Formation of fault damage zones in carbonates

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TREAD

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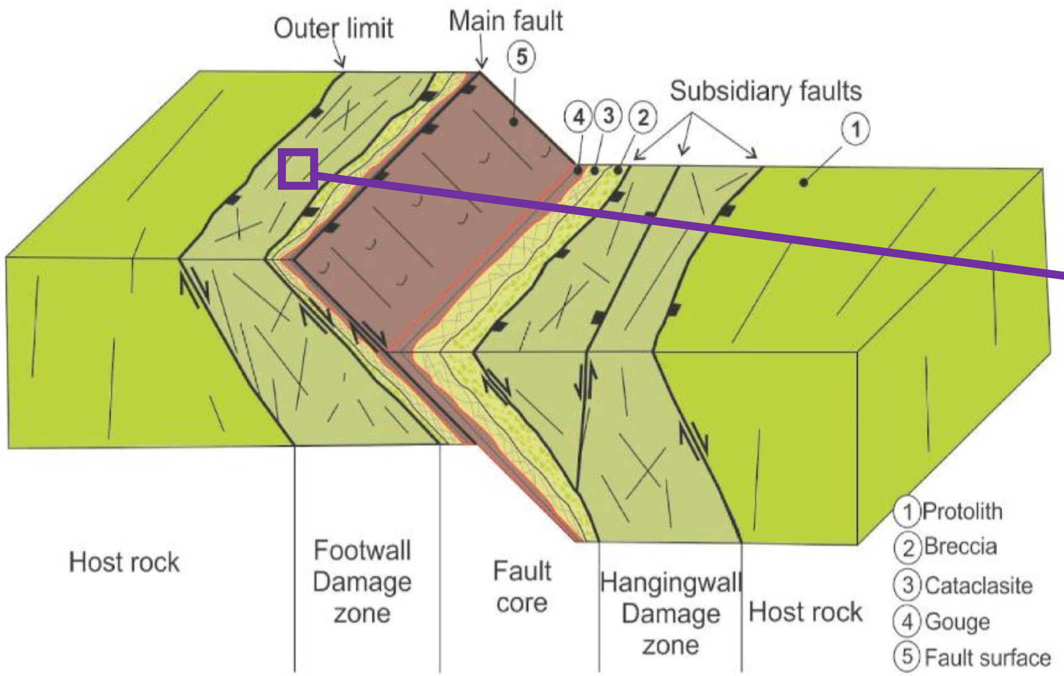
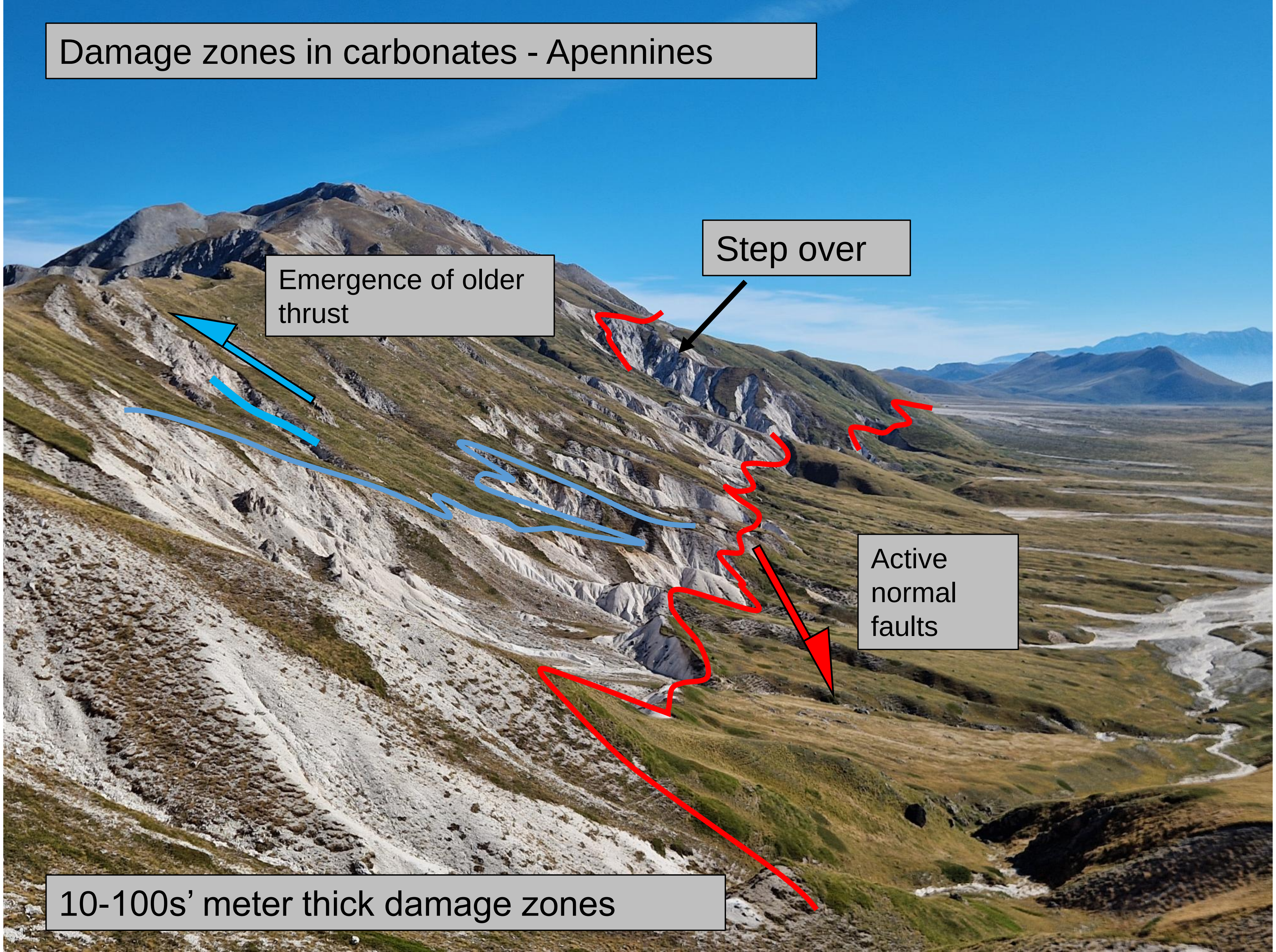
What is a fault damage zone?



(Celestino et al., 2020)


Damage zones in carbonates - Apennines
Emergence of older thrust
Step over
Active normal faults
10-100s’ meter thick damage zones

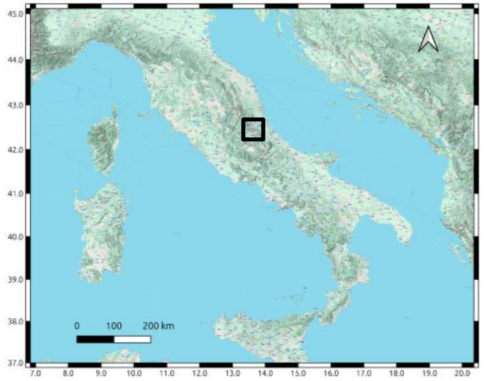
Motivation

Fault damage zones:

