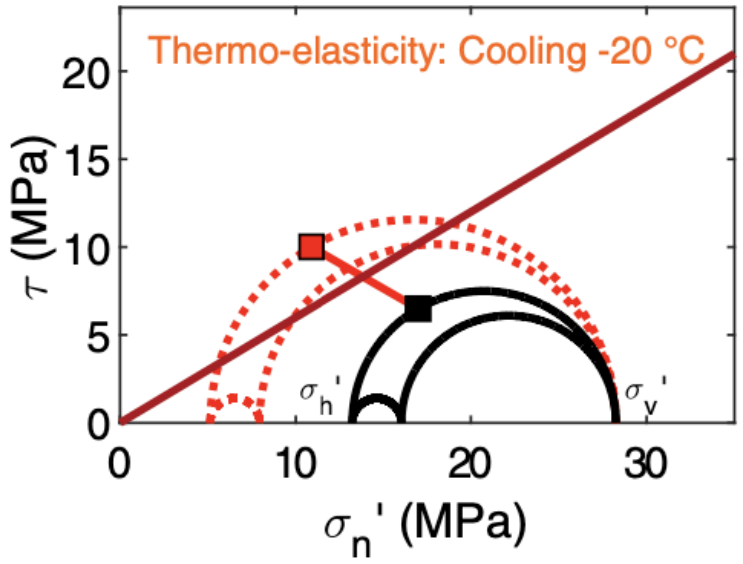
How do fluid injection–induced changes in temperature and pressure effect slip on a multiscale fracture network

Mhina de Vos[1,2], Dr. Ylona van Dinther[1], Dr. Loes Buijze[2], Prof. Dr. Jan-Diederik van Wees[1,2]

1. Utrecht University; 2. TNO

Problem

1. Simple geothermal models show that the temperature drop causes rock failure.
2. Dutch subsurface has two normal fault trends
3. On outcrop scale many more aseismic-scale faults are visible.



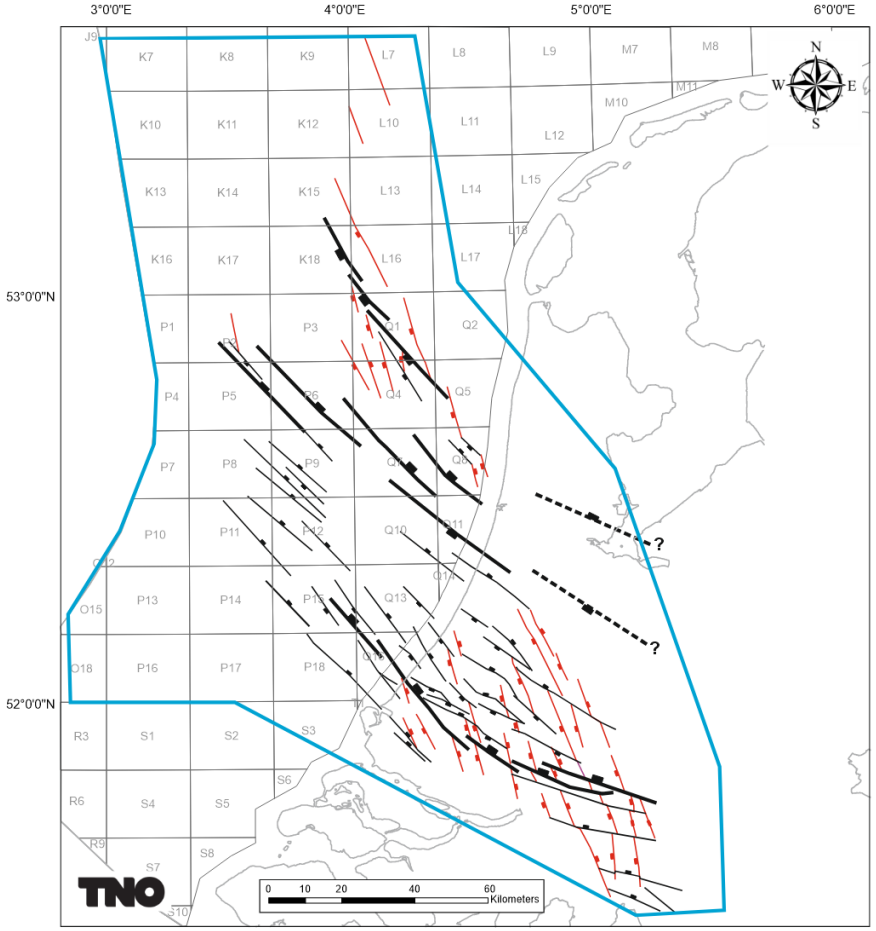


Figure: (Left) Thermo-elastic stress change due to 20° of cooling, adopted from L. Buijze et al., 2023. (Right) Fault trends in the West Netherlands Basin with in red the Mid-Kimmeridgian to Volgian trend (NNW-SSE) and in black the Ryazanian to Hauterivian trend (NW-SE), figure adopted from Verreussel & Peeters, 2024.

Intervention

1. What happens if we increase the number of considered faults in geo-mechanical forward models?

2. How are the events effected by changes in the injection location and fractal distribution?

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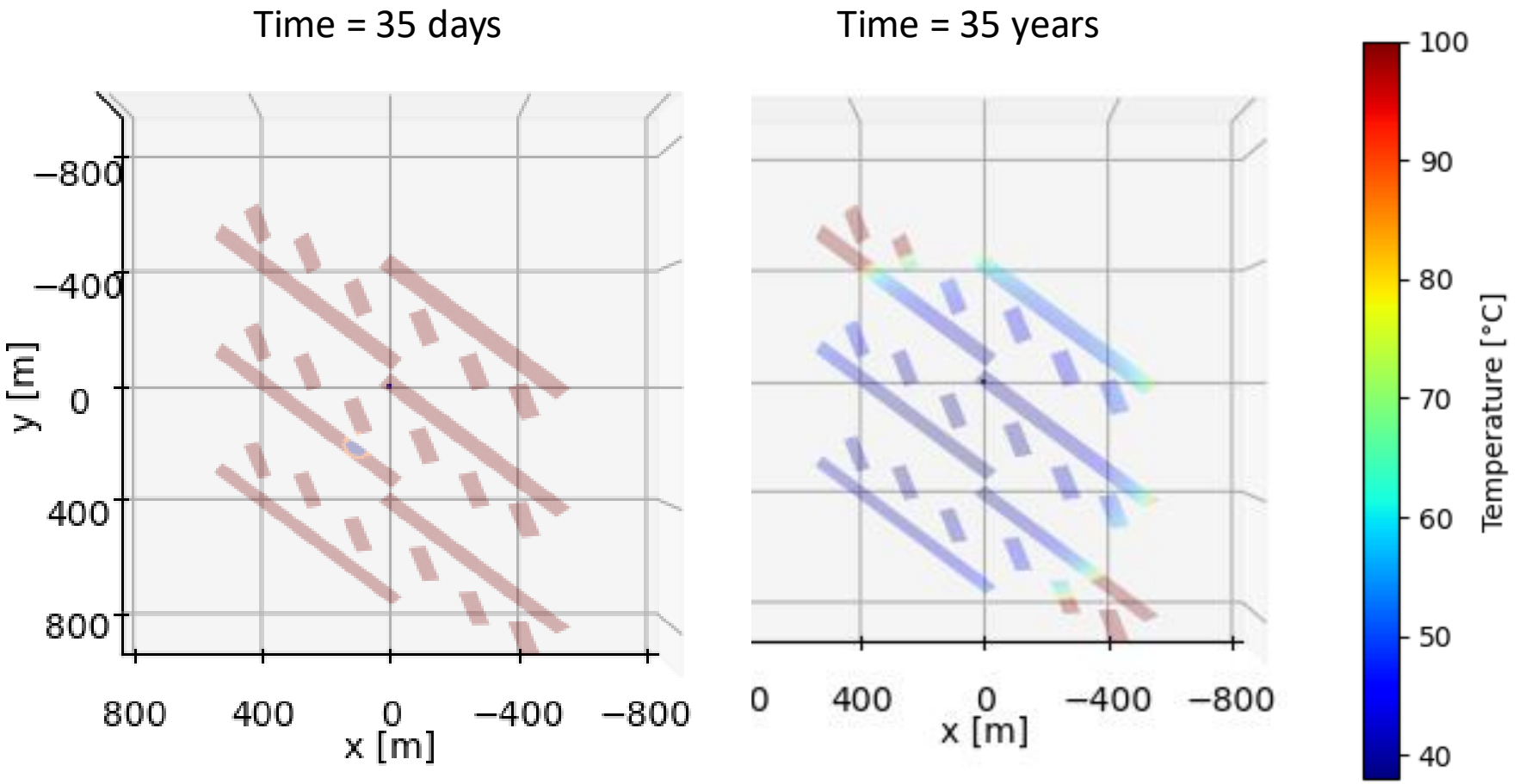


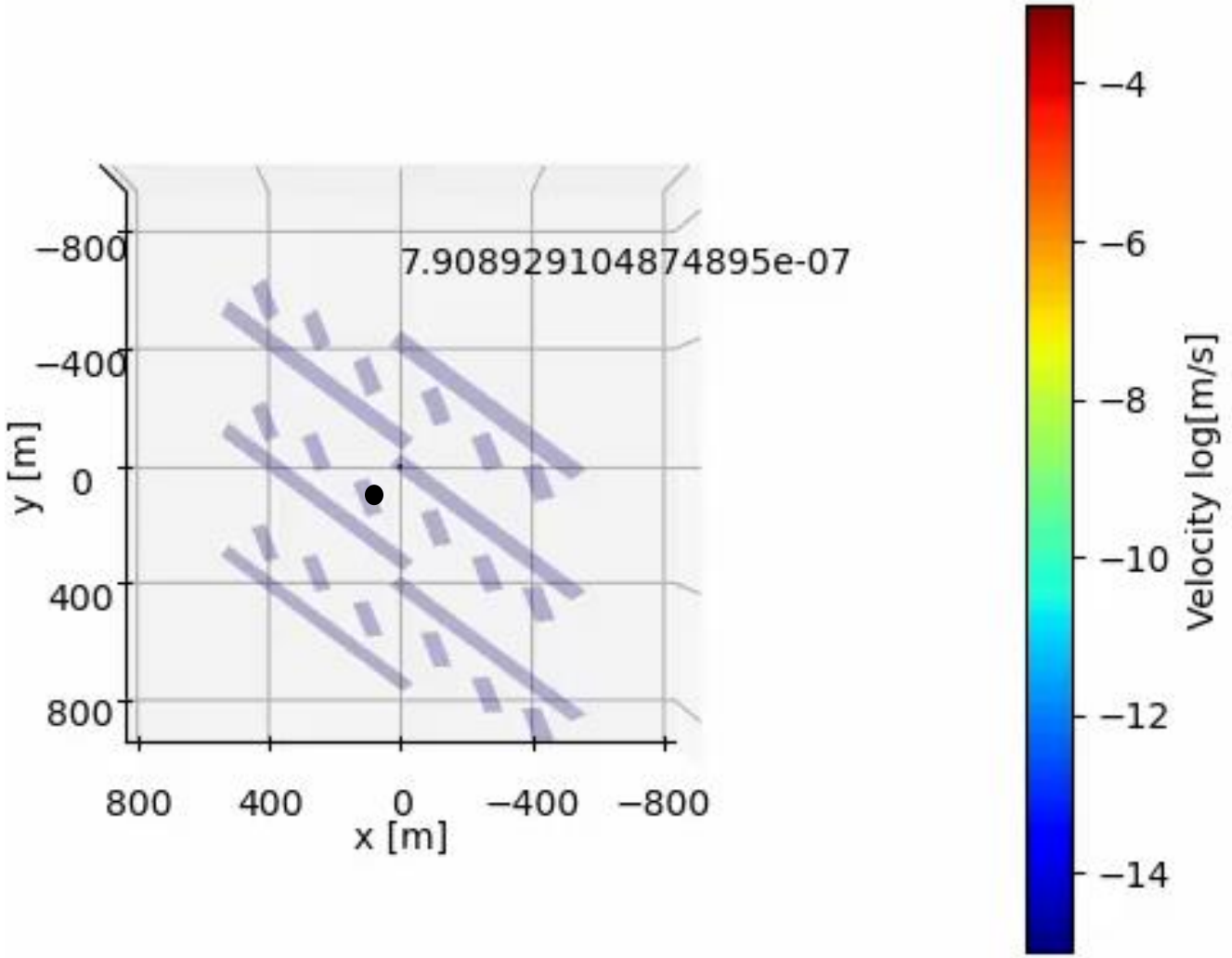
Figure: Temperature in the reservoir after 35 days (left) of production and after 35 years (right). Added thermo-mechanical change to Quake-DFN (Im, K., et al., 2024)

Outcome

35 days after start production largest event forms: M0 = 1.58

Second after 106 days after production.

After that slip rate stays aseismic.



