Helmholtz Centre Potsdam
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Modelling of induced seismicity and frequency-magnitude relation in multi-stage hydraulic stimulation of crystalline geothermal reservoir

Jeoung Seok Yoon(1)*, Arno Zang(1), Günter Zimmermann(2), Ove Stephansson(1), Ki-Bok Min(3)

(1) Section 2.6 Seismic Hazard and Stress Field; Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany

(2) Section 4.1 Reservoir Technologies, Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, Potsdam, Germany

(3) Energy Resource Engineering, Seoul National University, Seoul, Korea

* Corresponding author email: jsyoon@gfz-potsdam.de

Abstract

This study presents discrete element based numerical modeling of induced seismicity in multiple stage hydraulic fracturing in a crystalline granitic reservoir. Particle Flow Code 2D is used where fluid flow algorithm and seismicity computing algorithm are implemented. Crystalline rock simulated locates at 4-6 km depth. Hydraulic stimulation is modeled with five stages of fluid injection with distance of several hundreds of meters. Hydraulic fracturing is done on the stages from toe to heel direction along a series of sub-horizontally drilled wellbore with constant rate of fluid injection. This study addresses that inclined drilling of the wellbore in low permeability reservoir for multi-stage fracturing design tends to mitigate the hazard associated with induced seismicity, as well as generates optimum fracture path.

1. Multifrac

In shale-gas industry, productivity has been significantly increased by use of multistage fracturing along series of horizontally drilled wellbores. The same concept is being considered in design of Enhanced Geothermal Systems (EGS) in hard crystalline rock environment (Fig.1) in the state of Saxony Germany.

In a doublet system consisting of two horizontal wells connected by multiple fractures, it is possible to create a larger surface are of heat exchange between rock and fluid than in vertical wells. Instead of a larger single fracture, it is expected that several smaller ones are created, thus the risk of creating larger seismic events is reduced.

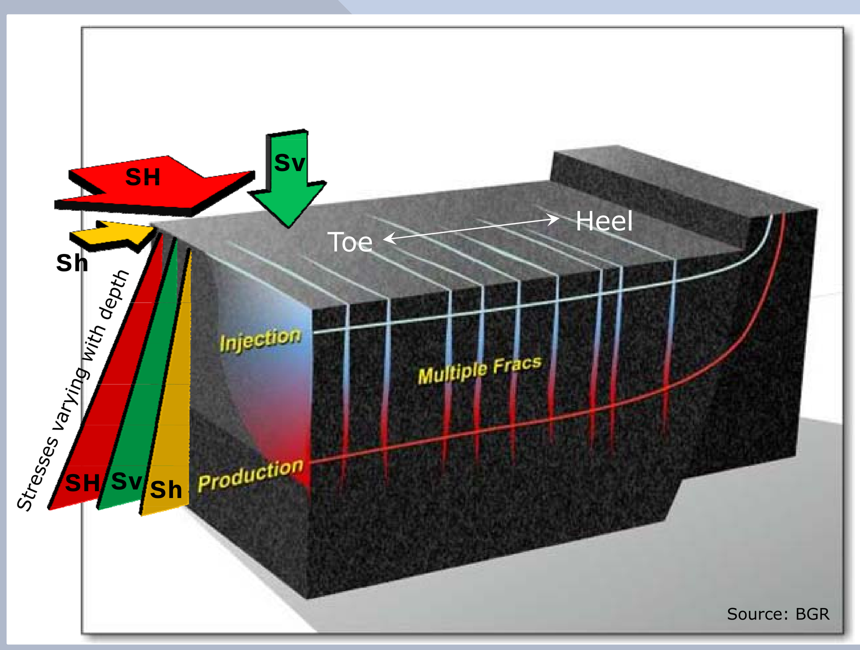

Fig.1: Multifrac concept design of a petrothermal Enhanced Geothermal System in a crystalline reservoir.

2. HMD coupled process

The numerical model simulates fluid injection induced seismicity which are processes **coupled Hydro-Mechanical-Dynamically** (Fig.2). The model outputs are synthetic seismicity catalogue and seismograms.