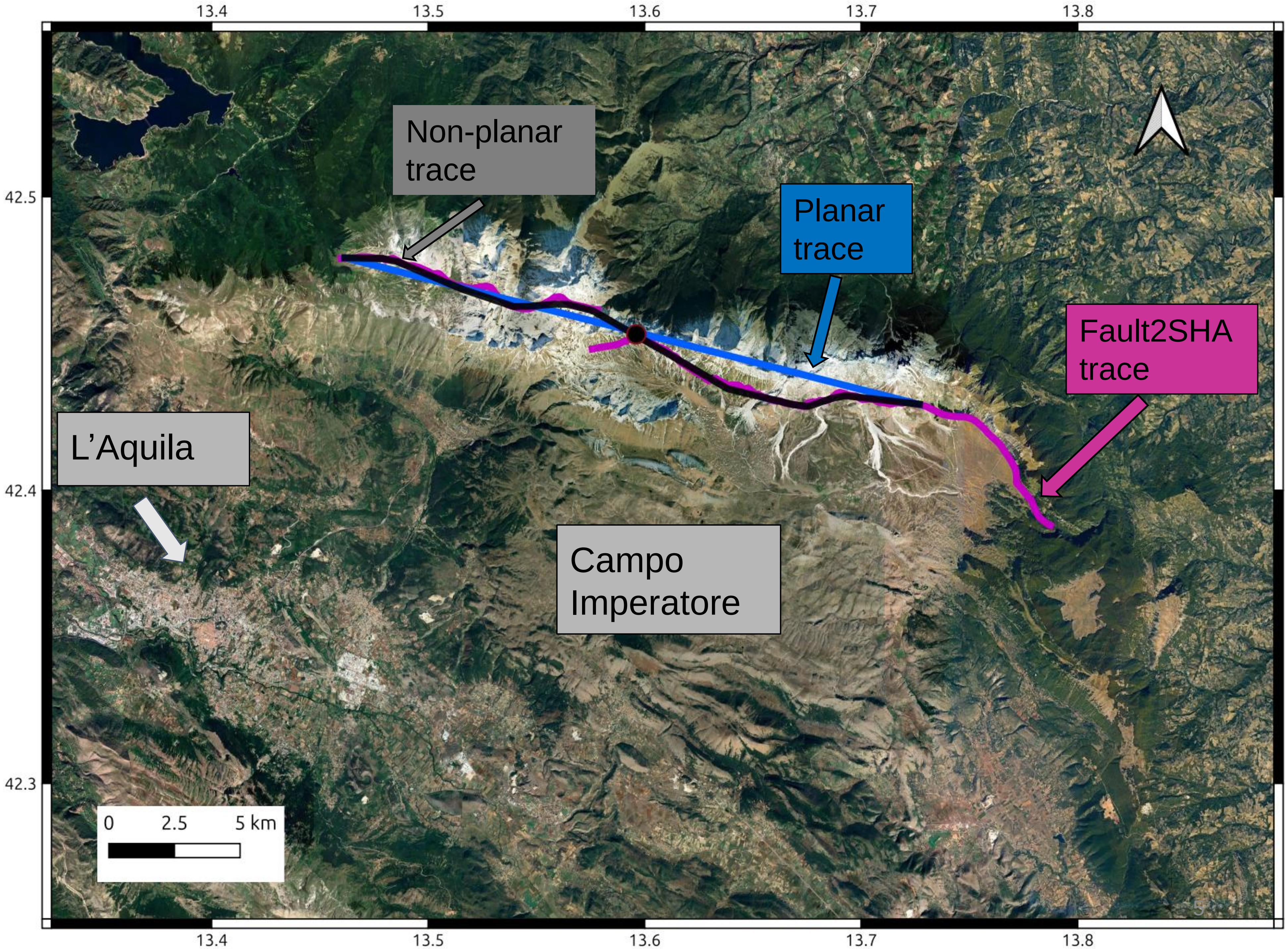
- What is their **mechanism of formation**?
- How do they influence the propagation of **individual seismic ruptures** and evolution of **seismic sequences?**
- How do they influence the **near field seismic wave radiation** and associated strong ground motions?
- How does **topography** influence damage zone formation and wave propagation?

Scientific approach

- **High-resolution geological surveys** (drone images, structural data collection, etc.) plus field data already available **(UNIPD)**
- Simulations of individual seismic ruptures & sequences with **SeisSol**

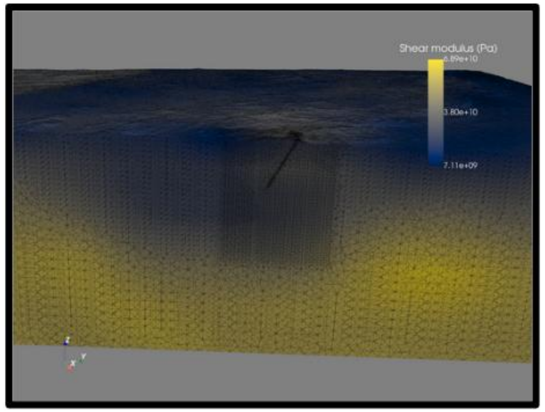


0 100 200 km



13.4
13.5
13.6
13.7
13.8
42.5
42.4
42.3
Non-planar trace
Planar trace
Fault2SHA trace
L'Aquila
Campo Imperatore
0 2.5 5 km

Elastic and plastic properties of the medium derived from a 3D-velocity model (Stallone et al., 2025)



Mesh dimensions: 400 x 400 x 100 km

Shear modulus:
$G = V_s^2 \rho$

Lambda:
$\lambda = V_P^2 \rho - 2G$

Plastic cohesion:
$C = 10^{-4} G$

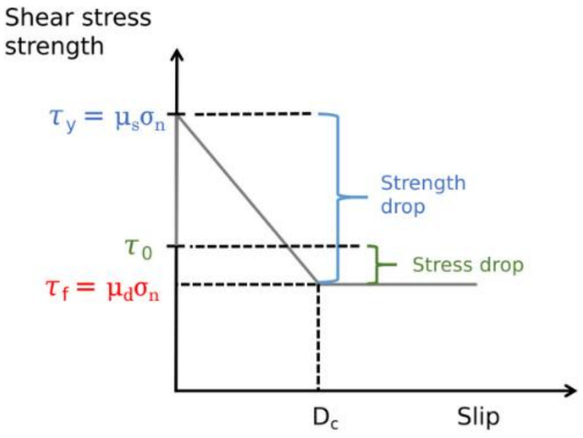
Drucker-Prager yield criterion:

$\tau_c = C \cos(\Phi) - \sigma_m \sin(\Phi)$

Φ = angle of internal friction

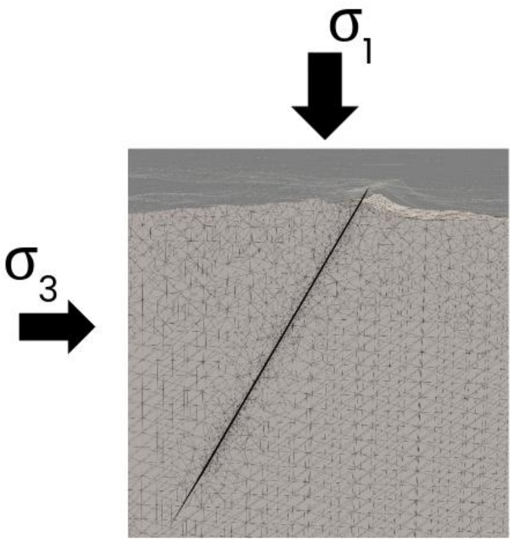
σ_m = mean stress

Fault friction: Linear slip weakening law



$$Ro = \frac{\tau_0 - \mu_d\sigma_n}{(\mu_s - \mu_d)\sigma_n} = \frac{\text{Stress drop}}{\text{Strength drop}}$$

Initial stress



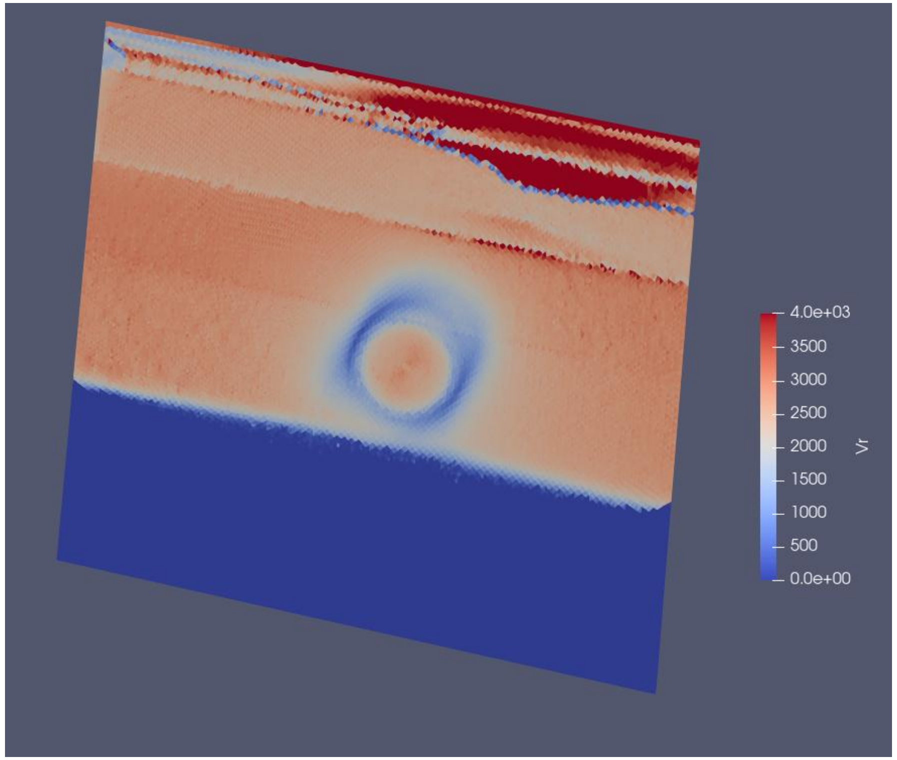
SeisSol Solver

Output: Seismic wave propagation, dynamic rupture, and seismic, geodetic synthetics in the near and far-field