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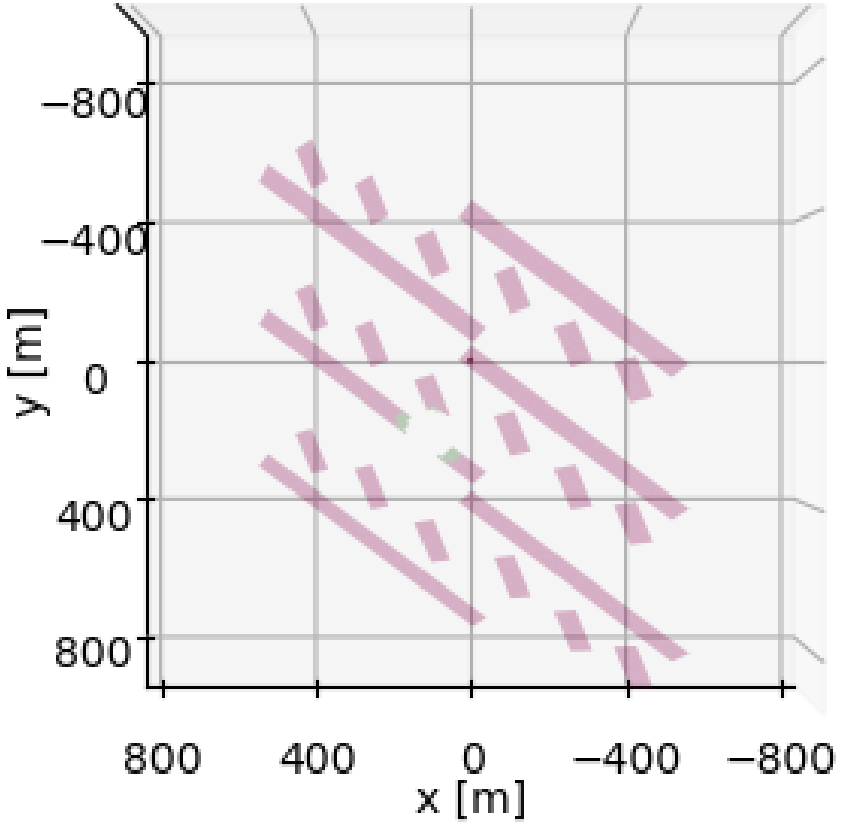

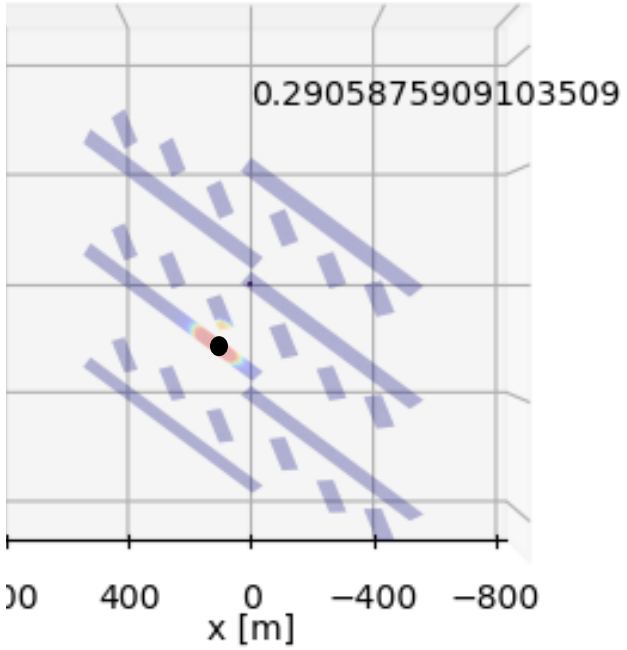

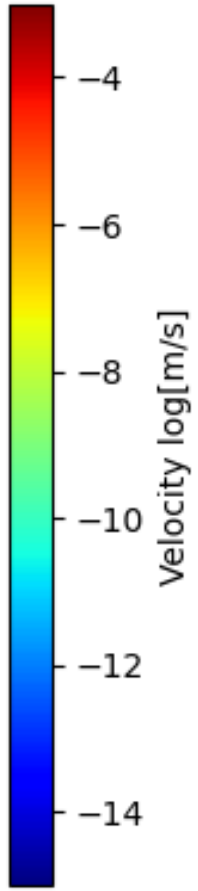

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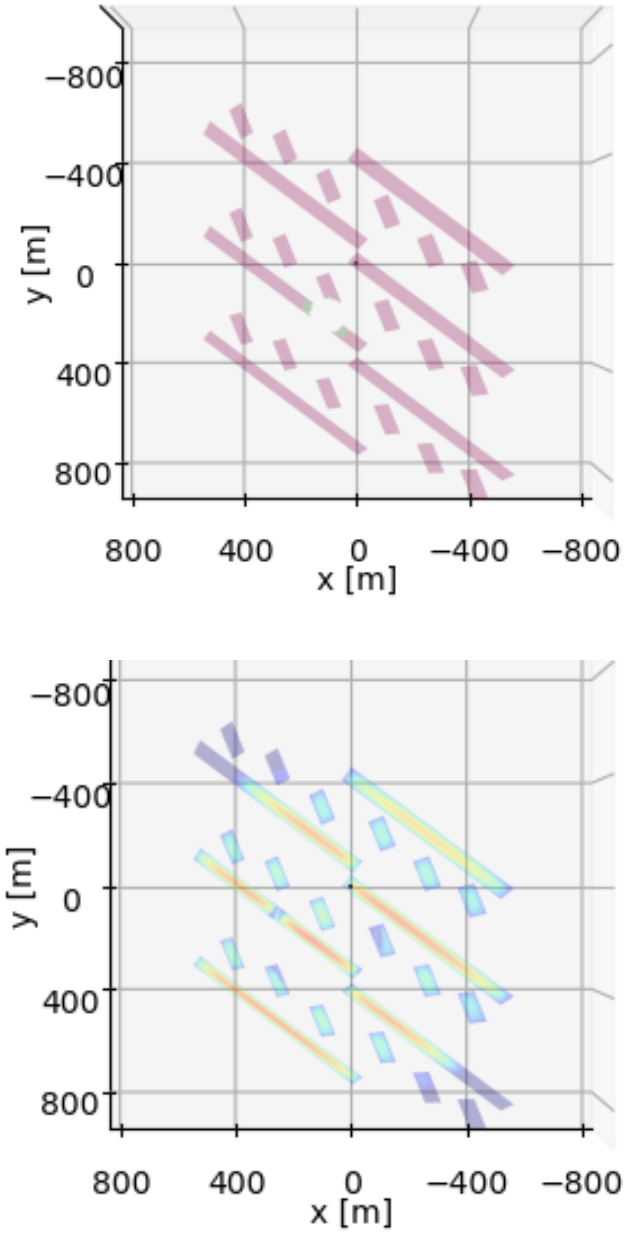
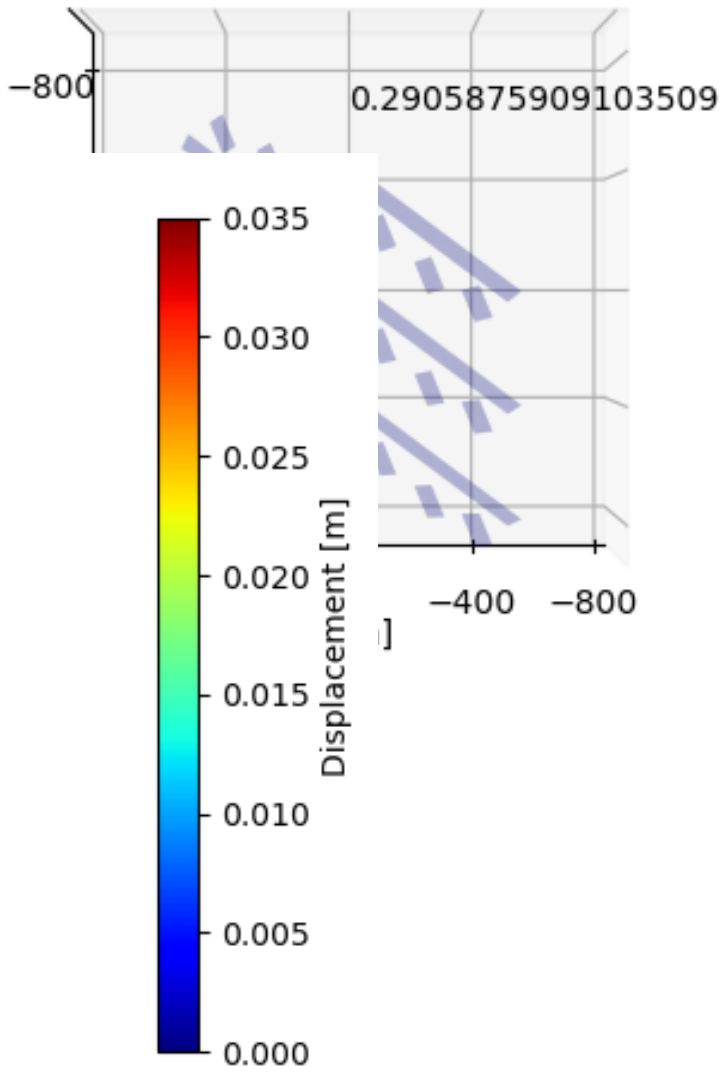




Outcome

By increasing the fault density, the magnitude, the location and number of events changes

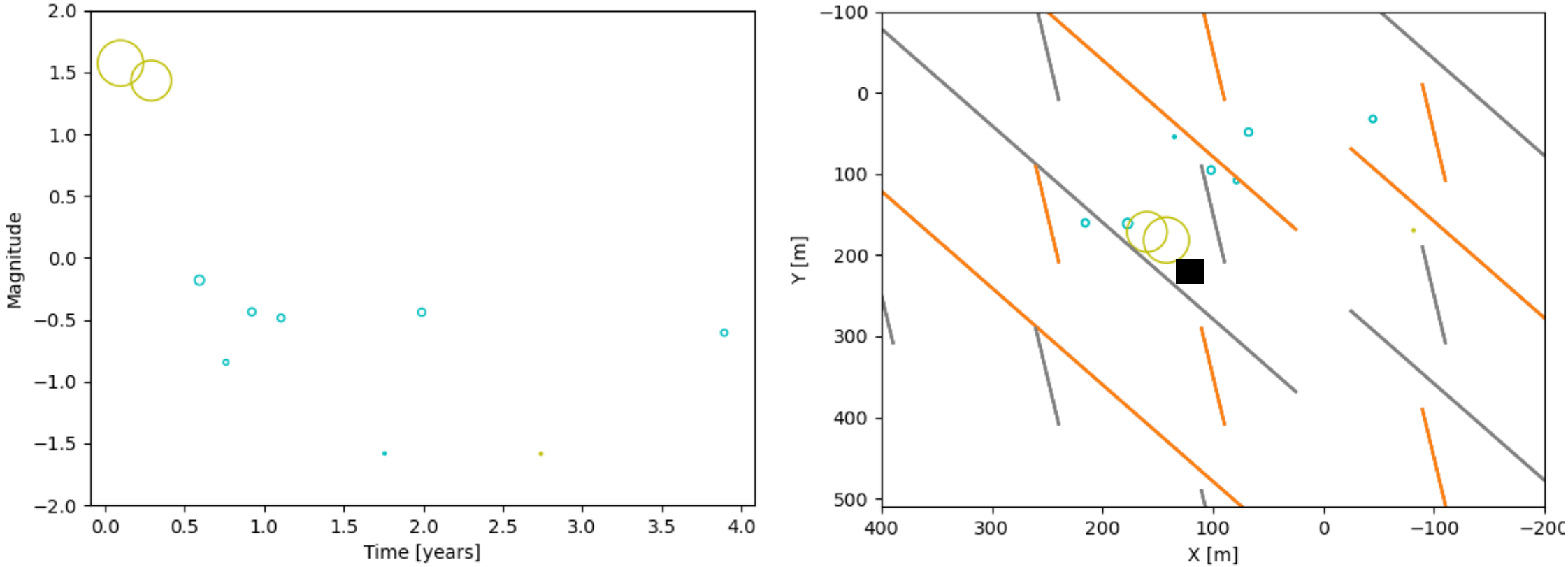
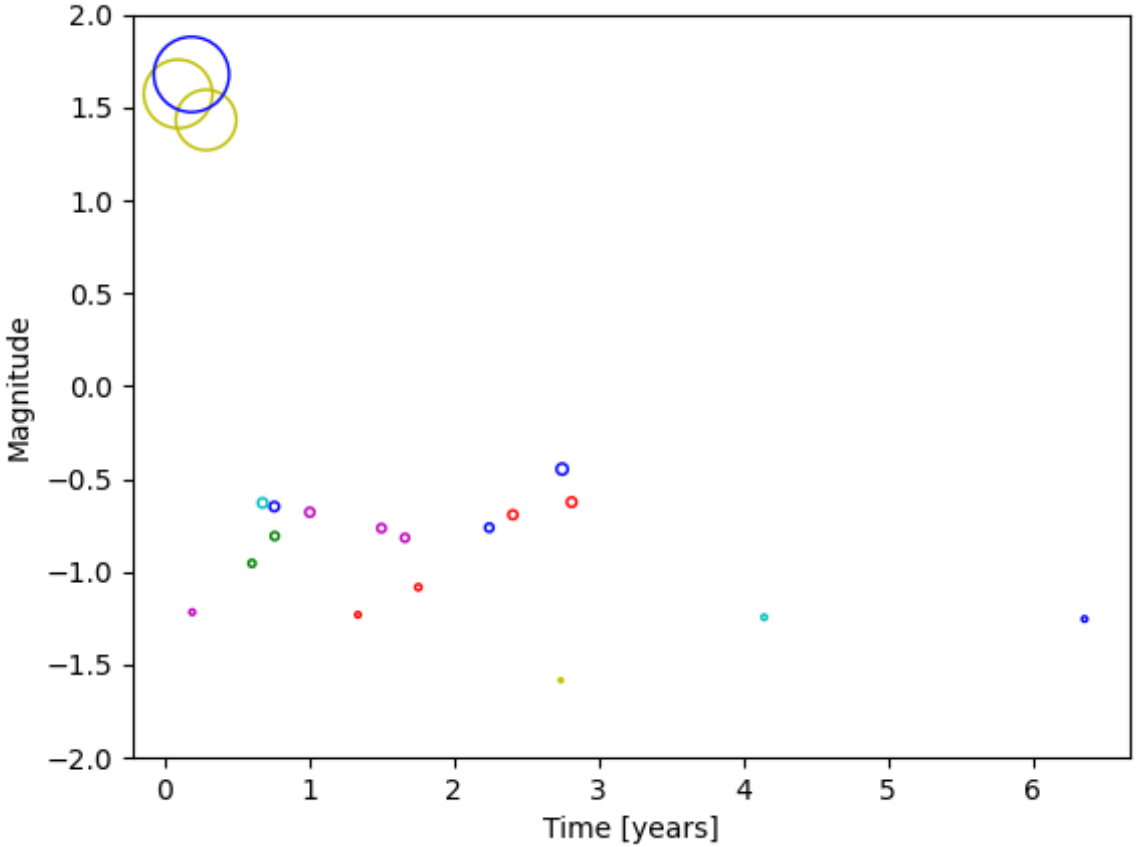


Figure: (Left) Magnitude through time. (Right) Location of the events on the X- and Y-axis with grey lines indicating faults of base case and in orange the added faults. The events of the base case model (fault area = 0.95km2) are in yellow and the events for the model with highest fault density (fault area = 1.59km2) are in cyan. The black square is the injection location.

