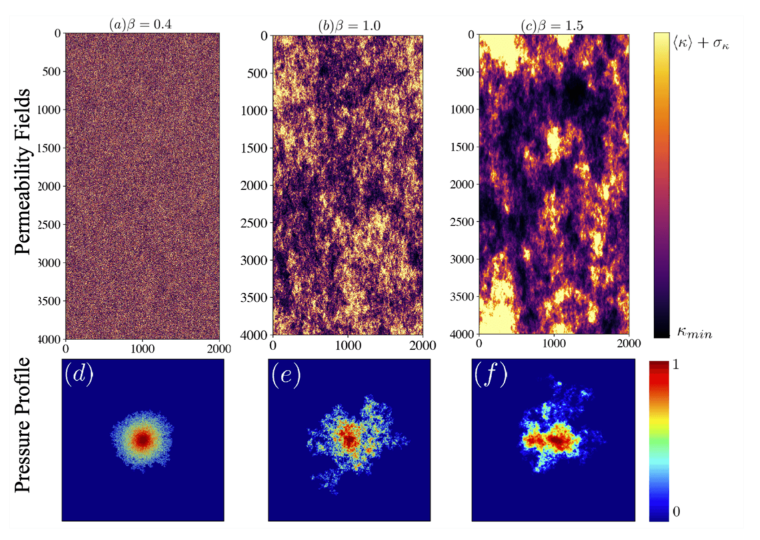
[VIDEO] https://www.youtube.com/embed/yPZKT_eH6q0?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

Short Description of video:

Modeling Fluid induced seismicity:

1. Fluid invasion and propagation





2. Rock fracture (with and without nonlinear viscoelastic effects)

$$\tau_i + p_{p,i} > S_i \qquad \text{Confinement and Friction: } S_i = [s_{min}, s_{max}] \quad \text{Shear Stress: } \tau_i$$

$$\Delta\tau_{i,j\pm1}(t') = \Delta\tau_{i\pm1,j}(t') = \frac{1}{4}\tau_{ij}(0) \qquad \text{Stress Redistribution}$$

$$\Delta = \sum_{i \in event} \tau_{s,i} \qquad \text{Stress Released during seismic response}$$

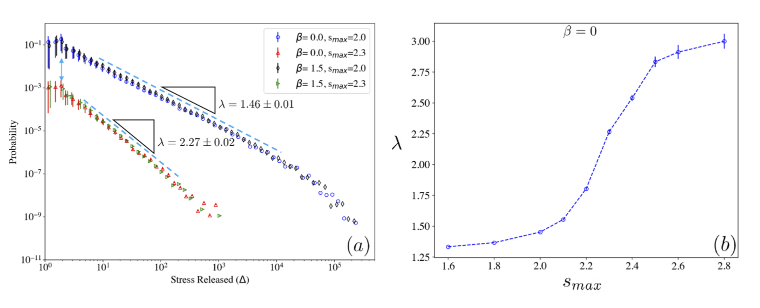
Stress redistribution with nonlinear viscoelasticity

$$\Delta\tau_{i,j\pm1}(t_d) = \Delta\tau_{i\pm1,j}(t_d) = \nu\tau_{ij}(0) - \frac{\nu - \psi}{(\frac{t_d}{q_0} + \tau_{ij}(0)^{1-n})^{\frac{1}{n-1}}}$$

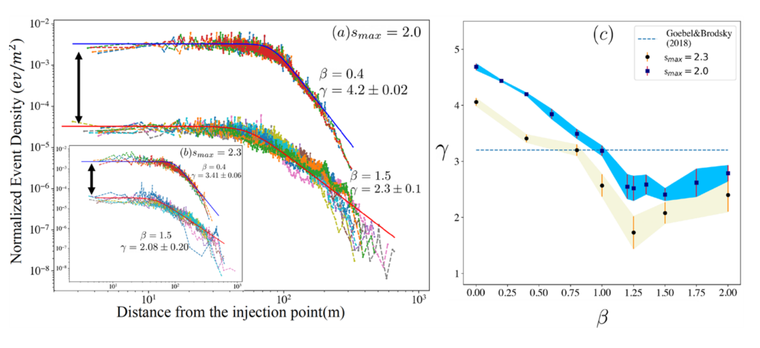
RESULTS

[VIDEO] https://www.youtube.com/embed/uFpR0T-wiTc?rel=0&fs=1&modestbranding=1&rel=0&showinfo=0

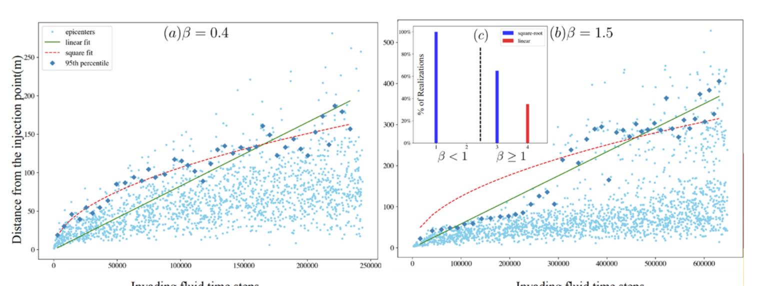
1. Stress Released Distribution:



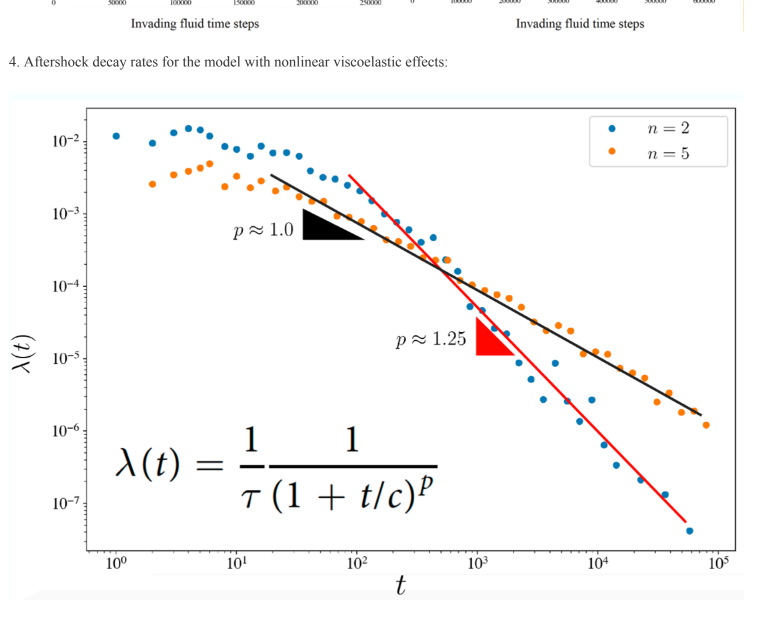
2. Seismicity Density



3. Spatiotemporal Migration of Events



4. Aftershock decay rates for the model with nonlinear viscoelastic effects:



CONCLUSION & ACKNOWLEDGMENTS

Conclusion

In summary, we have introduced a novel conceptual model of fluid-induced seismicity in disordered porous media by integrating the notion of fluid diffusion and a local stick-slip dynamics with or without nonlinear viscoelastic effects. The stick-slip dynamic is described by the Mohr-Coulomb friction condition. The model accounts for spatially correlated heterogeneities in hydraulic properties as well as fluctuations in local yielding thresholds. The latter feature, along with a fracture propagation rule, leads to a scale-free statistics associated with stress released and event size, while the former feature largely controls the algebraic decay associated with the density of scattered seismic activities away from the injection point and the spatio-temporal migration patterns. The model behavior is consistent with field observations of seismicity density and provides an explanation for the observed behavior. In addition, we have studied the decay rate of aftershocks when considering the nonlinear viscoelasticity and found a relationship among the power law exponent of the Omori-Utsu law and the nonlinear exponent. Our results should allow an improved seismic hazard assessment for fluid injections in the future.

Acknowledgments

Field data were not created for this research. The well-log data that are presented in well-log data section and support our conclusions are from different sources. The data for Kimama well (J. Shervais, 2011a), Kimberly well (J. Shervais, 2011b), Mountain Home well (J. Shervais,3502012), and Newberry well (Cladouhos, 2012) are publicly available. We would like to thank Dr.Martyn Unsworth for the Hunt well data (Majorowicz et al., 2014). The porosity measurements of the Outokumpu well is owned by ©Geological Survey of Finland(2020). Sponsors of the Microseismic Industry Consortium are sincerely thanked for their support of this initiative. This work was supported by funding from a Collaborative Research and Development grant from the Natural Sciences and Engineering Research Council of Canada.

ABSTRACT

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REFERENCES

Goebel, Thomas HW and Emily E Brodsky (2018). "The spatial footprint of injection wells in a global compilation of induced earthquake sequences". In: Science 361.6405, pp. 899–904.

Zhang, Xiaoming and Robert Shcherbakov (2016). "Power-law rheology controls aftershock triggering and decay". In: Scientific reports6, p. 36668

Gu, Chad, Aicko Y Schumann, Marco Baiesi, and J¨orn Davidsen(2013). "Triggering cascades and statistical properties of aftershocks". In:Journal of Geophysical Research: Solid Earth118.8, pp. 4278–4295.

Maghsoudi, Samira, Jordi Baro, Alana Kent, David W Eaton, andJ¨orn Davidsen (2018). "Interevent triggering in microseismicity induced by hydraulic fracturing". In:Bulletin of the Seismological Society of America108.3A, pp. 1133-1146

Martinez-Garz´on, Patricia, Ilya Zaliapin, Yehuda Ben-Zion,Grzegorz Kwiatek, and Marco Bohnhoff (2018). "Comparativestudy of earthquake clustering in relation to hydraulic activitiesat geothermal fields in California". In:Journal of GeophysicalResearch: Solid Earth123.5, pp. 4041–4062.

Baro, Jordi and J¨orn Davidsen (2018). "Universal avalanchestatistics and triggering close to failure in a mean-field model of rheological fracture". In:Physical Review E97.3,p. 033002.

Shervais, John, (July 2011a). "Project HOTSPOT: Kimama WellBorehole Geophysics Database". In:DOI:10 . 15121 /1148774.

Shervais, John, (July 2011b). "Project HOTSPOT: Kimberly Well BoreholeGeophysics Database". In:DOI:10.15121/1148780.

Shervais, John,, (Nov. 2012). "Project HOTSPOT: Mountain Home Well Bore-hole Geophysics Database". In:DOI:10.15121/1148779.

Majorowicz, J., Chan, J., Crowell, J., Gosnold, W., Heaman, L. M., K¨uck, J., . . . others(2014). The first deep heat flow determination in crystalline basement rocks beneath the western canadian sedimentary basin. Geophysical Journal International,197(2),483731–747

Cladouhos, T. T. (2012, 12). Newberry volcano EGS demonstration well 55-29 stimulation data. doi: 10.15121/1357916

Lord-May, Cole, Jordi Baro, David W Eaton, and Joern Davidsen (2017). "Conceptual models of microseismicity induced by fluid injection". In: Microseismic Industry Consortium 8,pp. 437–444

Wilkinson, David and Jorge F Willemsen (1983). "Invasion percolation: a new form of percolation theory". In:Journal of Physics A: Mathematical and General16.14, p. 3365.