Problem: Rupture velocity at shallow depths

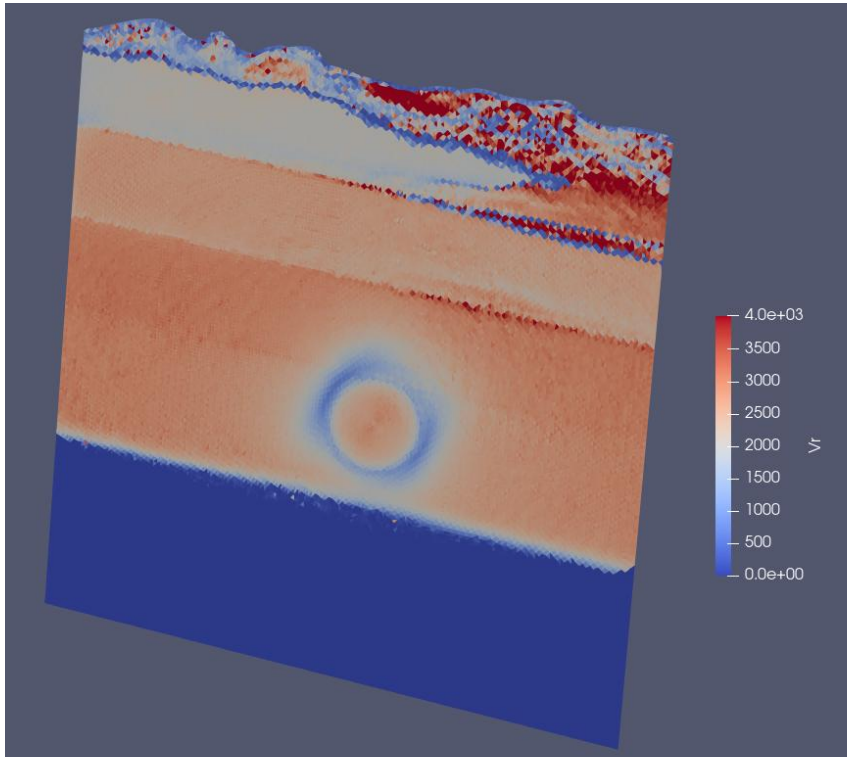
Without topography,

1D velocity model



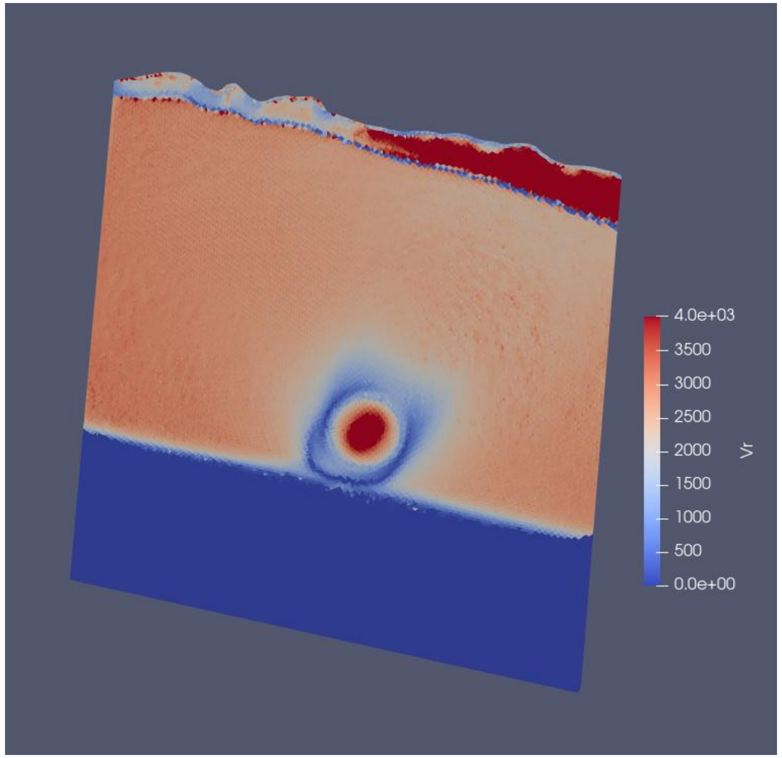
Considering topography,

1D velocity model

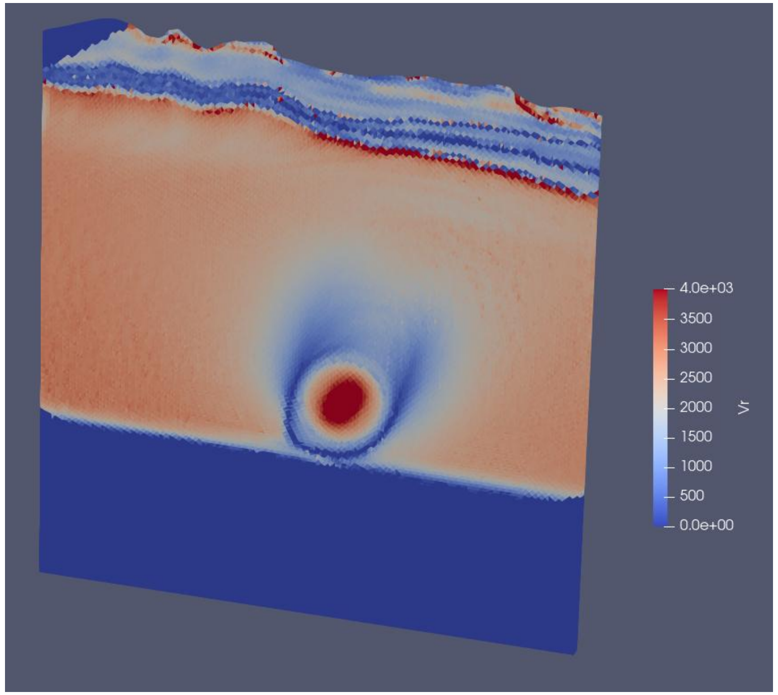


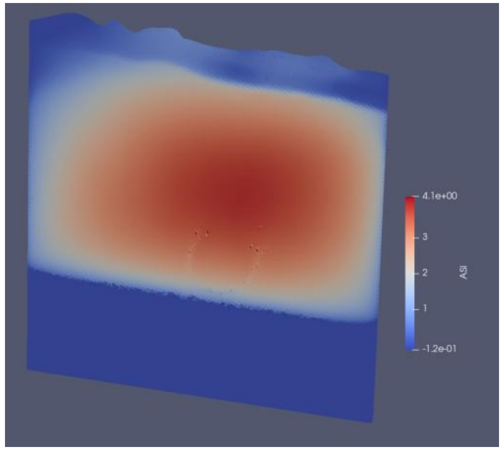
Considering topography,

3D velocity model

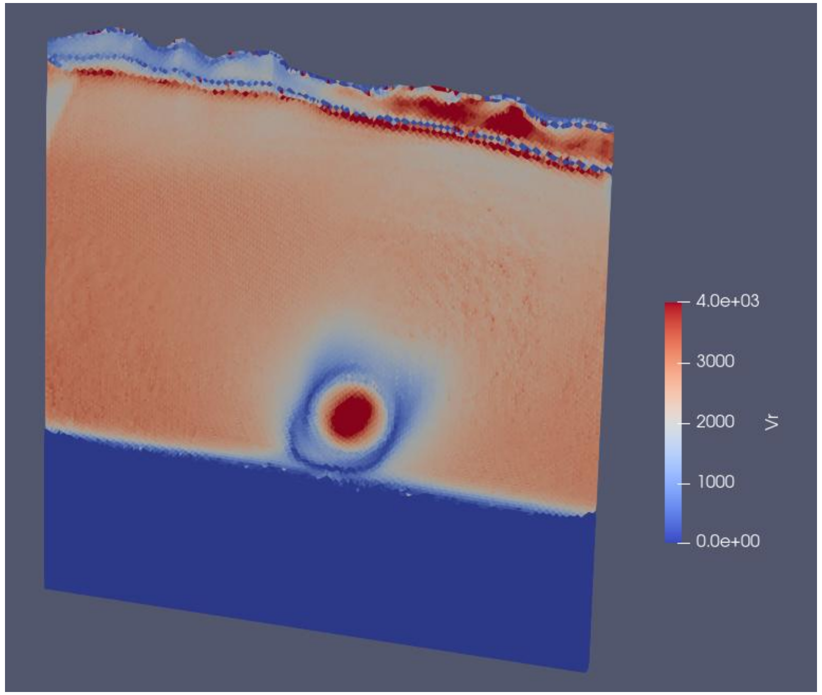


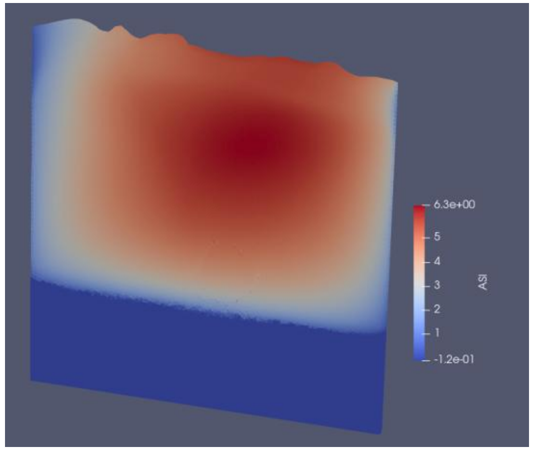
Possible fixes: Adjusting stresses and critical slip distance