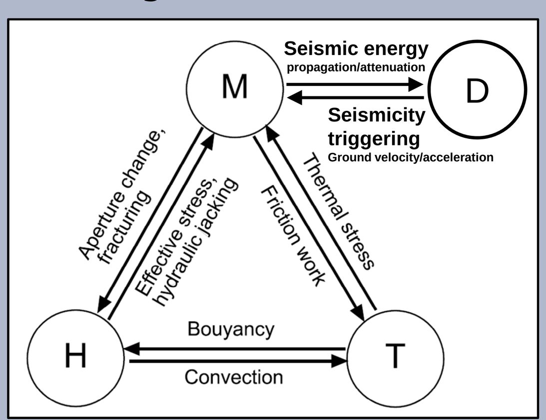

Fig.2: Principles of THMD coupling in a jointed rock mass. H-M-D coupled processes are modeled in this study.

3. Fluid flow model (HM)

Hydro-mechanical coupling is realized by the implemented fluid flow algorithm. Fluid flows through the flow channels (Fig.3) driven by pore fluid pressure and simulated using:

$Q = e^3 \Delta P_f / 12 \mu L$ --- eqn.(1)

e = hydraulic aperture;
$\Delta P_f/L$ = pressure gradient between pores;
L = flow channel length;
μ = fluid viscosity

Fluid pressure buildup is computed by:

$P_f = \int (K/V_d)(\Sigma Q dt - \Delta V_d) dt$ --- eqn.(2)

K = fluid bulk modulus;
V_d = pore volume;
ΔV_d = pore volume change

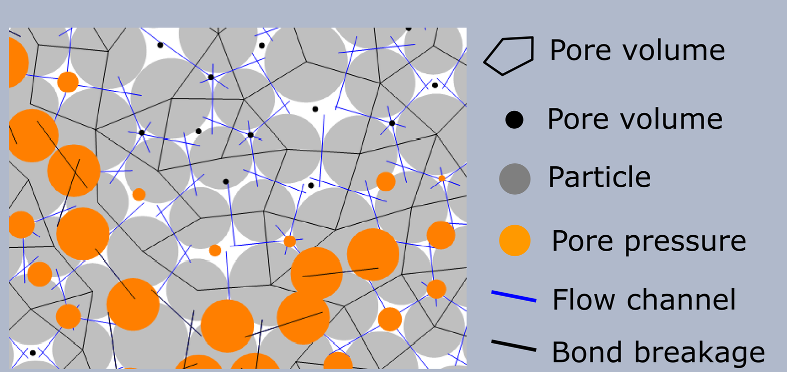

Fig.3: Pore space network model and distribution of fluid pressure and induced bond breakages.

Table 1: Reservoir rock mechanical parameters.

Mechanical parameters	Values
Density (kg/m^3)	2630
Friction coefficient	0.9
Young's modulus (GPa)	50
Tensile strength (MPa)	9
Cohesion (MPa)	25
Friction angle (Deg.)	53

4. Seismicity model (MD)

Fluid pressure driven breakage of bonded contacts are assumed as a dynamic process of fracturing where stored strain energy is released in a form of seismic energy, i.e. seismic event, and attenuates as it travels.

Magnitude of event is computed by moment tensor using contact force change around the bond failure:

$M_{ij} = \Sigma \Delta F_i R_j$ --- eqn.(3)

ΔF = change in contact force;
R = distance from contacts and event centroid

Seismic moment is computed:

$M_0 = (\Sigma m_j^2/2)^{1/2}$ --- eqn.(4)

m_j = eigenvalues of the moment tensor M_{ij} (j=1,2)

Moment magnitude M_w of events is computed by:

$M_w = 2/3 \log(M_0) - 6$ --- eqn.(6)

Stress drop of an event is calculated by:

$\Delta\sigma = 7M_0/16R^3$ --- eqn.(7)

M_0 = seismic moment;
R = event source radius (m)

5. Model description

The reservoir model has following parameters.