Outcome

Highest magnitudes if injection location is close to the NNW-SSE dipping fault.

Seismic slip only present in the first 6 years of production



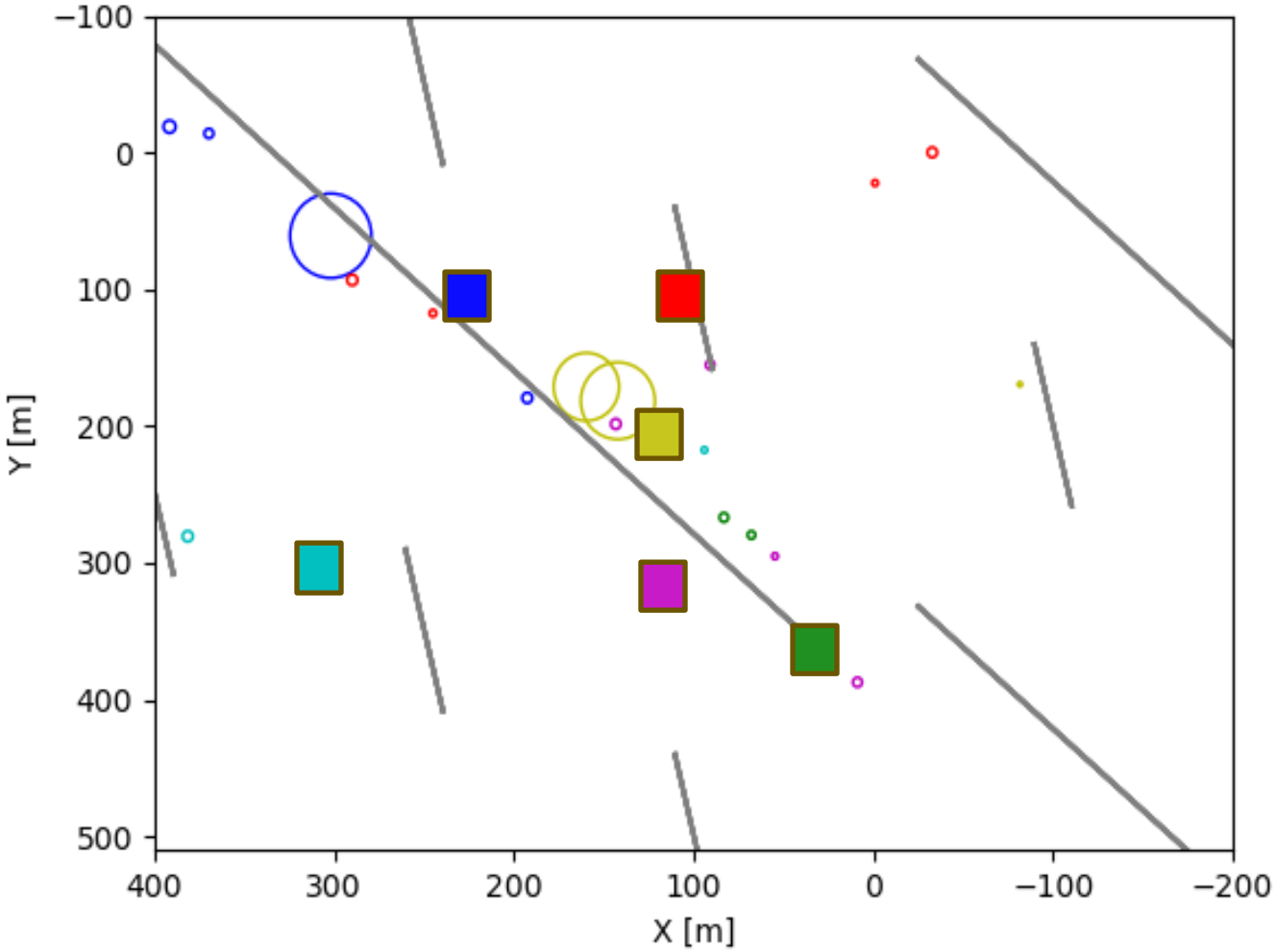


Figure: (left) Magnitude vs record time with colors indicating different models and size of circles correspond to size of the event. (Right) Same events on X- and Y-axis with squares indicating the injection location and grey lines the faults.

Conclusion

- Seismic slip forms in the first few years of production.
- Events nucleate at the boarder of the cooling front and do not propagate much further.
- By increasing the fault density the magnitude of the events decrease, but the number of events increase.
- By changing the injection location the magnitude, location and amount of events can be changed.

How do fluid injection–induced changes in temperature and pressure effect slip on a multiscale fracture network – Extra material

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Problem

From models with simple geometries, containing only one fault we know that in geothermal systems the temperature drop causes an increase in shear stress and decrease in normal stress leading to rock failure.

What happens when we add more faults?

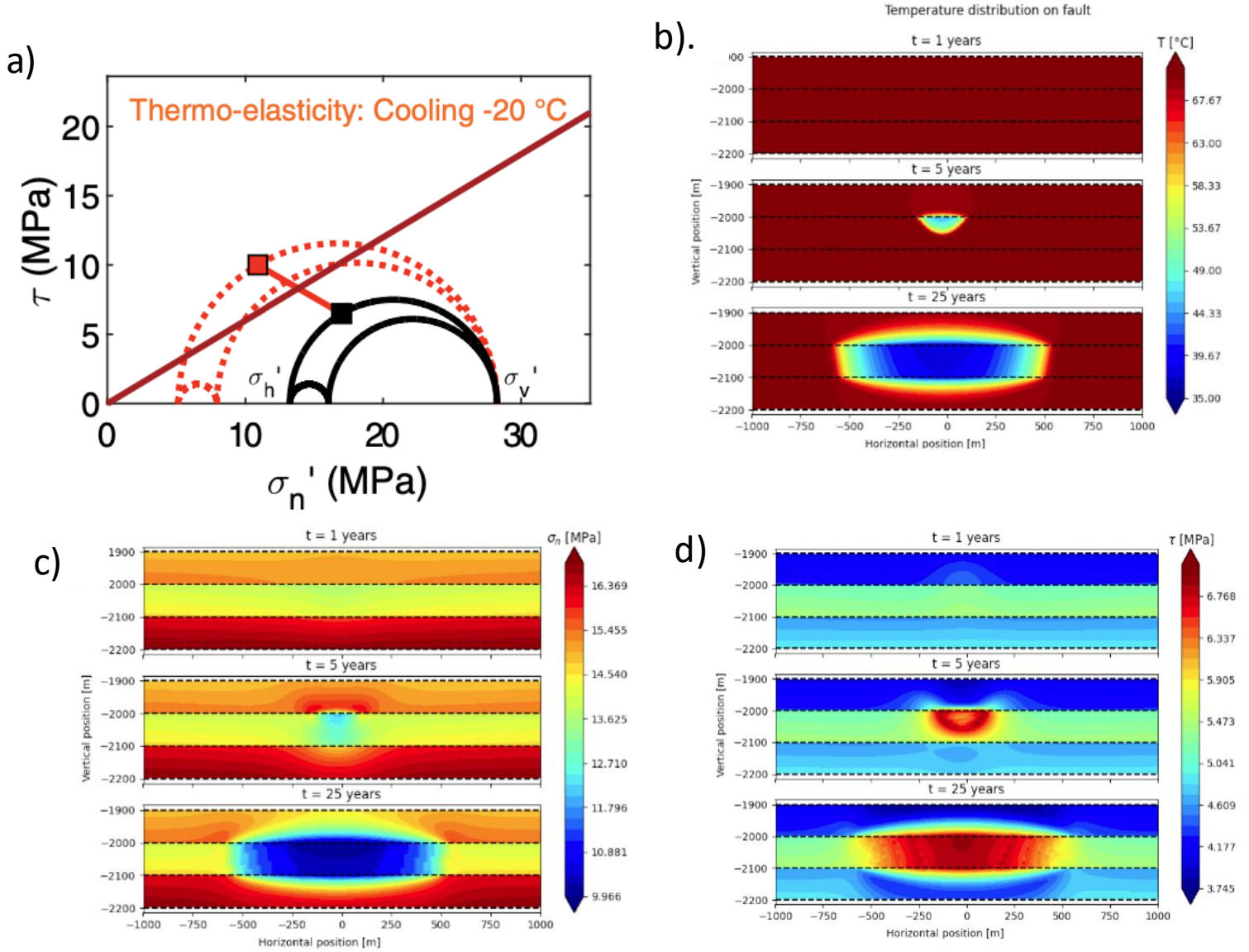
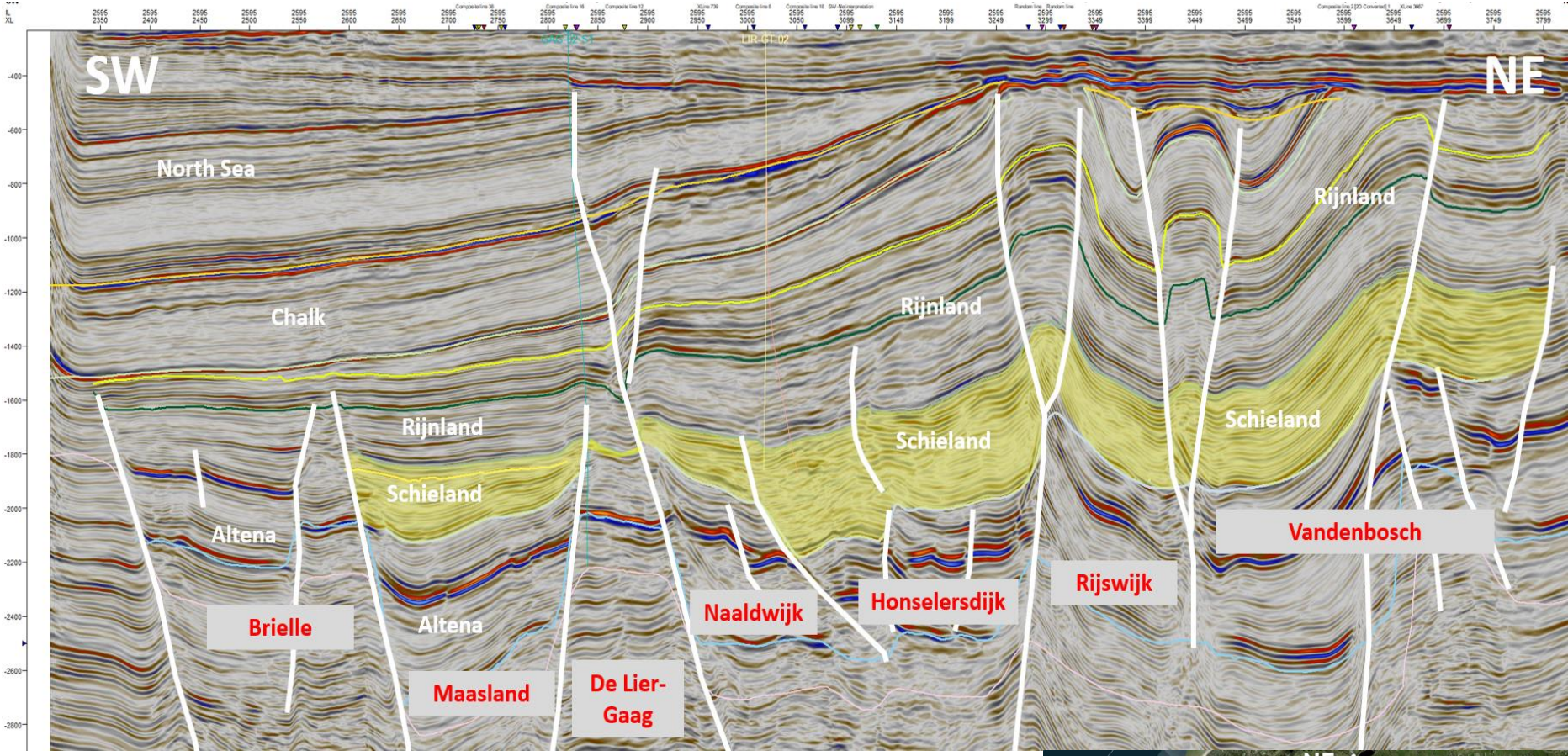


Figure: (a) Thermo-elastic stress change due to 20° of cooling adapted from Buijze et al., 2023. (b, c, d) Adapted from Fokker et al., 2019 Results are shown for three timesteps: 1 year, 5 years and 25 years. Reservoir depth is indicated by the dashed lines. (b) Temperature changes. (c) Normal stress changes. (d) Shear stress changes.

Problem

West Netherlands basin is a rift basin formed in the Jurassic to Early Cretaceous

Two main normal fault trends:
1. Oriented NW-SE, 25° to 50° from 2nd trend (red)
2. Oriented NNW-SSE (black)



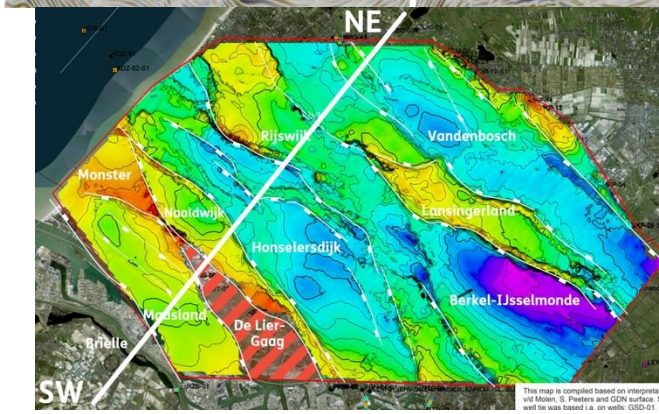


Figure adopted from Verreussel & Peeters, 2024. Top) Seismic line illustrating the basin architecture and seismic horizons that were mapped. Bottom) Time thickness map of the Nieuwerkerk formation.