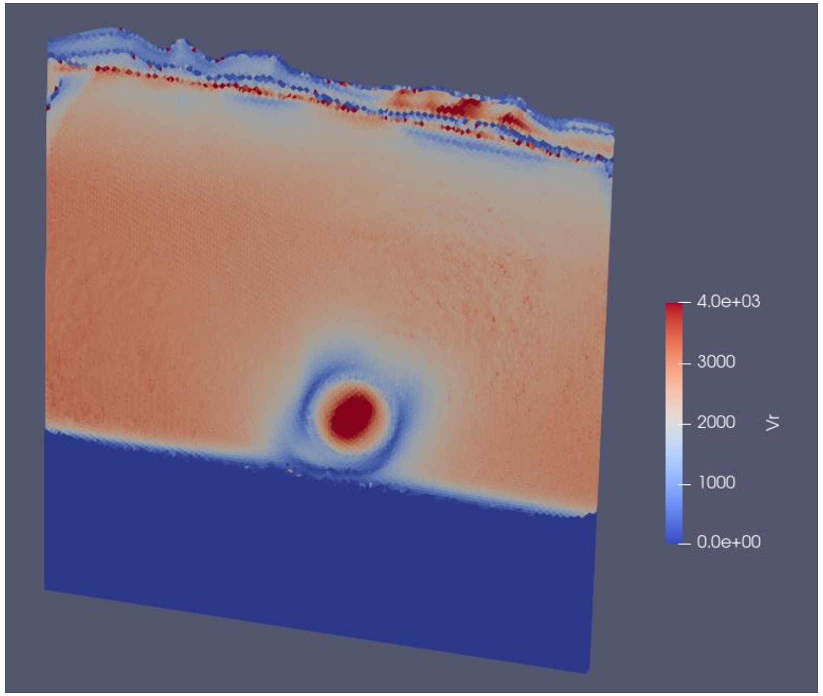


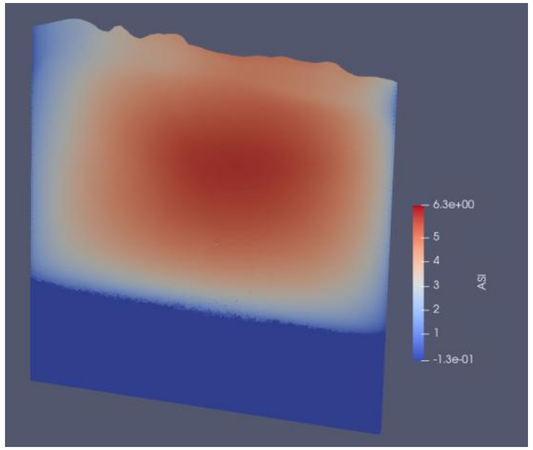
adjusting vertical stress and shallow d_c





adjusting shallow d_c





adjusting shallow R and d_c

Input parameters

- **Initial stress**: Assuming Andersonian stress regime;

  SHmax = 140° N

  Stress shape ratio = 0.5

- Pre-stress level on the fault system R is controlled by the ratio R0 (Ulrich et al. 2019) , the pre-stress level of an optimally-oriented fault. $R \leq R0 \leq 1$.

- **z < -3000 m (deep):**

  R = 0.6;