- 4 km x 2 km in size
- 112,682 particles, avg. radius 12.4 m
- Sv gradient = 20 MPa/km
- Sh gradient = 25 MPa/km
- Bulk permeability k = 1e-16 m^2
- Two cases of sub-horizontal drilling
- Five stage stimulations
- Stage distance 500 m
- Injection rate 15 l/s for 1 hr.
- Total injection volume 270 m^3

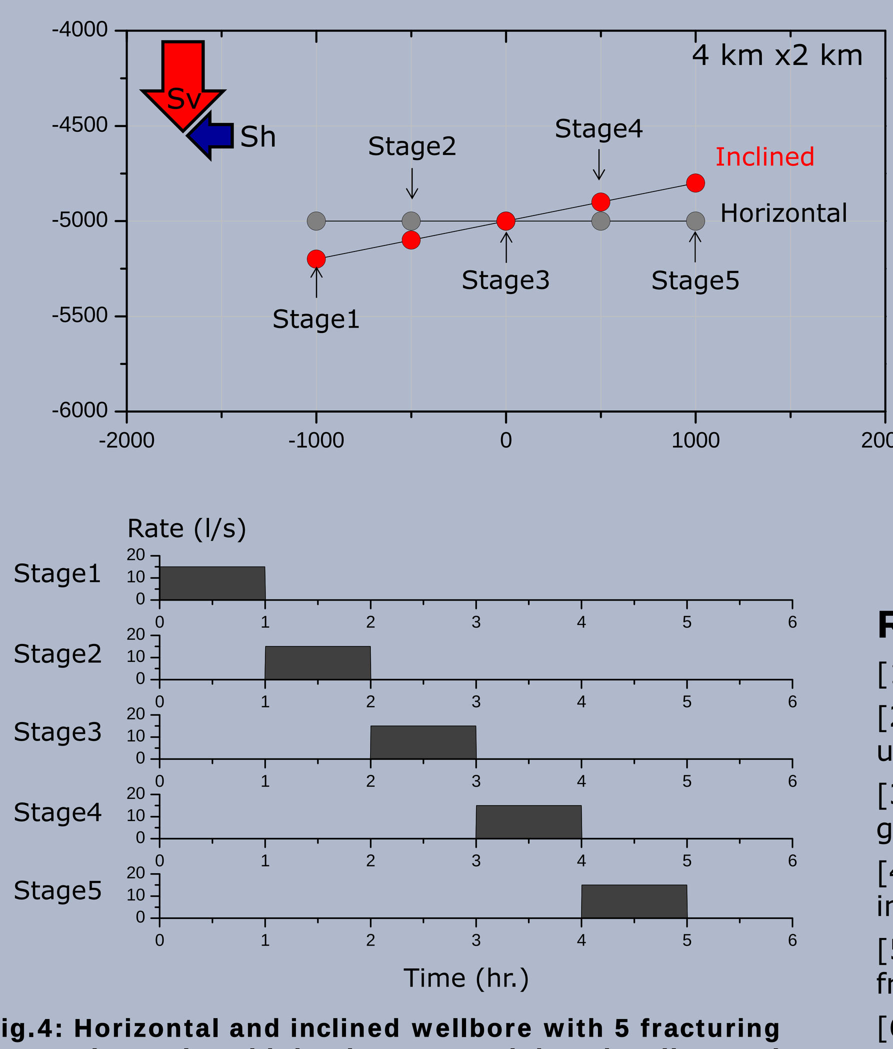

Fig.4: Horizontal and inclined wellbore with 5 fracturing stages (upper) and injection rate and duration (bottom).