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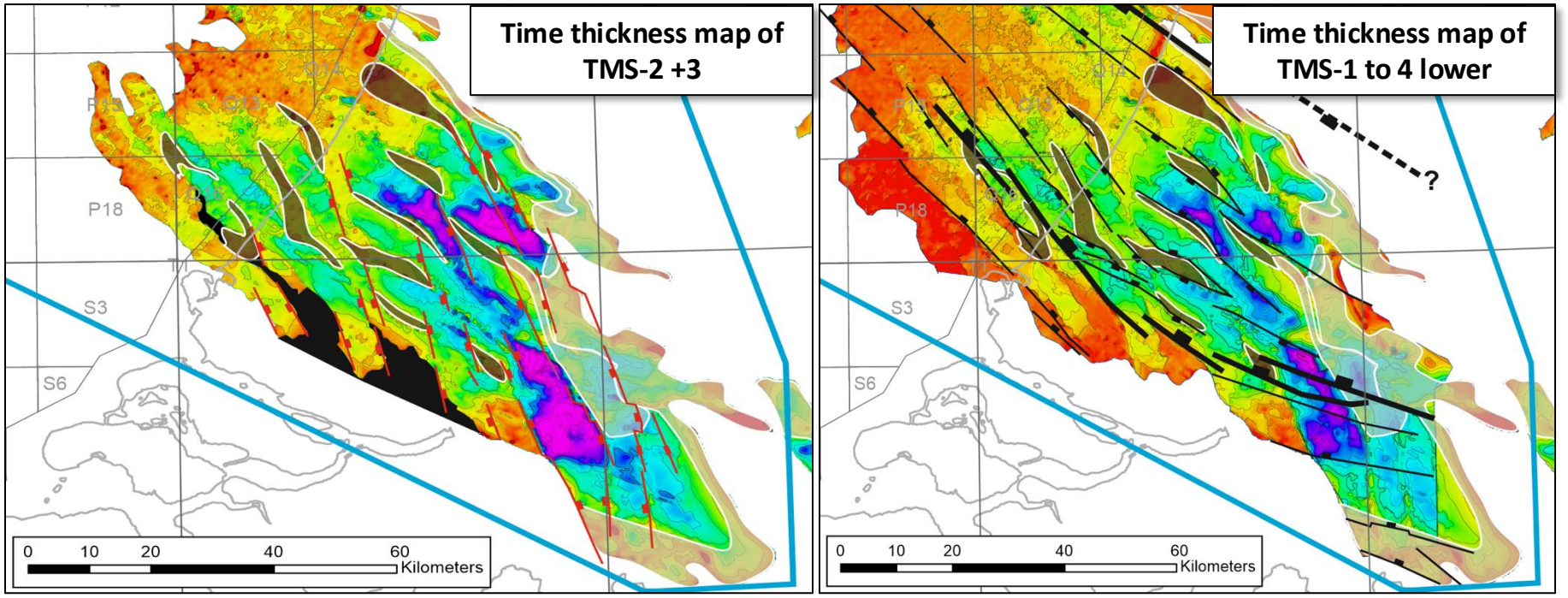
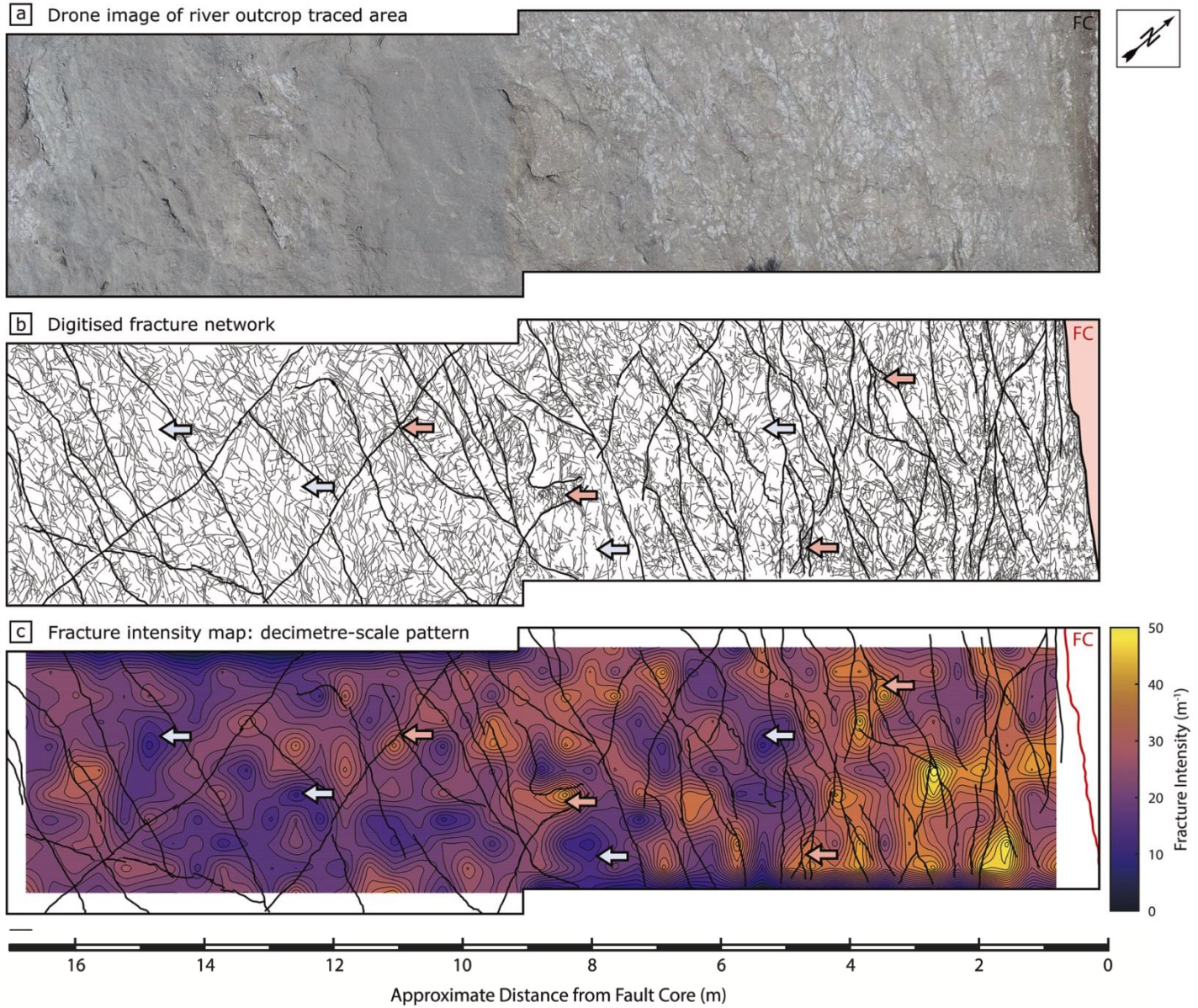


Figures: adopted from Bouroullec et al., 2024. (Left) Faults active during the depositional time of TMS-2 and early part of TMS-3 (Mid-Kimmeridgian to Late Volgian) and oriented NNW-SSE. (Right) Faults active during the depositional time of TMS-3 and TMS4-lower (Late Volgian to Hauterivain) and oriented NW-SE.

Problem

When looking at the outcrop-scale smaller faults are visible. The density decays with distance away from the main fault following an inverse exponential relationship.

In this research the seismic scale is combined with the aseismic.



Figures: adopted from G.A. Ostermijer et al., 2020. (a) Drone image of the platform outcrop. (b) Digitised fracture network with minor subsidiary faults highlighted. (c) Fracture intensity map on decimetre scale.

Intervention

- What happens when if we increase the number of considered faults in geo-mechanical forward models?
- How are the events effected by changes in the injection location and fractal distribution?

Intervention

Quake-DFN: Quasi-dynamic simulator, with inertial effects approximated by radiation damping and a lumped mass (1).

Faults are governed by rate and state friction and the aging law (2).

Added thermo-mechanical change (3).

1. $$M_i(\ddot{\delta}_i) = \sum_j \kappa_{ij}^{\tau}(\delta_{0j} - \delta_j) - \mu_i\left(\sigma'_{0i} + \sum_j \kappa_{ij}^{\sigma}\delta_j + \sigma_i^E\right) - \frac{G}{2\beta}\dot{\delta}_i + \tau_i^E$$

2. $$\mu = \mu_0 + a\log\left(\frac{V}{V_0}\right) + b\log\left(\frac{V_0\theta}{Dc}\right)$$

$$\frac{d\theta}{dt} = 1 - \frac{V\theta}{Dc} - \alpha\frac{\theta\dot{\sigma}}{\beta\sigma'}$$

3. $$T_{aq}(r,t) = T_0 + \Delta T_0 erfc\left[\frac{ar^2}{\sqrt{t - cr^2}}\right] H(t - cr^2)$$

$$a = \frac{\pi K_{rock}}{\dot{m} c_w \sqrt{K_t}} \qquad c = \frac{\pi h \xi \rho_{fluid}}{\dot{m}} \qquad K_T = \frac{K_{rock}}{(\rho C)_{rock}} \qquad \xi = \frac{(\rho C)_{rock}}{(\rho C)_{fluid}}$$

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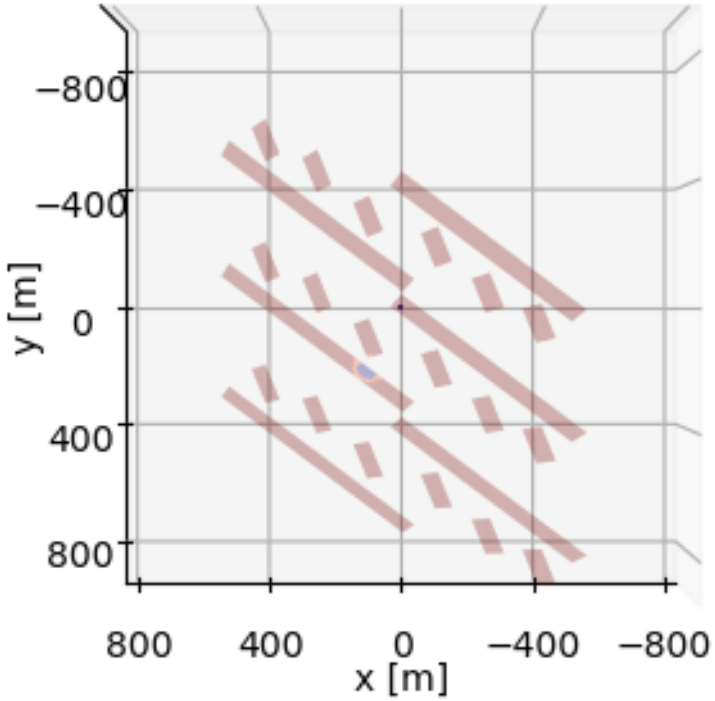
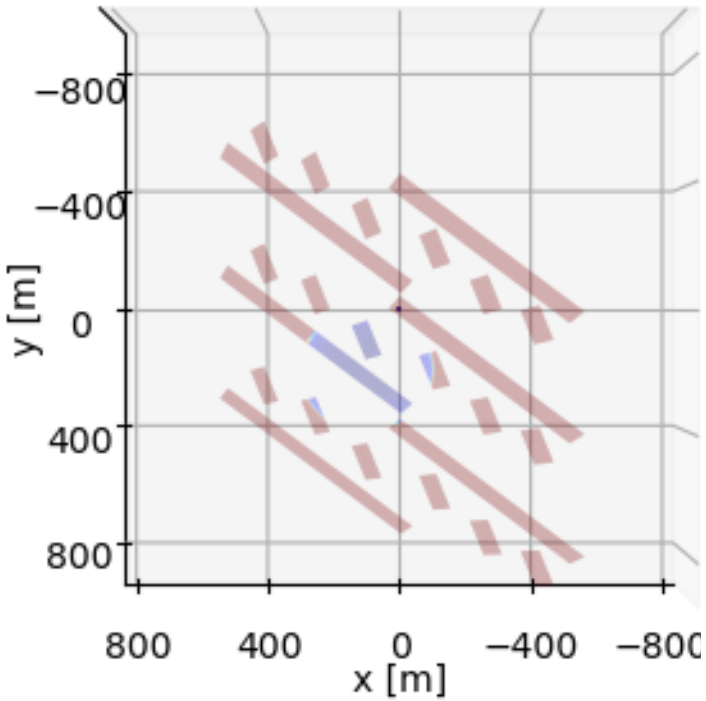
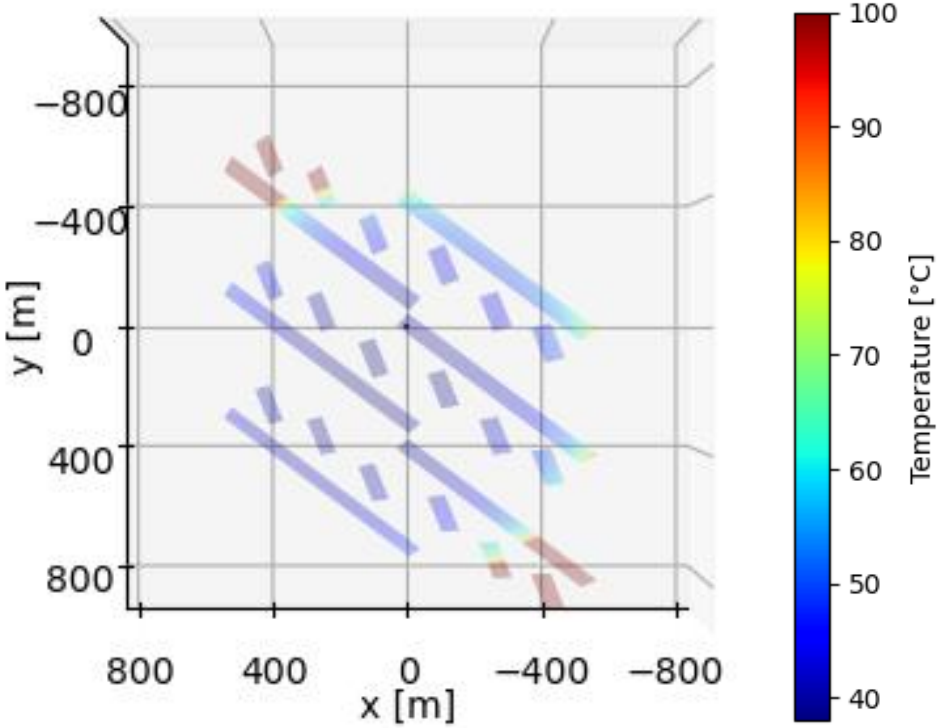