  static friction µs= 0.6

  dynamic friction µd = 0.2

  critical slip distance Dc = 0.4 m

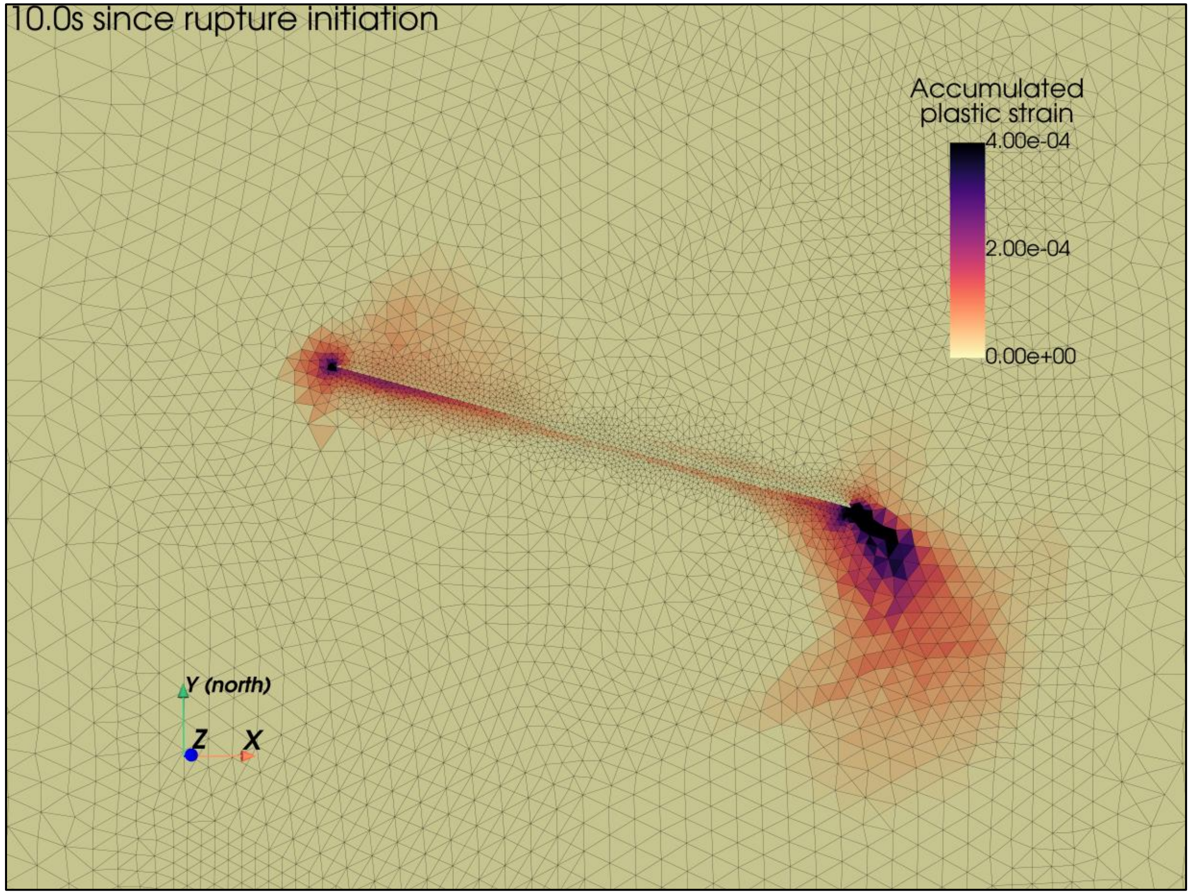
- **z > -3000 m (shallow):**

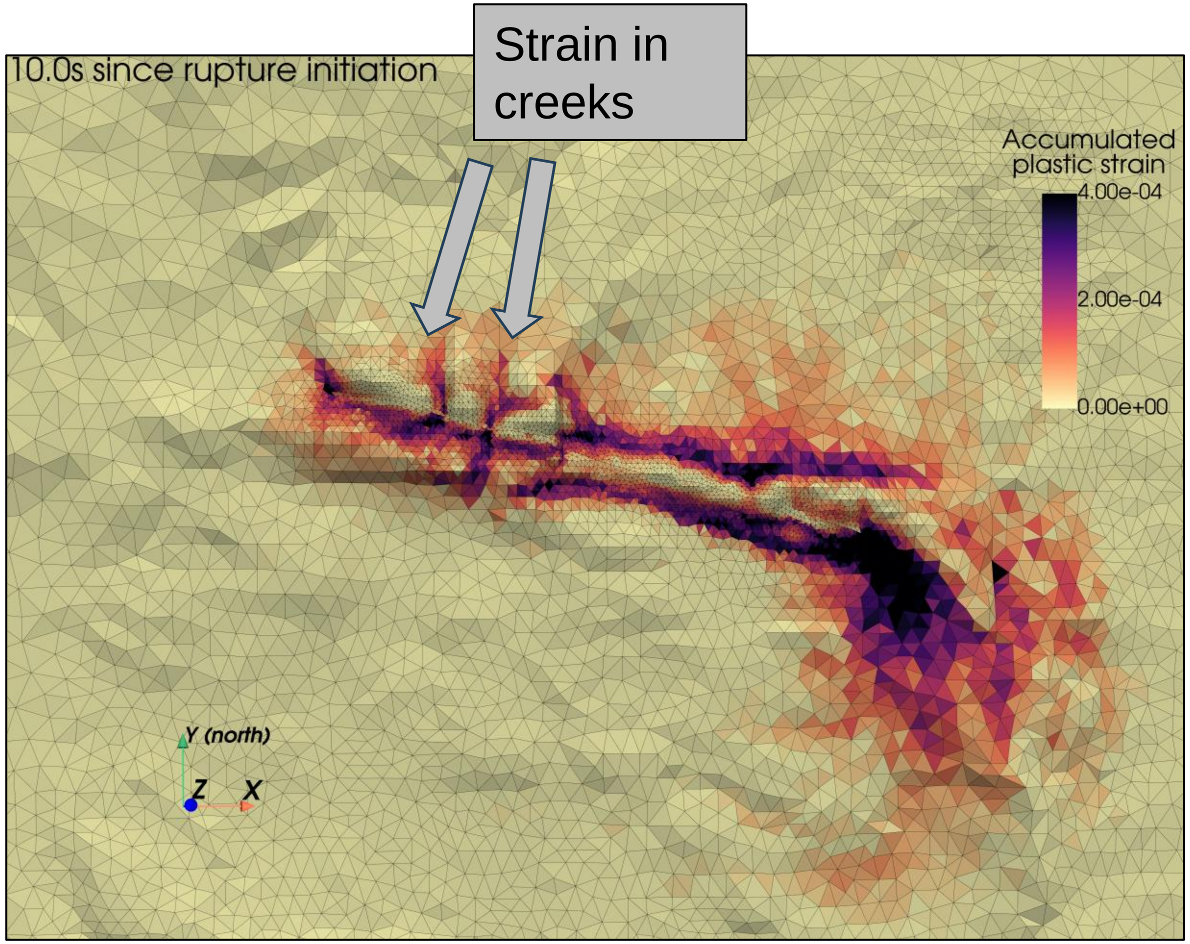
  Dc: linear increase towards surface

  R: linear decrease towards surface

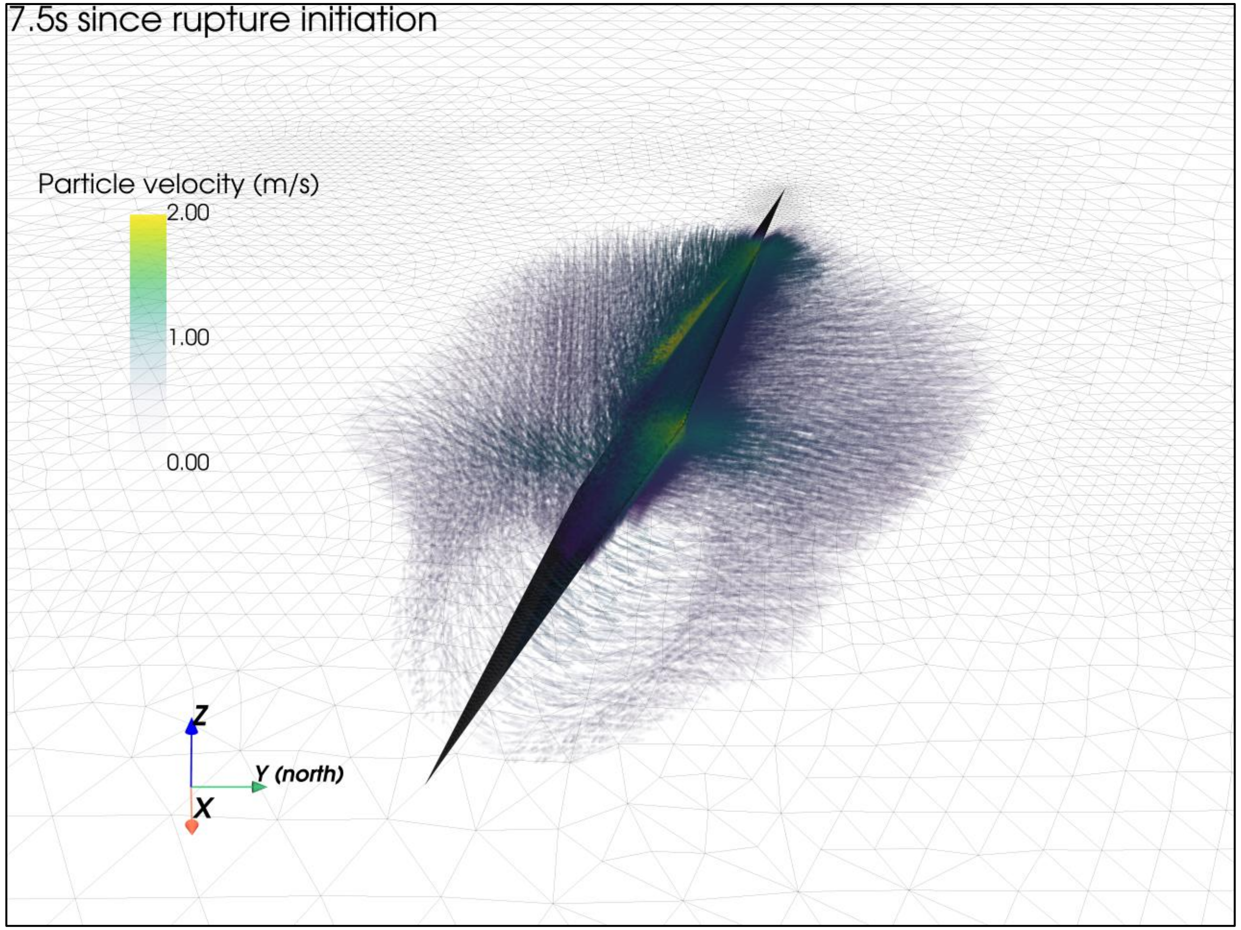
Adjusted R and dc for the shallow part of the fault