6. Distribution of fluid pressure and induced seismicity

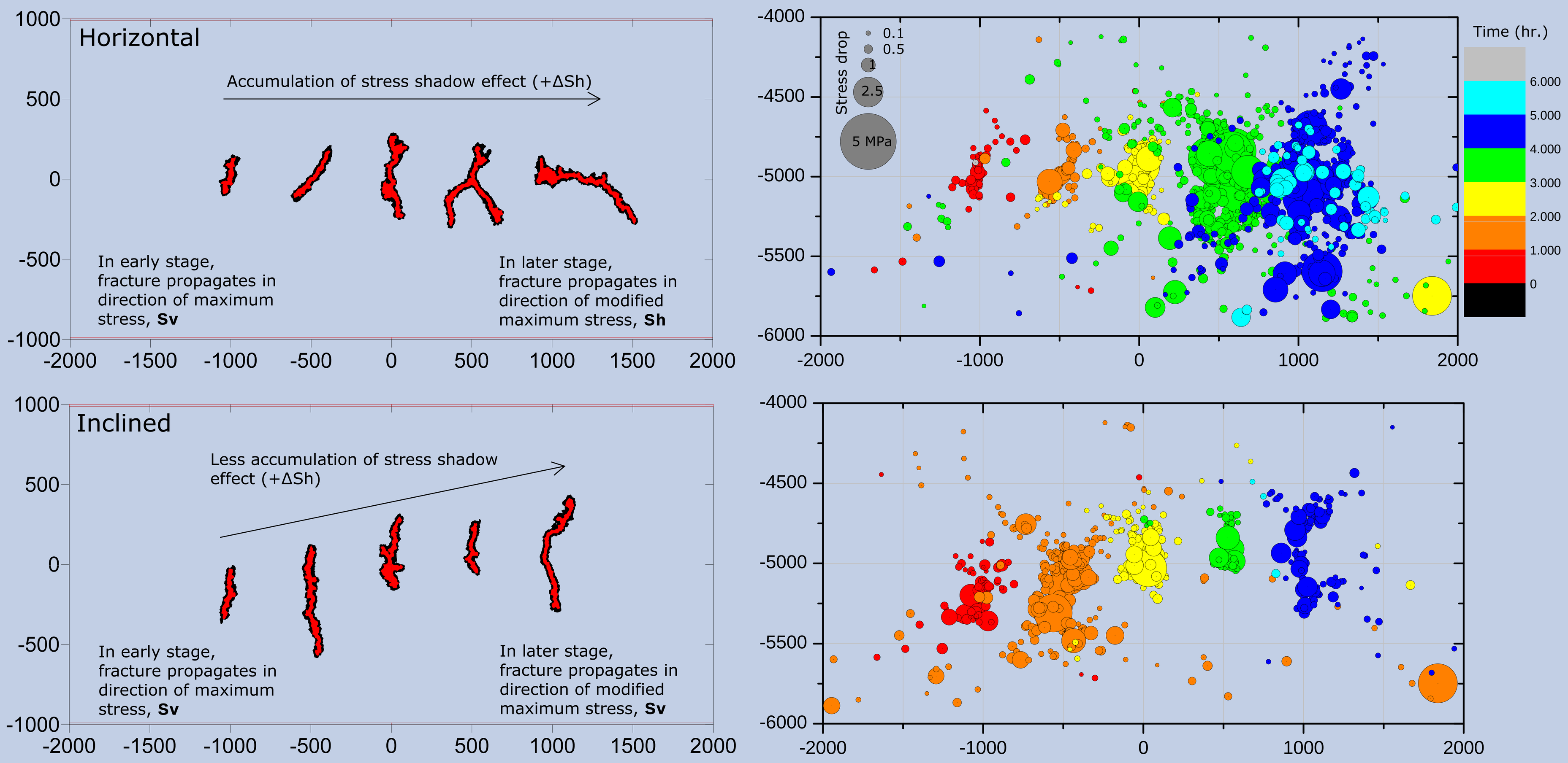

Fig.5: Distribution of injected fluid pressure (left) and spatio-temporal distribution of induced seismic events (right) for horizontal (upper) and inclined (bottom) wellbore multi-frac stimulations. Events are scaled by the stress drop and colored according to the occurrence time (red: stage1; orange: stage2; yellow: stage3; green: stage4; blue: stage5).