Time is 35 days



Time is 3 years



Time is 35 years

Outcome

<u>Base case:</u>

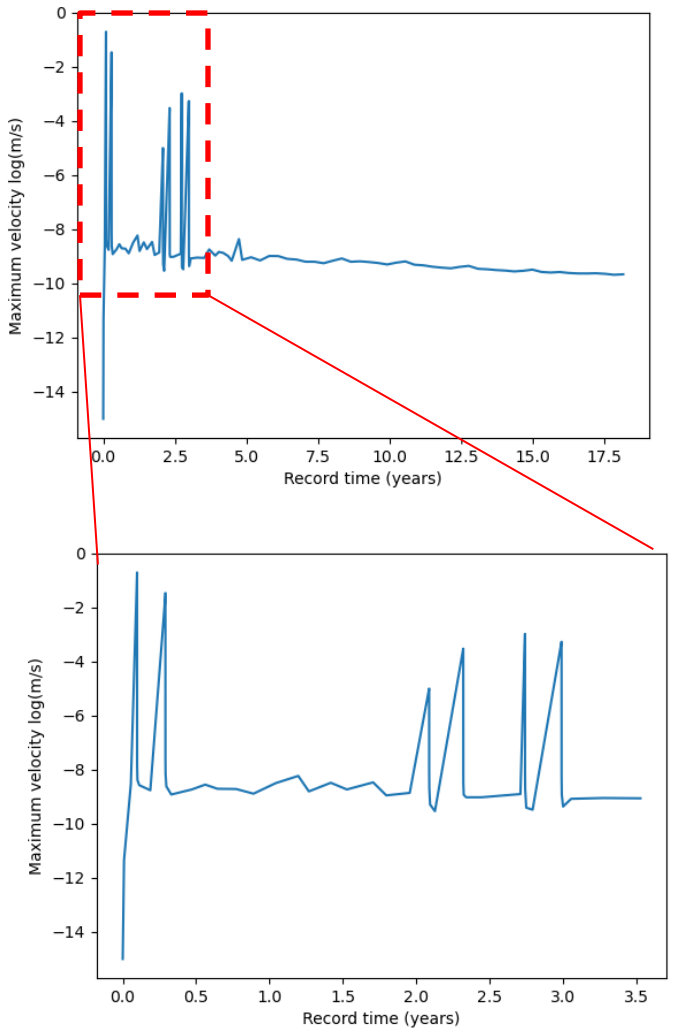
1st family

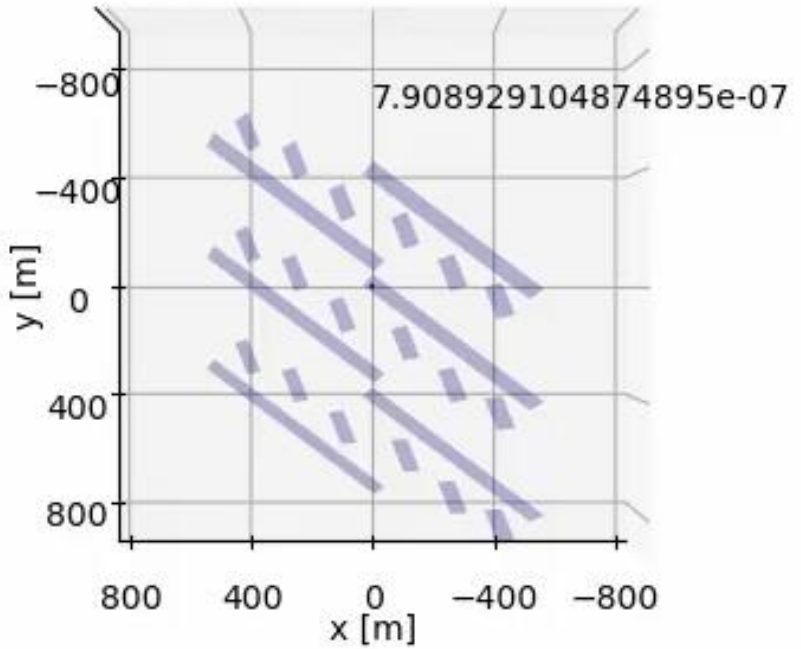
- 6 faults
- Dip 70°
- Strike 140°
- Area: 700m*150m

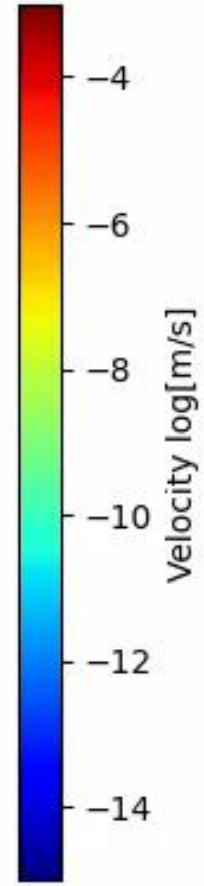
2nd family

- 18 Faults
- Dip 70°
- Strike 110°
- Area: 120m*150m

Event with highest magnitude after 35 days. M0 =1.57







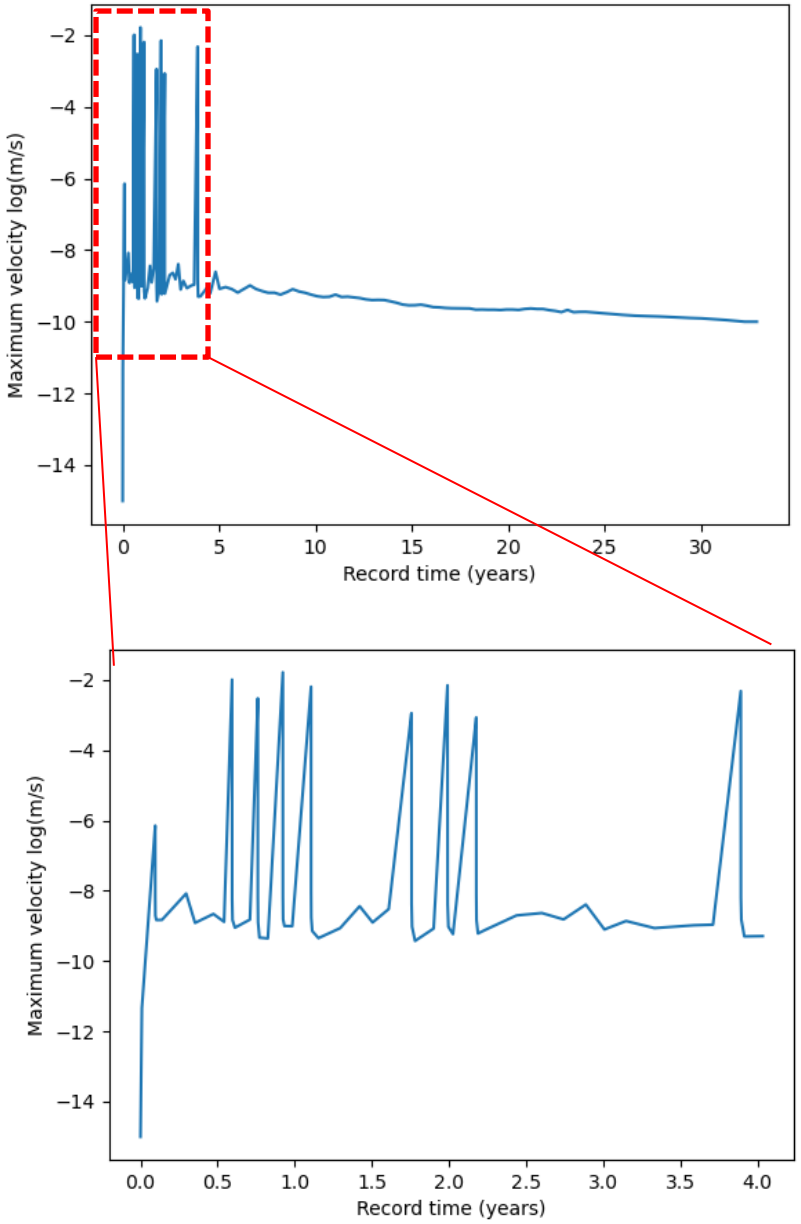
Outcome

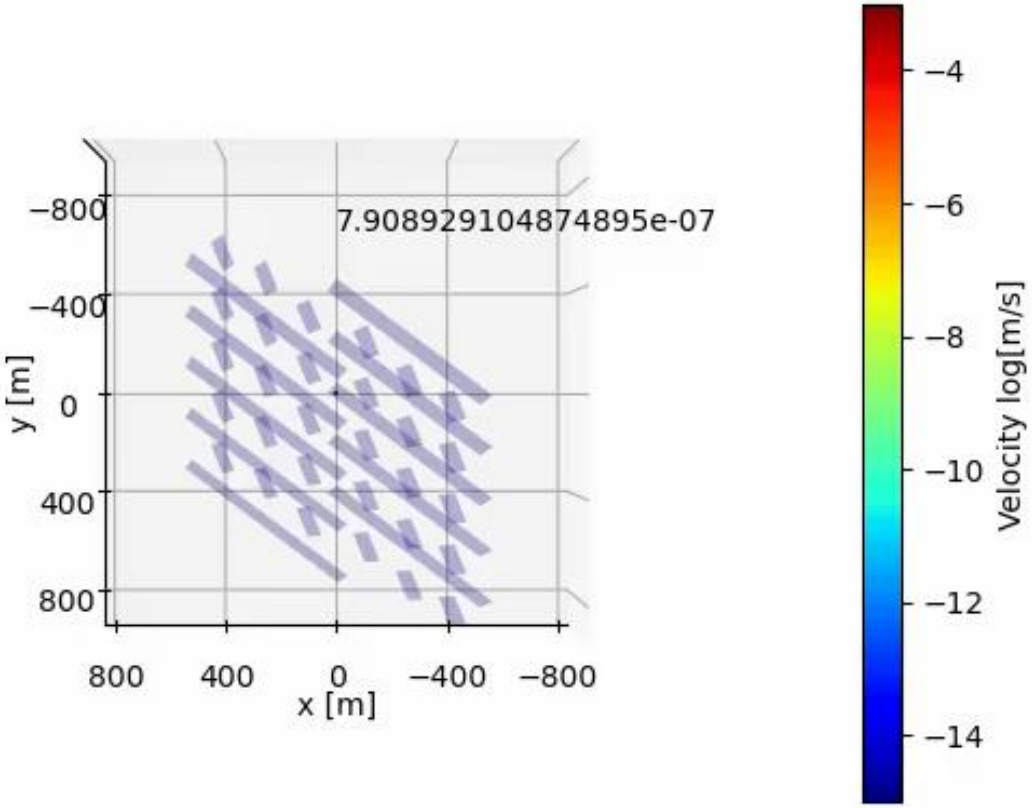
Case: highest fault density

1st family increases with 4 faults and 2nd family with 12.

First seismic event is delayed by 10 months, M0 = -0.18

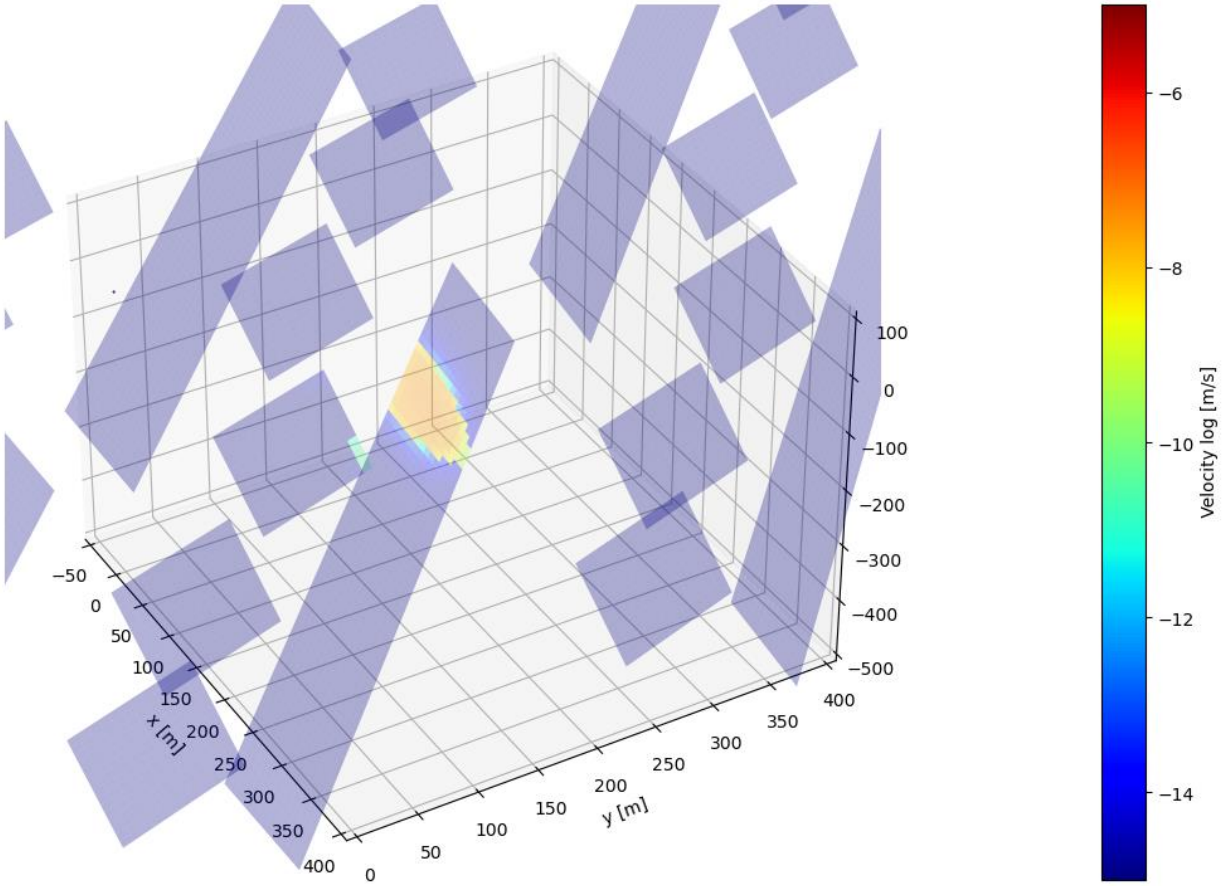
Increased number of low magnitude events.