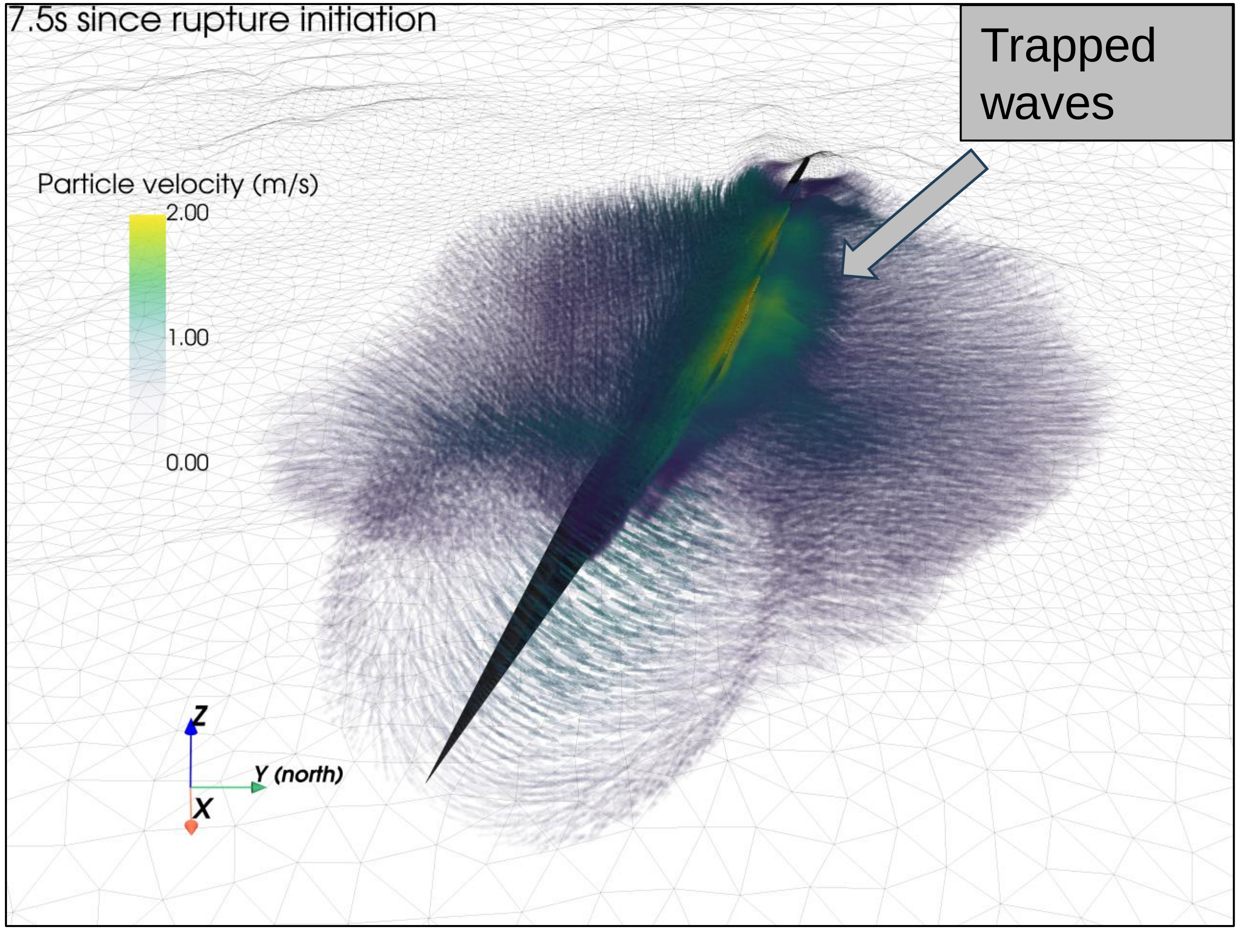
Flat topography vs. Real topography





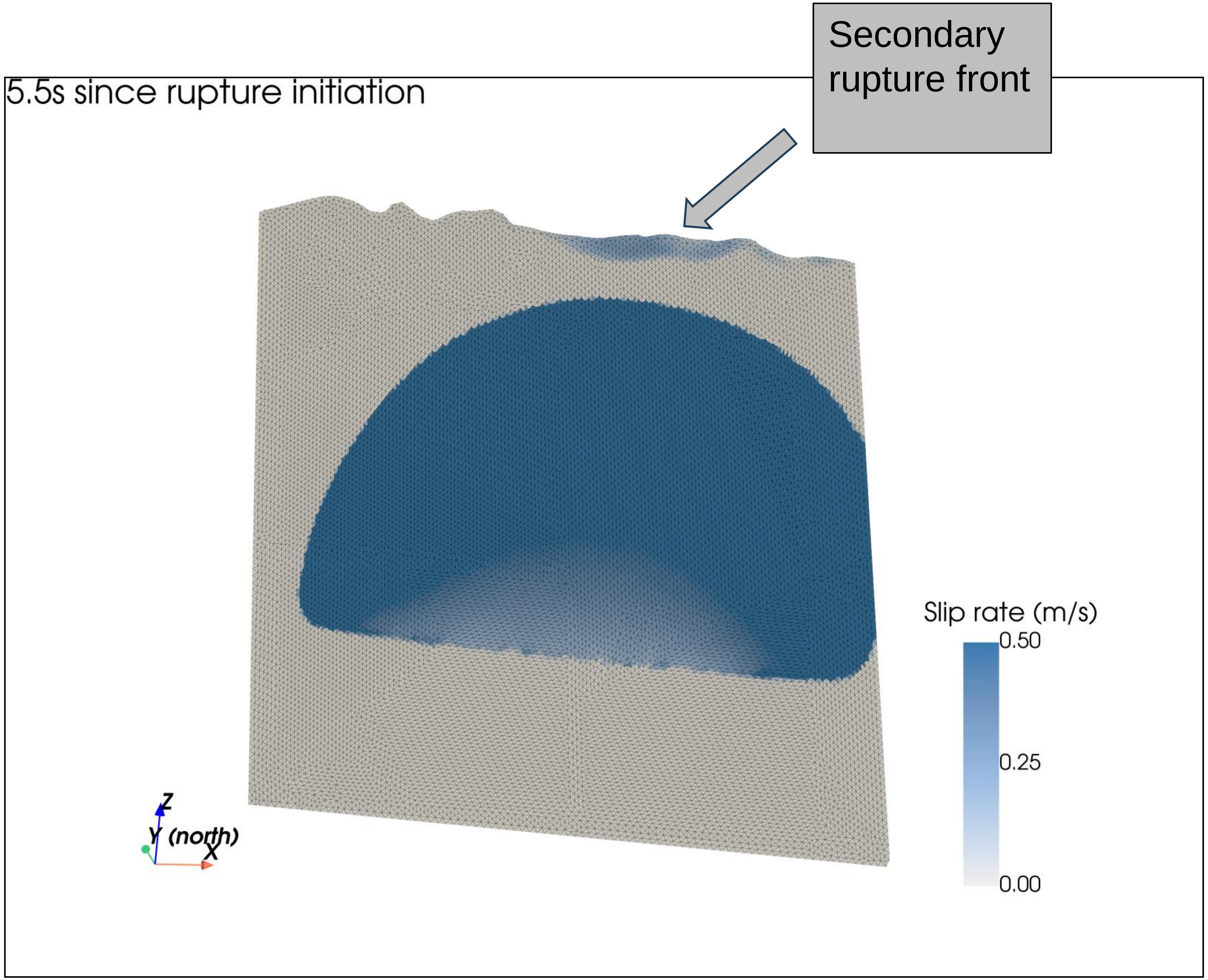
Flat topography vs. Real topography

