Tracking deviation from stable seismic energy release during hydraulic stimulations using physics-informed features

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Near-realtime high-frequency seismic monitoring of fluid injection allowed mitigating induced seismicity during two hydraulic stimulations performed in 2018 and 2020 in a deep geothermal well near Helsinki, Finland. Using near-realtime information on the evolution of seismic and hydraulic energy, pumping was either stopped or varied, following the theoretical predictions from a physics-based model of maximum magnitude, avoiding occurrence of project stopping large earthquakes. In this talk we present factors contributing to the project success: 1) adaptive stimulation strategy, 2) structural inventory of the reservoir and 3) limited stress transfer and discuss the pool of physics-informed seismo-mechanical and statistical parameters that can be used to characterize the propensity of the geothermal reservoir to display an unstable (runaway) behavior. We then discuss the development of unsupervised machine learning framework to characterize the stability of the complex fault system under natural or anthropogenic loading and test it on data from a series of laboratory triaxial stick-slip experiments. Physics informed features reveal a transition from stable deformation in the fault zone to an intermittent criticality state allowing the occurrence of runaway events. In this stage, numerous confined slips superimpose and interact, collectively preparing the fault zone for a runaway event by progressive smoothing of the longer length scales of the stress field. We find that runaway earthquake occurring at this stage is a statistical event that cannot be predicted deterministically. However, the combination of physics-informed parameters empowered with unsupervised ML techniques allows identification of onset time when a fault system enters a critical stage, potentially allowing to trigger relevant mitigation actions.