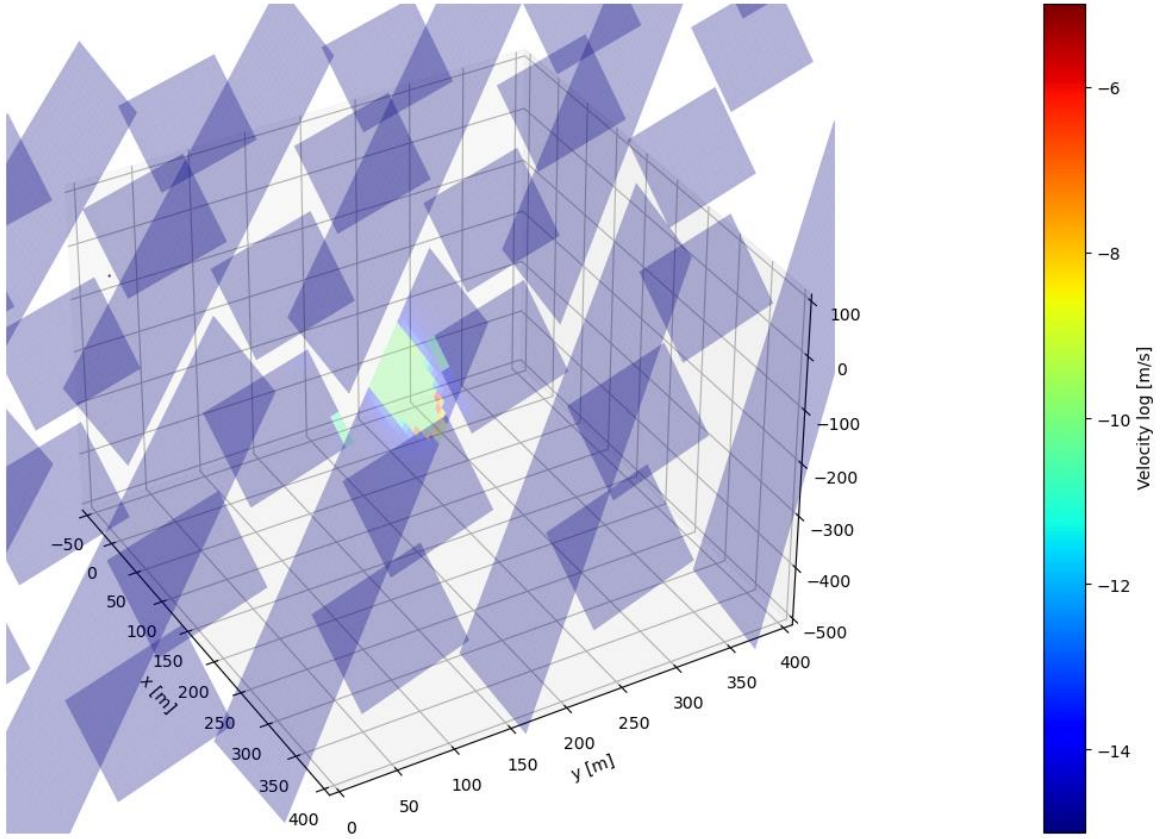




Outcome

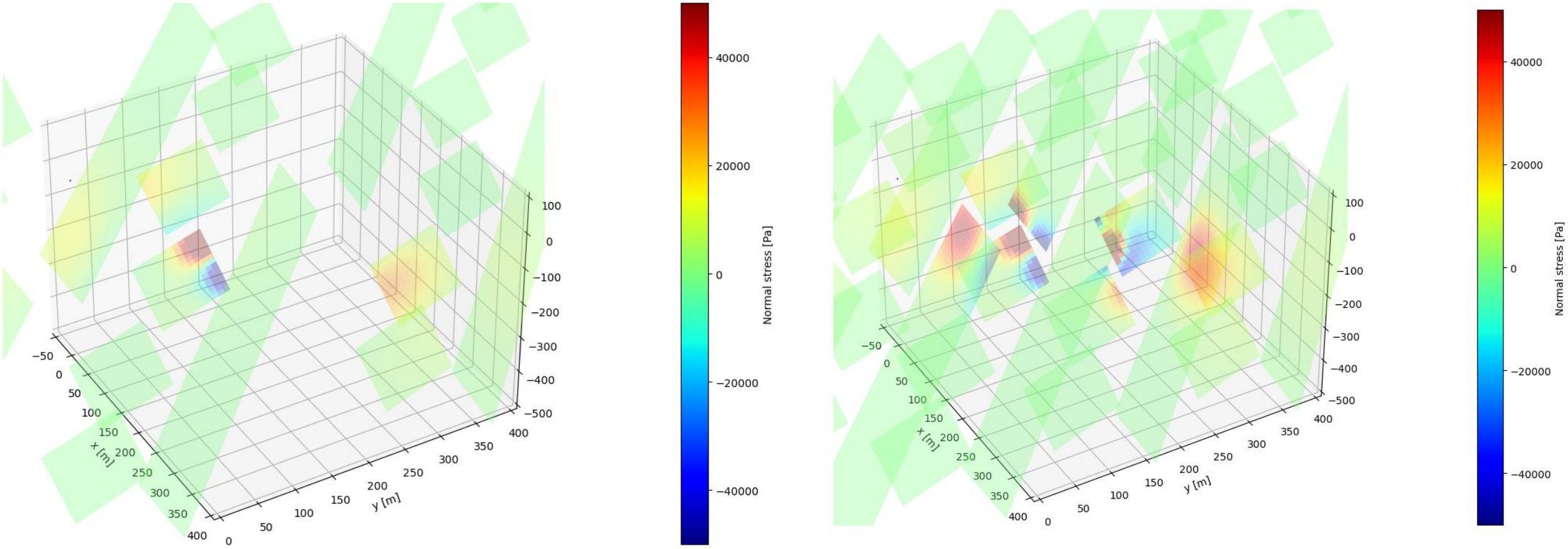
Zoom of the slip rate after 35 days of production for the base case (left) and highest fault density case (right). For the base case this is the onset of the first seismic event.





Outcome

Zoom of the normal stress change caused by fault interactions after 35 days of production for the base case (left) and highest fault density case (right).



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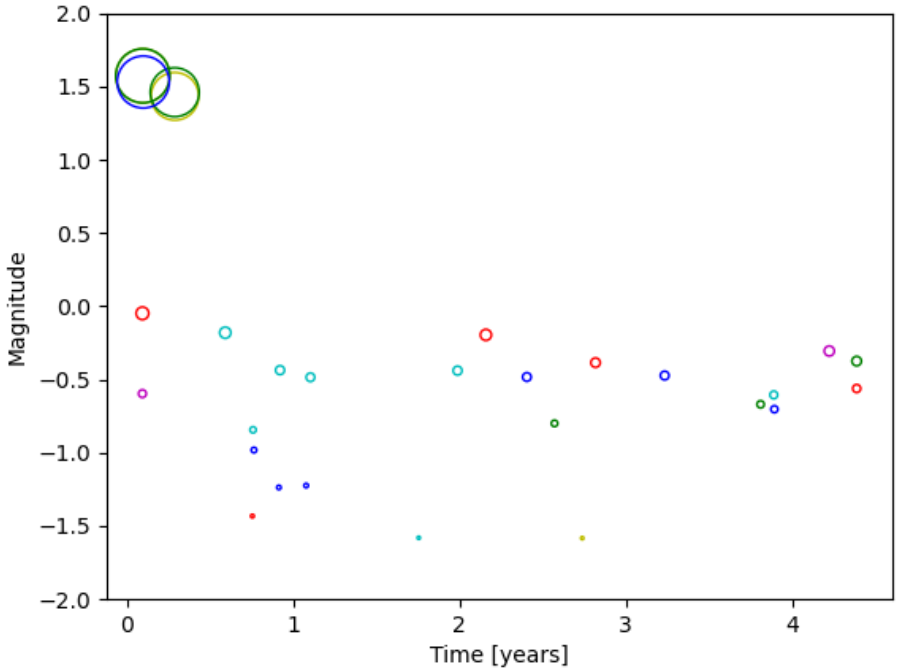
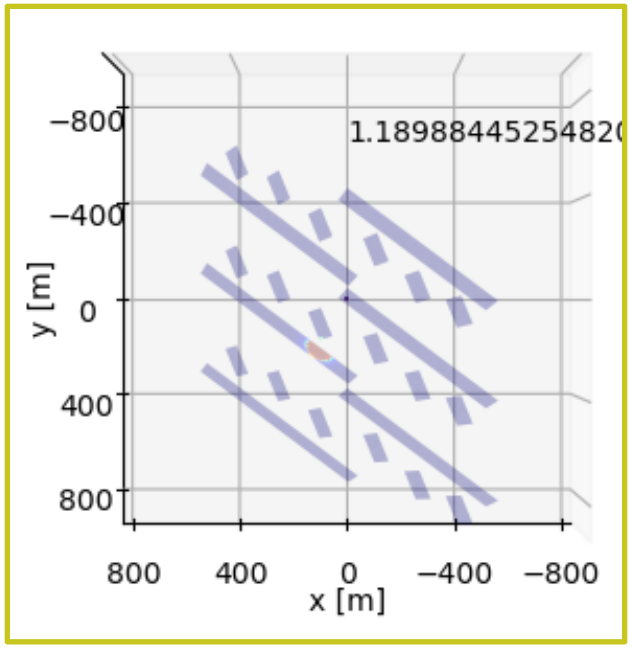
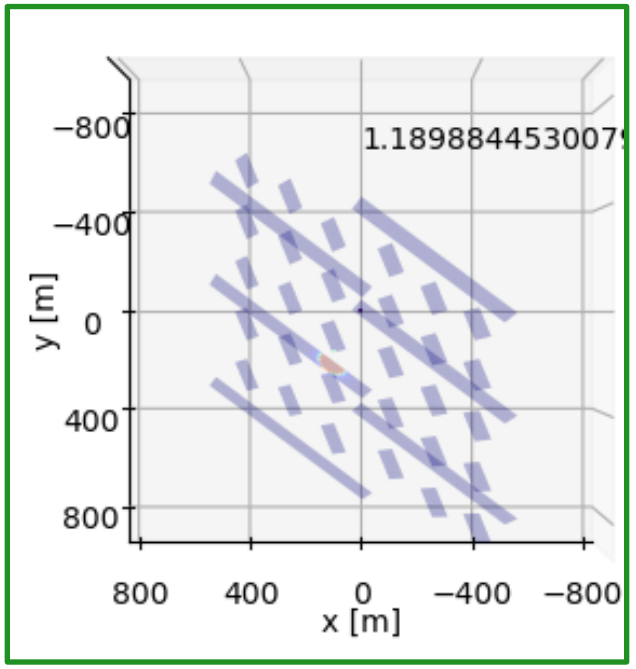
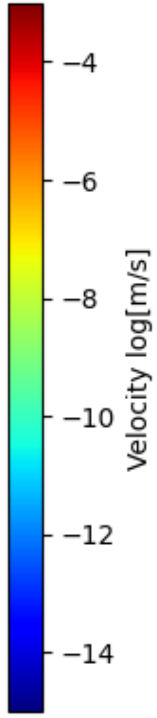
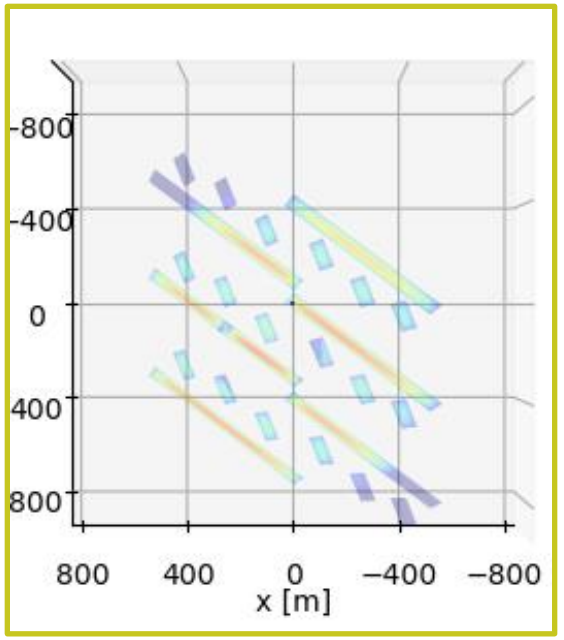
Outcome