In horizontal wellbore fractures propagate vertically in early stage. However, due to accumulation of stress shadow effect, the maximum stress direction changes and results in horizontal growth of fracture (Fig.5 top left) and increased seismicity in terms of number, magnitude and stress drop (Fig.5 top right). **In inclined wellbore** the stress shadow effect is less and seismicity cloud develops mostly in vertical in all stages (Fig.5 bottom left), and with less seismicity (Fig.5 bottom right).

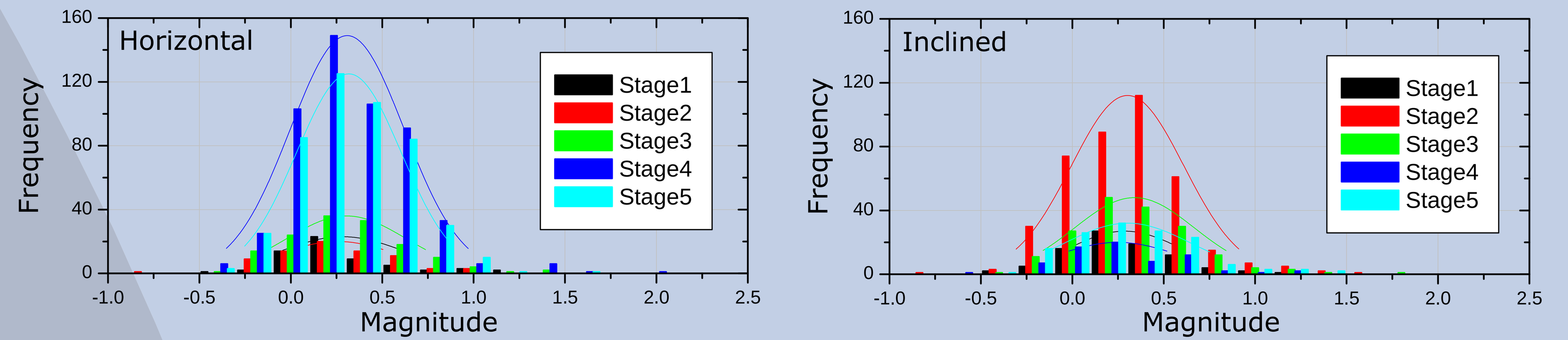

Fig.6: Histogram of induced seismicity in horizontal wellbore case (left) and in inclined wellbore cae (right).

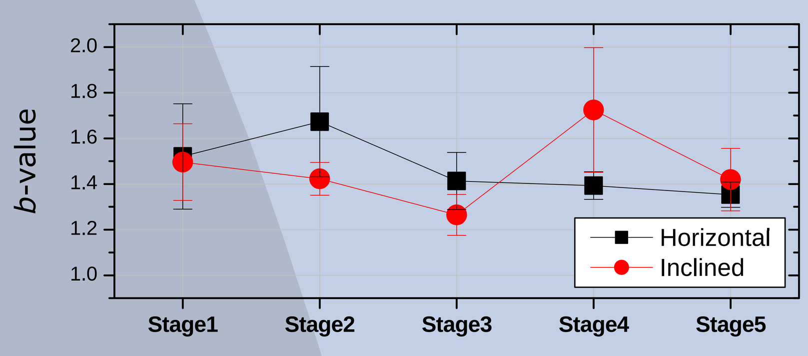

Fig.7: *b*-values of the induced seismicity at different stages.