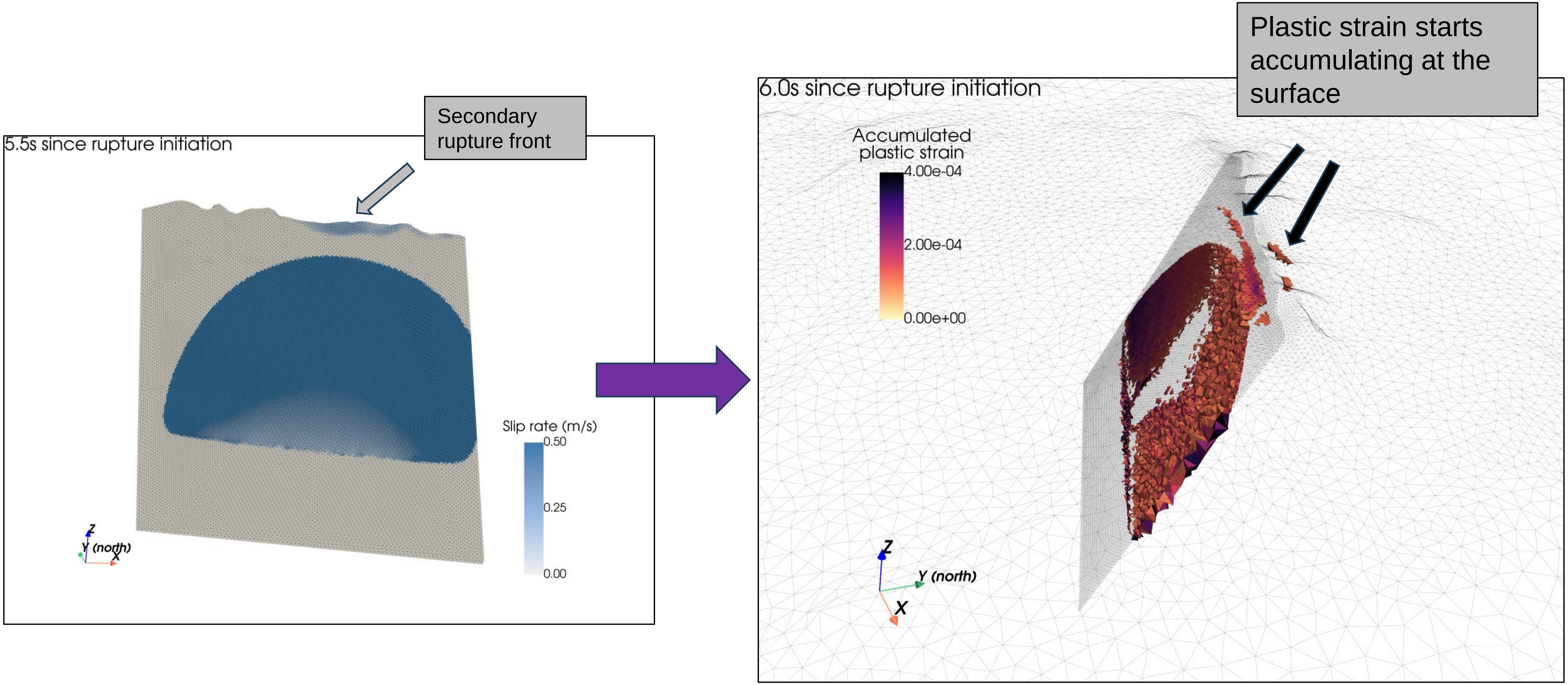




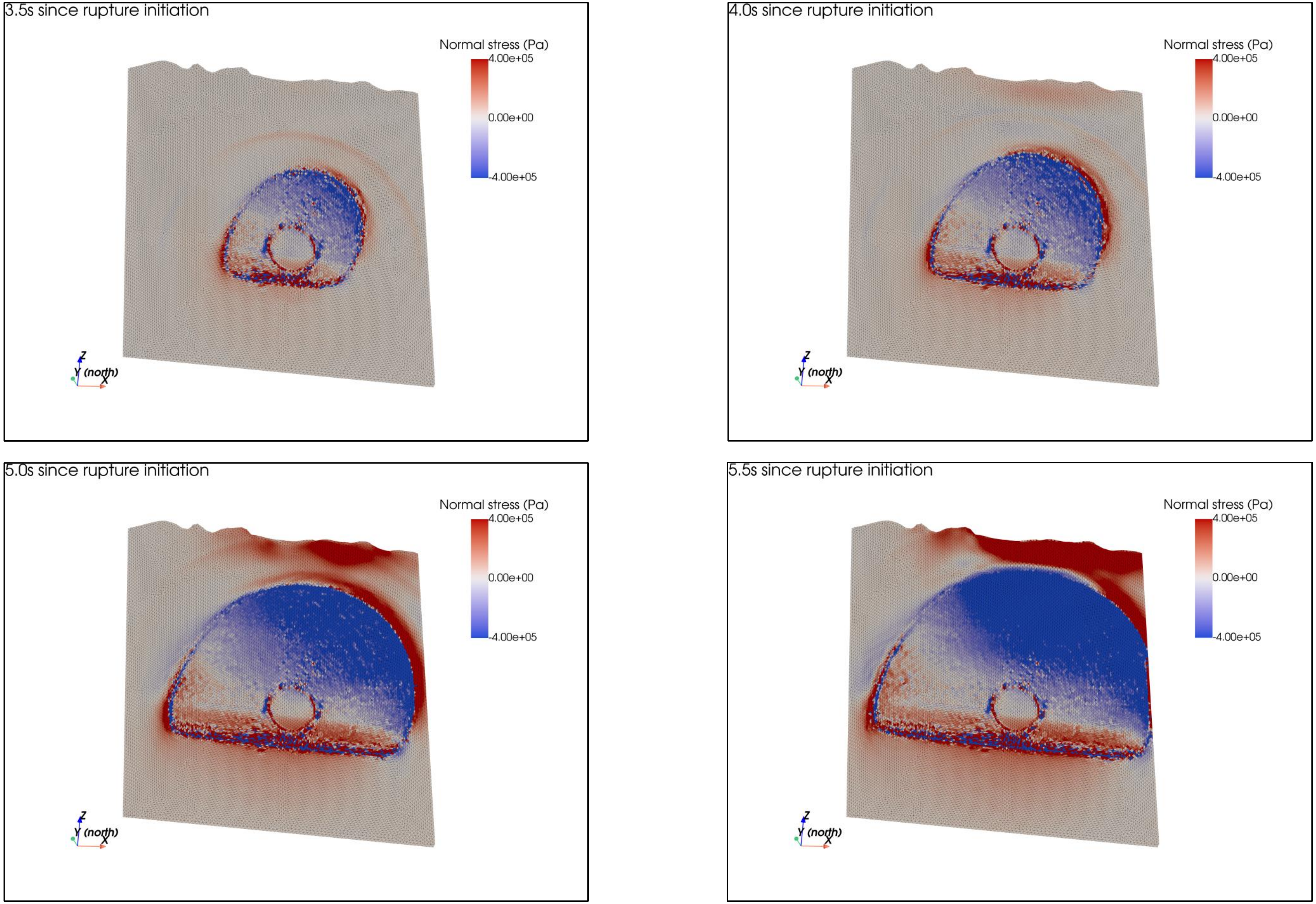
Trapped waves amplifying plastic strain in the footwall