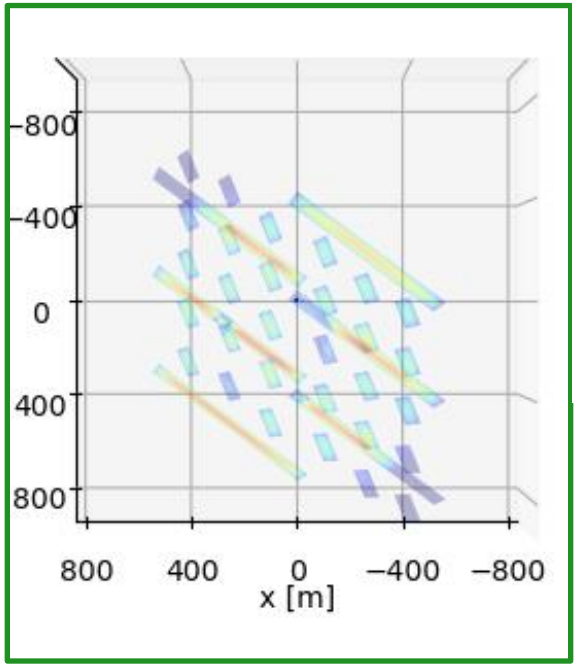


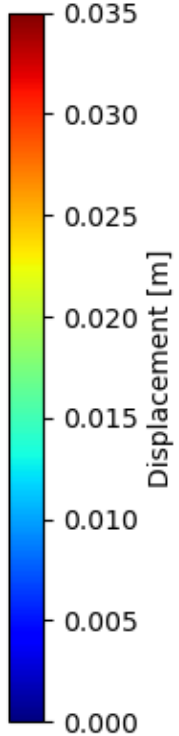












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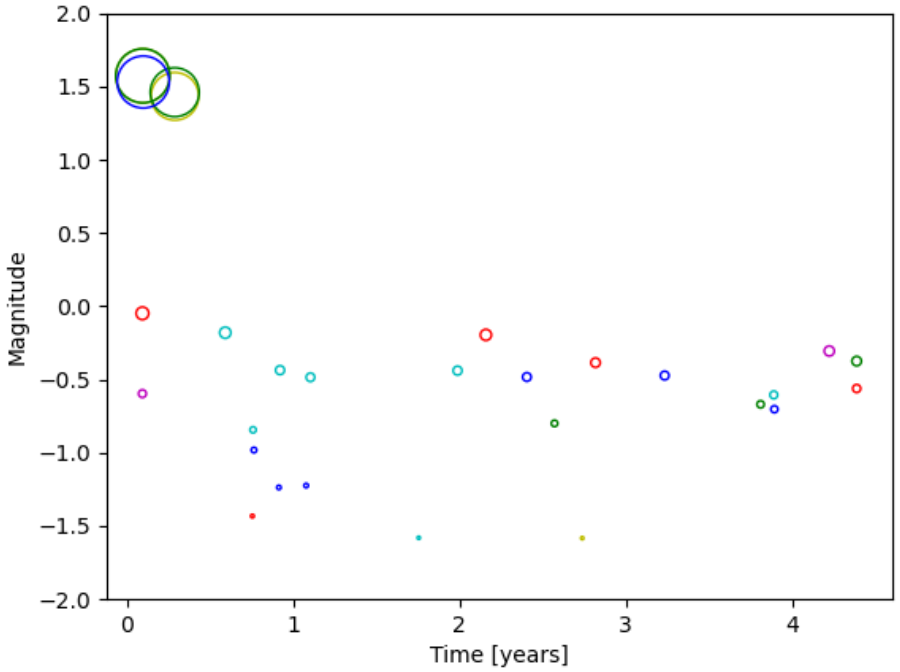
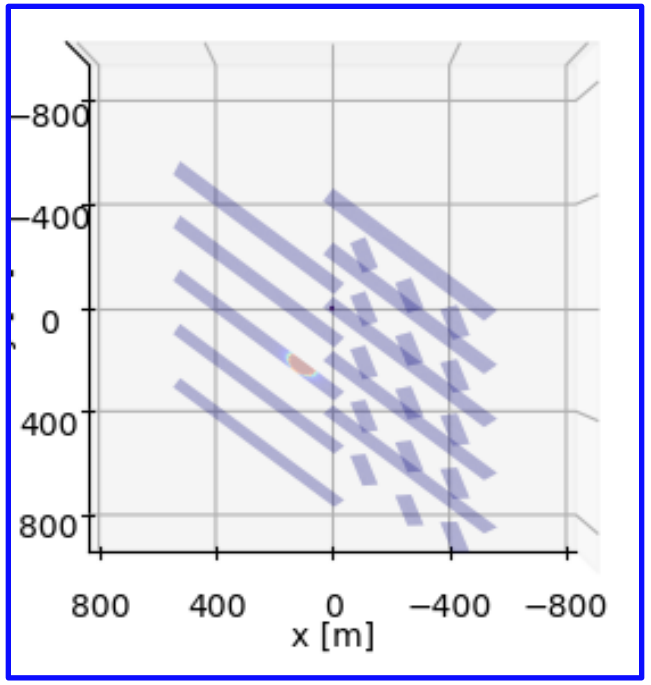
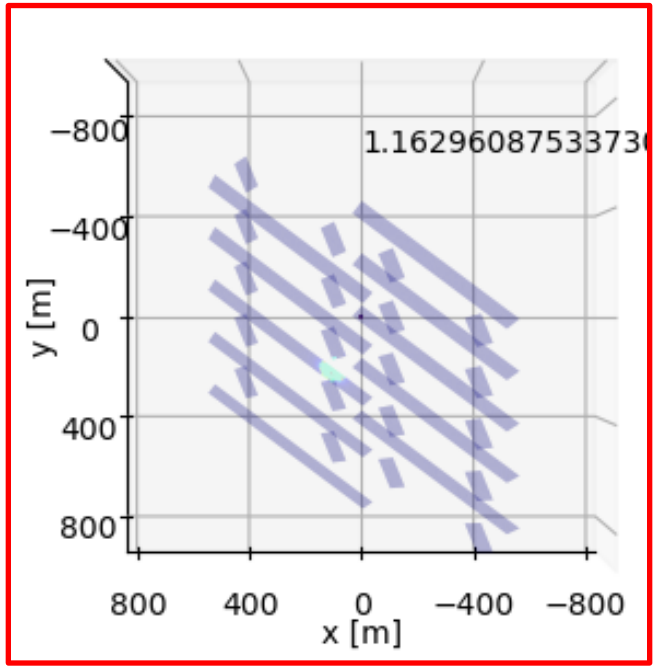
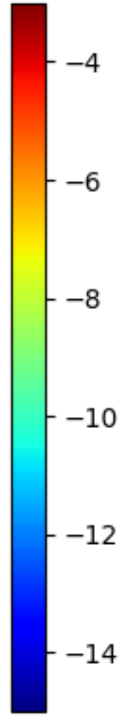
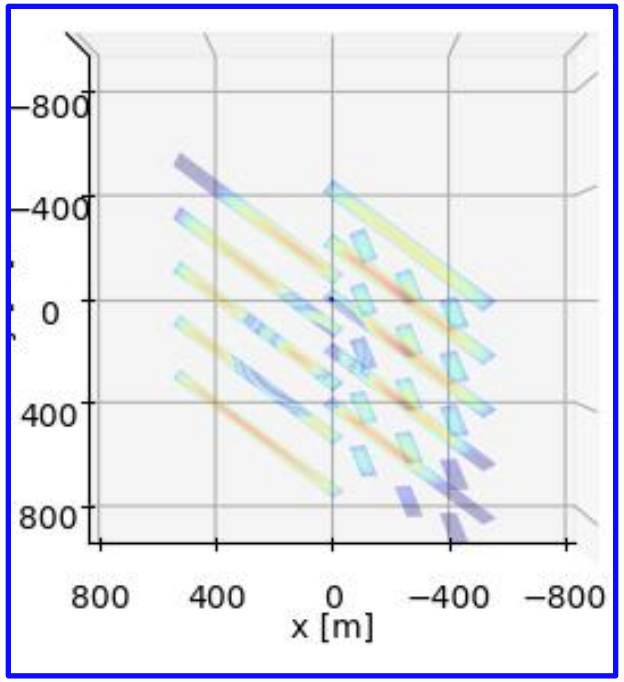
Outcome

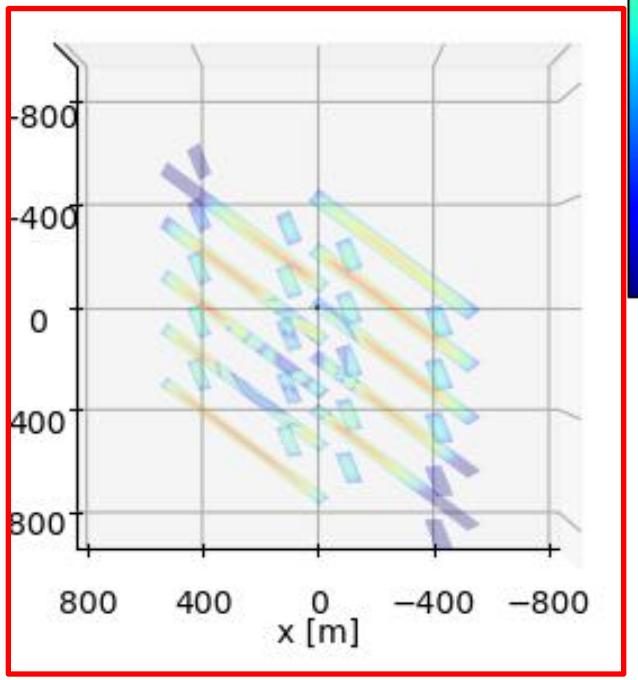


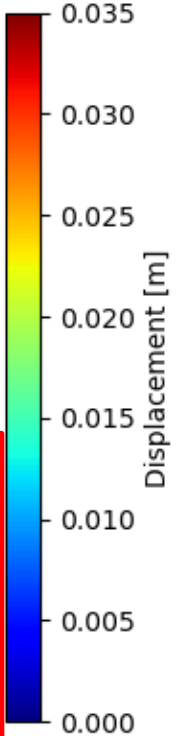












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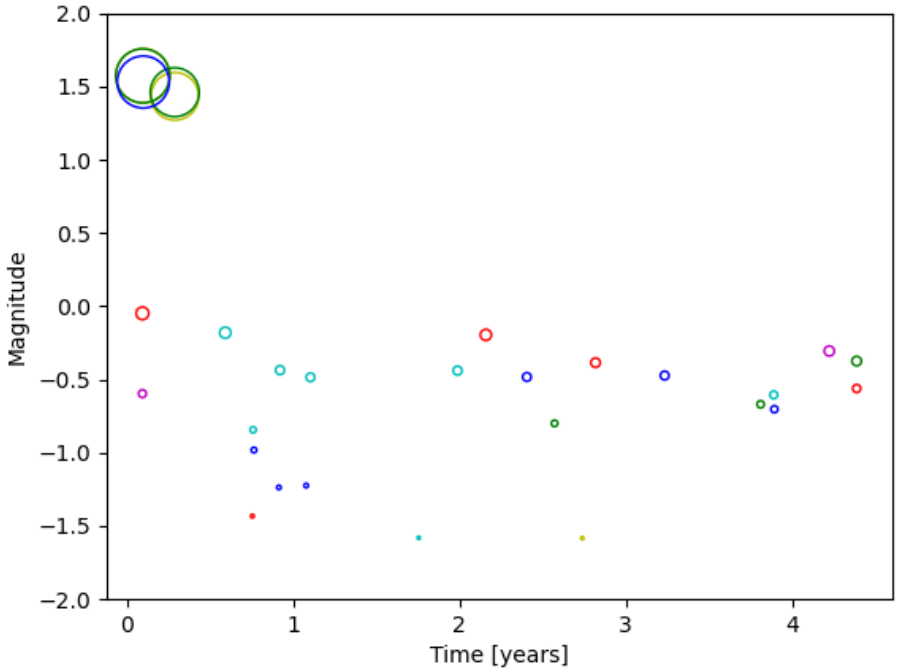
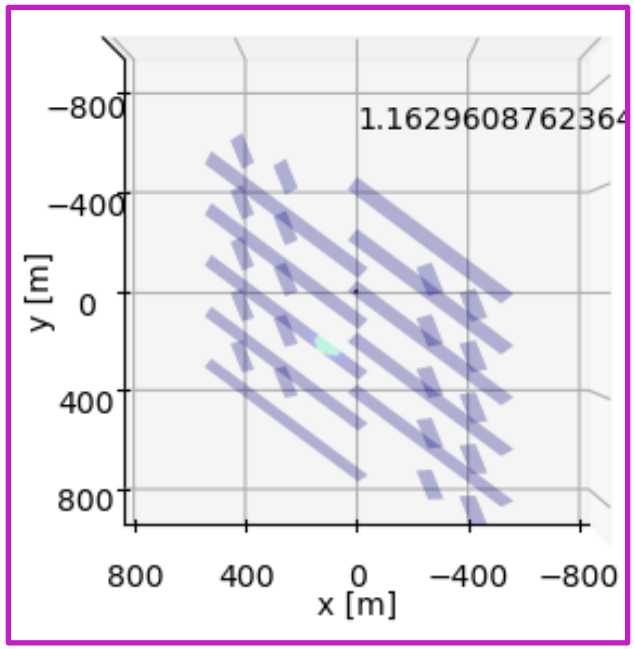
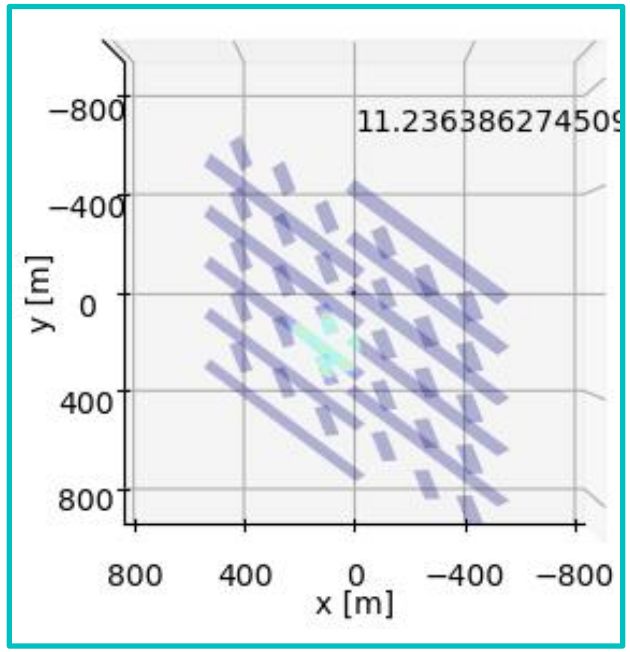
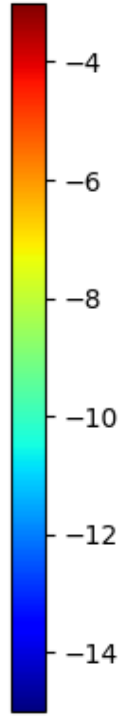
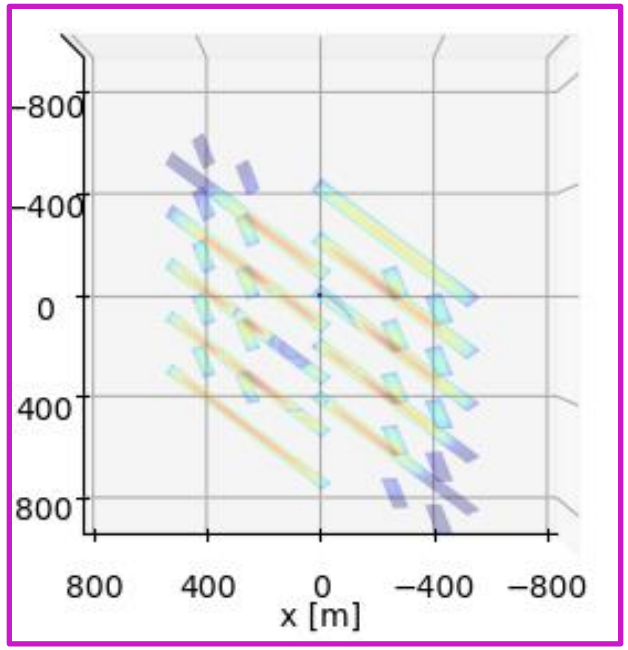
Outcome