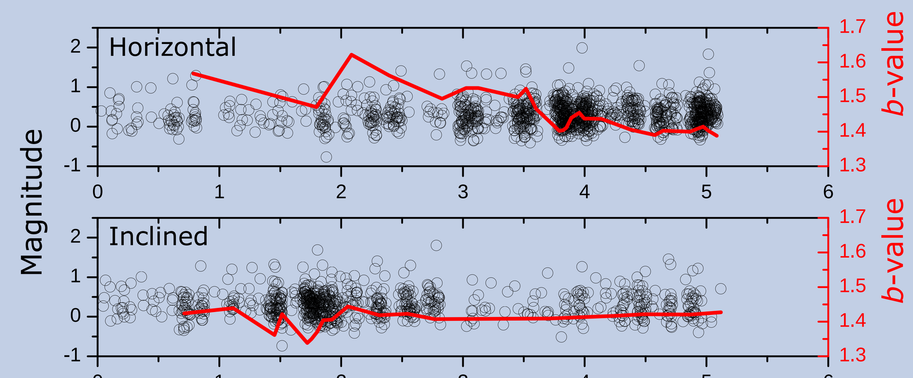

Fig.8: Temporal changes of *b*-values of the induced seismicity.

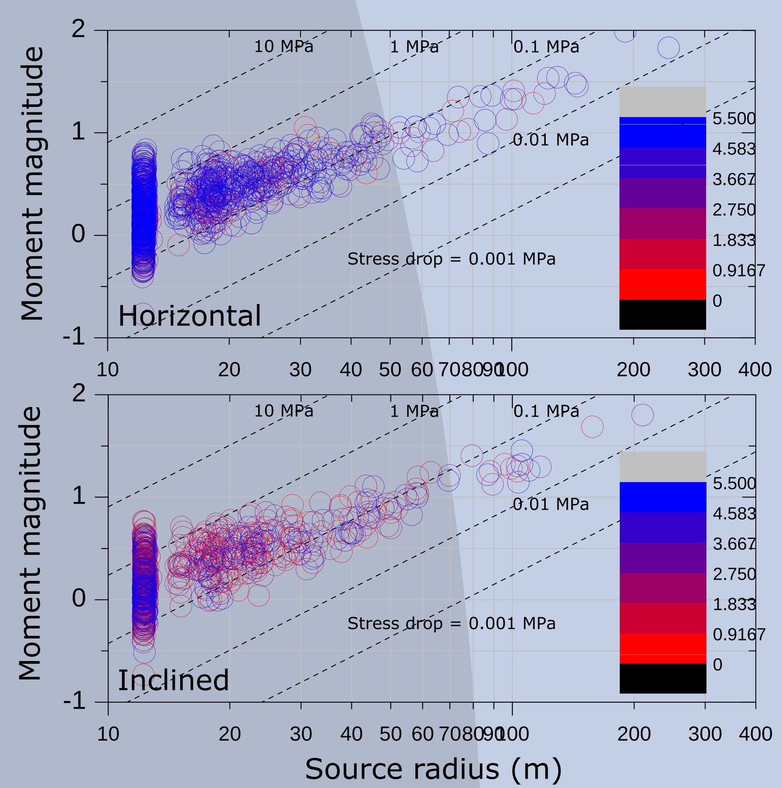

Fig.9: Source radius vs. moment magnitude of the induced seismicity.

Number of seismicity and magnitudes increases with progression of stages in horizontal wellbore, whereas the opposite is simulated in inclined (Fig.6). Maximum magnitude in horizontal wellbore increases with progression of stage, but decreases in inclined wellbore.

***b*-values** of the seismicity are calculated using Maximum Likelihood Method. They decrease with progression of stages (Fig.7) and over time (Fig.8) as more large magnitude events tend to occur at later stages.

Stress drop of the later stage seismicity (blue) tends to be larger than the early stage seismicity (red) in the horizontal wellbore. Inclination of the wellbore mitigates such trend (Fig.9).

7. Summary and conclusions

- The numerical model **simulates hydro-mechanical-dynamic coupled processes** of fluid injection induced seismicity.
- Multi-frac induced seismicity in a granitic reservoir by **horizontal and inclined wells** are simulated.
- In the inclined wellbore setting, (i) fractures propagate more **vertical and parallel**; seismic events show (ii) **less number, magnitudes and stress drop**; (iii) **lower maximum magnitudes**; (iv) **increasing *b*-value** with stage progression.
- The numerical results demonstrate that the **inclined drilling has several advantages in design of multifrac enhanced geothermal systems** in low permeability crystalline reservoirs.

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