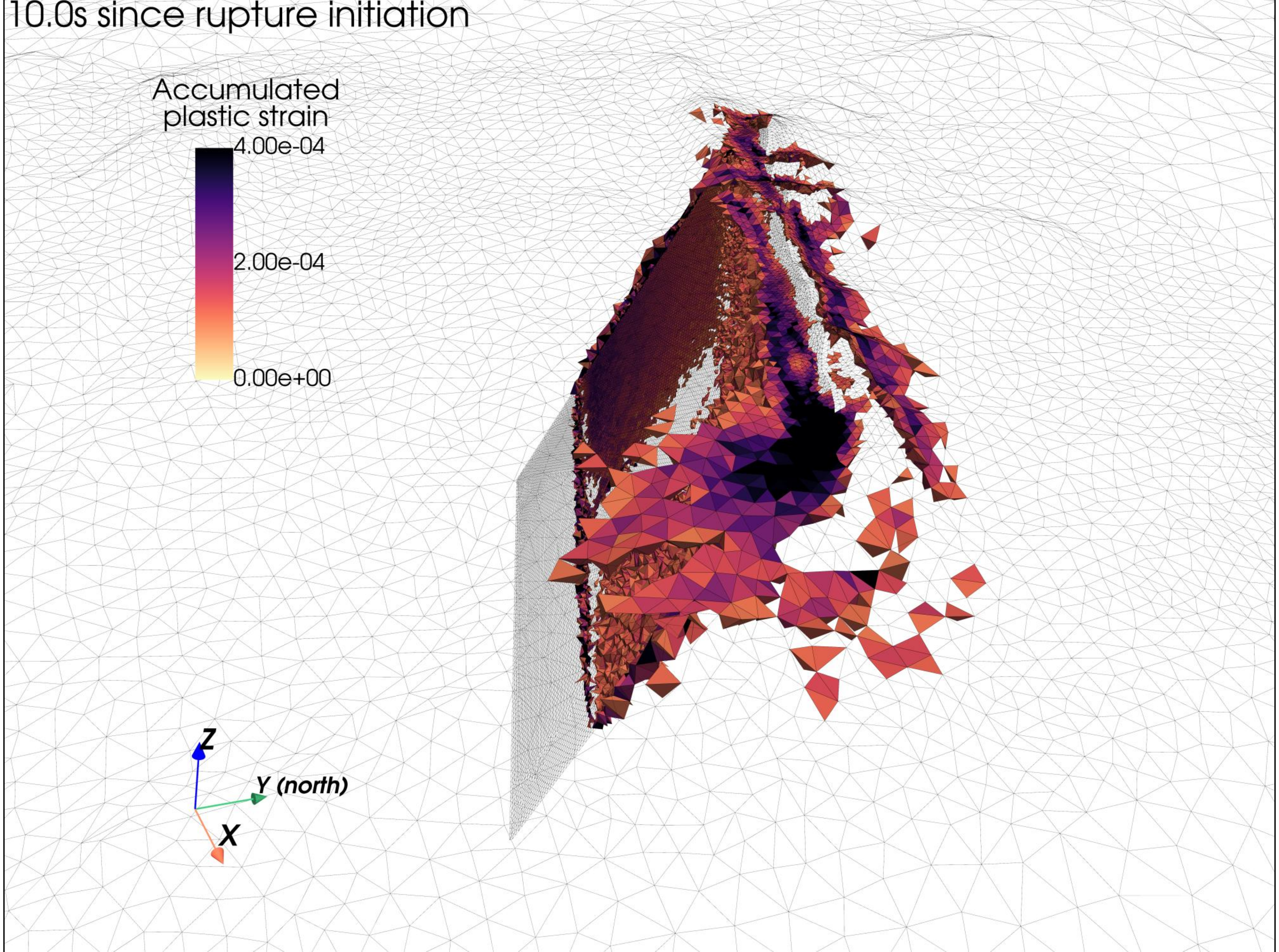
Real topography



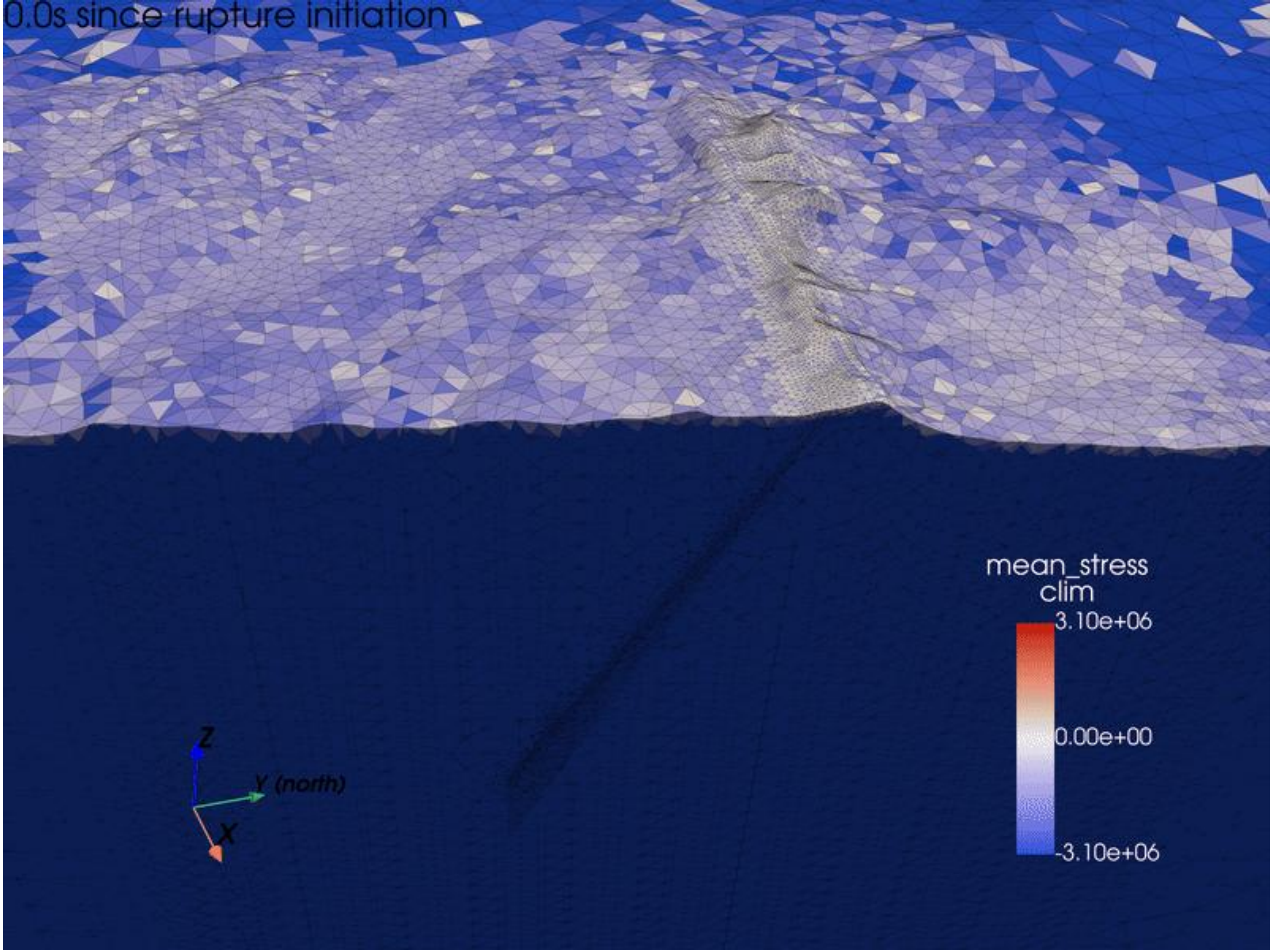


5.5s since rupture initiation
Secondary rupture front
Slip rate (m/s)
0.50
0.25
0.00
Z
Y (north)
X
6.0s since rupture initiation
Plastic strain starts accumulating at the surface
Accumulated plastic strain
4.00e-04
2.00e-04
0.00e+00
Z
Y (north)
X


3.5s since rupture initiation
4.0s since rupture initiation
5.0s since rupture initiation
5.5s since rupture initiation
Normal stress (Pa)
4.00e+05
0.00e+00
-4.00e+05
Z
Y (north)
X


10.0s since rupture initiation
Accumulated plastic strain
4.00e-04
2.00e-04
0.00e+00
Z
Y (north)
X

Shallow plastic strain caused by tensile stresses



Conclusions:

- **Strain** mostly accumulates at the **fault tips** in the **hanging wall**, as well as in **creeks and valleys**
- Simulations including a **flat free surface** yield **simple along-strike strain distributions** at the surface, indicating that topography significantly controls the spatial pattern of accumulated strain.
- Mountains **trap** seismic waves, which **amplify strain in valleys and creeks**
- A **secondary shallow rupture front** can nucleate, **causing shallow strain** in the hanging wall and footwall