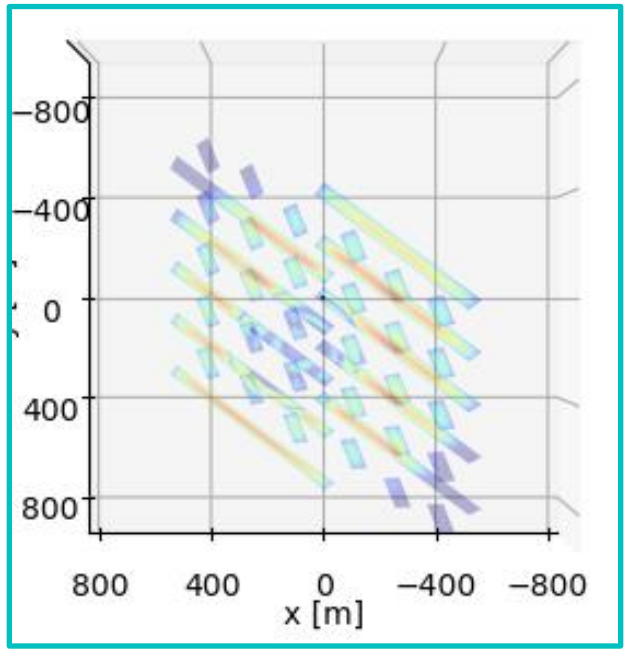


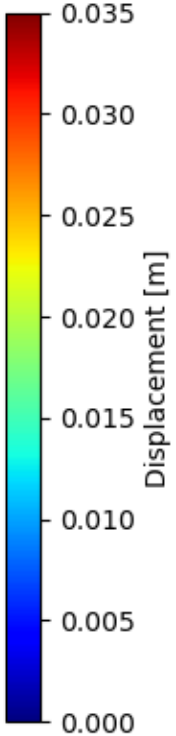












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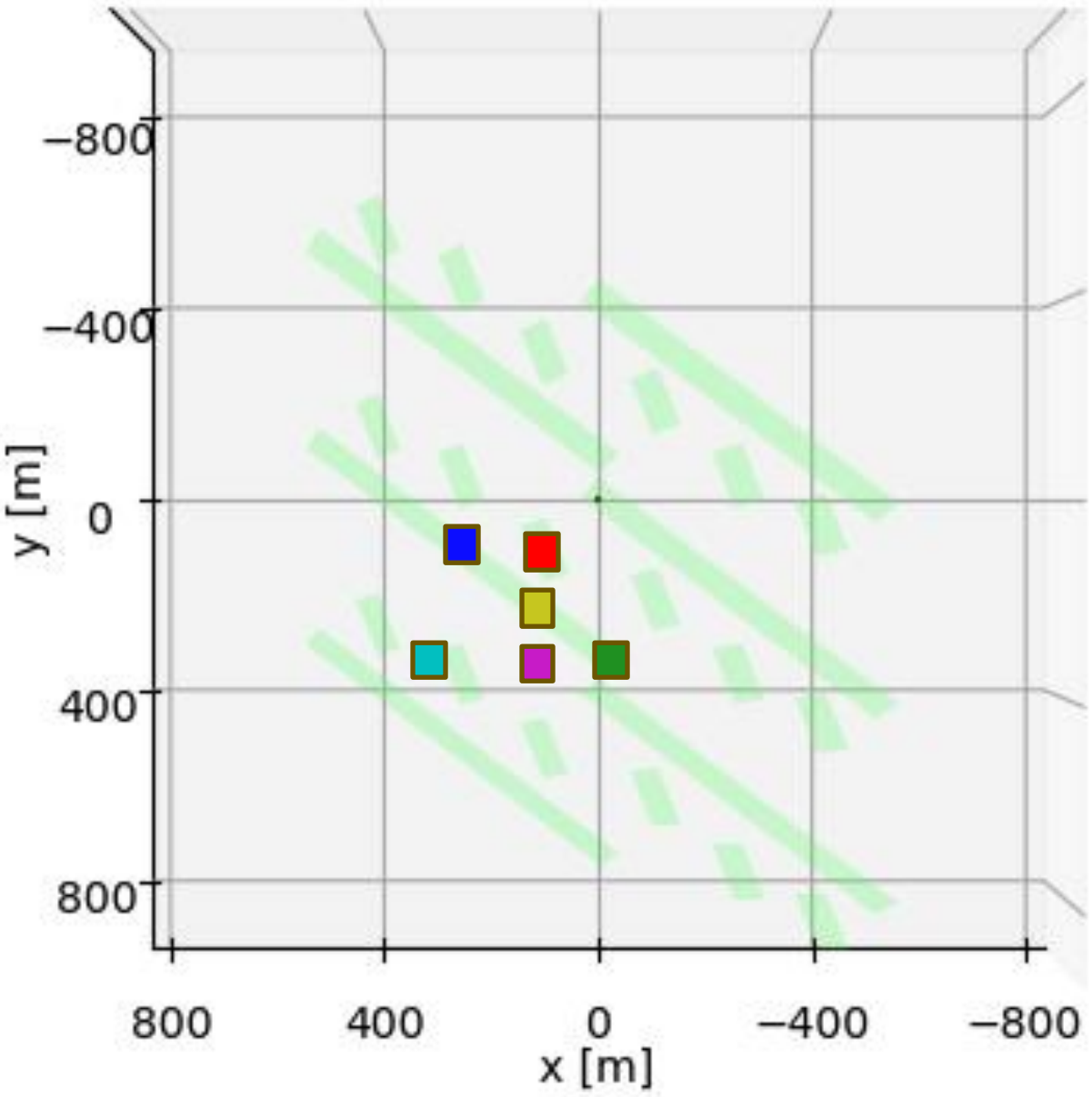
Outcome

Run 5 models with different injection locations.

All other parameters are kept the same.

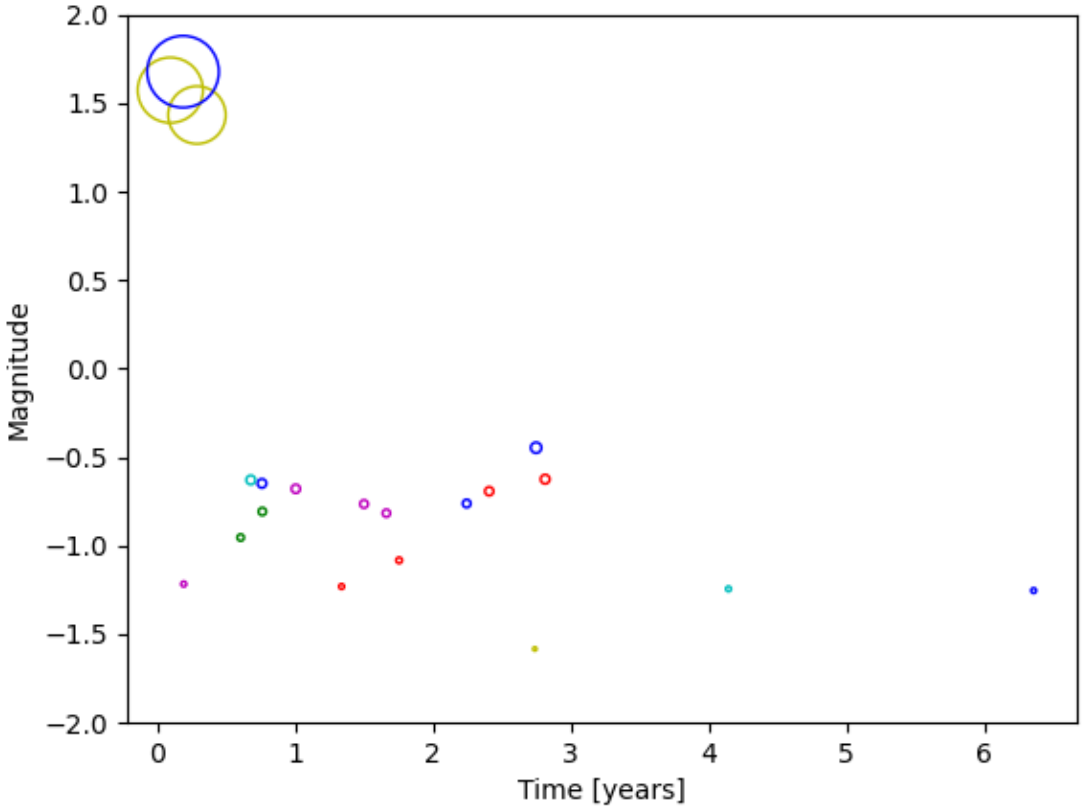


- Base case
- Injection at 25,368
- Inection at 250,100
- Injection at 100,100
- Injection at 110, 300
- Injection at 300,300

Outcome

Highest magntude if injection location is located (almost) on the NNW-NNW-SSE faults dipping faults.

Seismic slip only forms in the first 6 years of production.



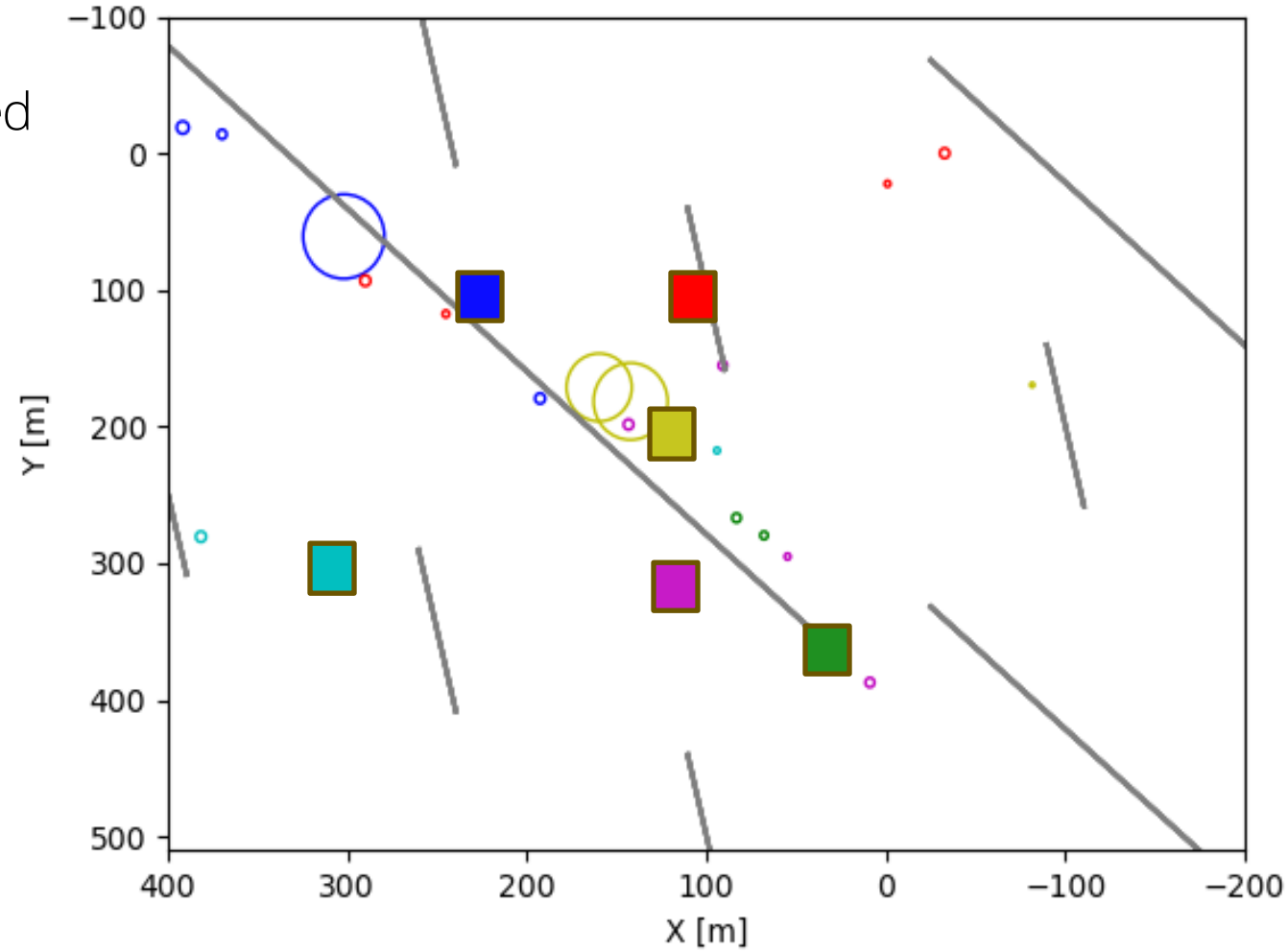


Figure: (left) Magnitude vs record time with colors indicating model and size of circles correspond to size of the event. (Right) Same events on X- and Y-axis with squares indicating the injection location and grey lines the faults.

Conclusion

- Seismic slip forms in the first few years of production.
- Events nucleate at the boarder of the cooling front and do not propagate much further.
- By increasing the fault density the magnitude of the events decrease, but the number of events increase.
- By changing the injection location the magnitude, location and amount of events can be changed.

Next step

- Add aseismic faults, more heterogeneous fault network
- Larger differentiation in dip

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