3-D Discrete Element Modeling of Continental Fault System Evolution Under Oblique Boundary Conditions

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1. Motivation

Continental earthquakes, their associated consequences, and the inability to reliably predict their occurrence emphasize the need to better understand and characterize the controlling parameters governing fault system evolution. In particular, the influence of tectonic obliquity on fault initiation, growth, and rupture propagation remains poorly constrained.

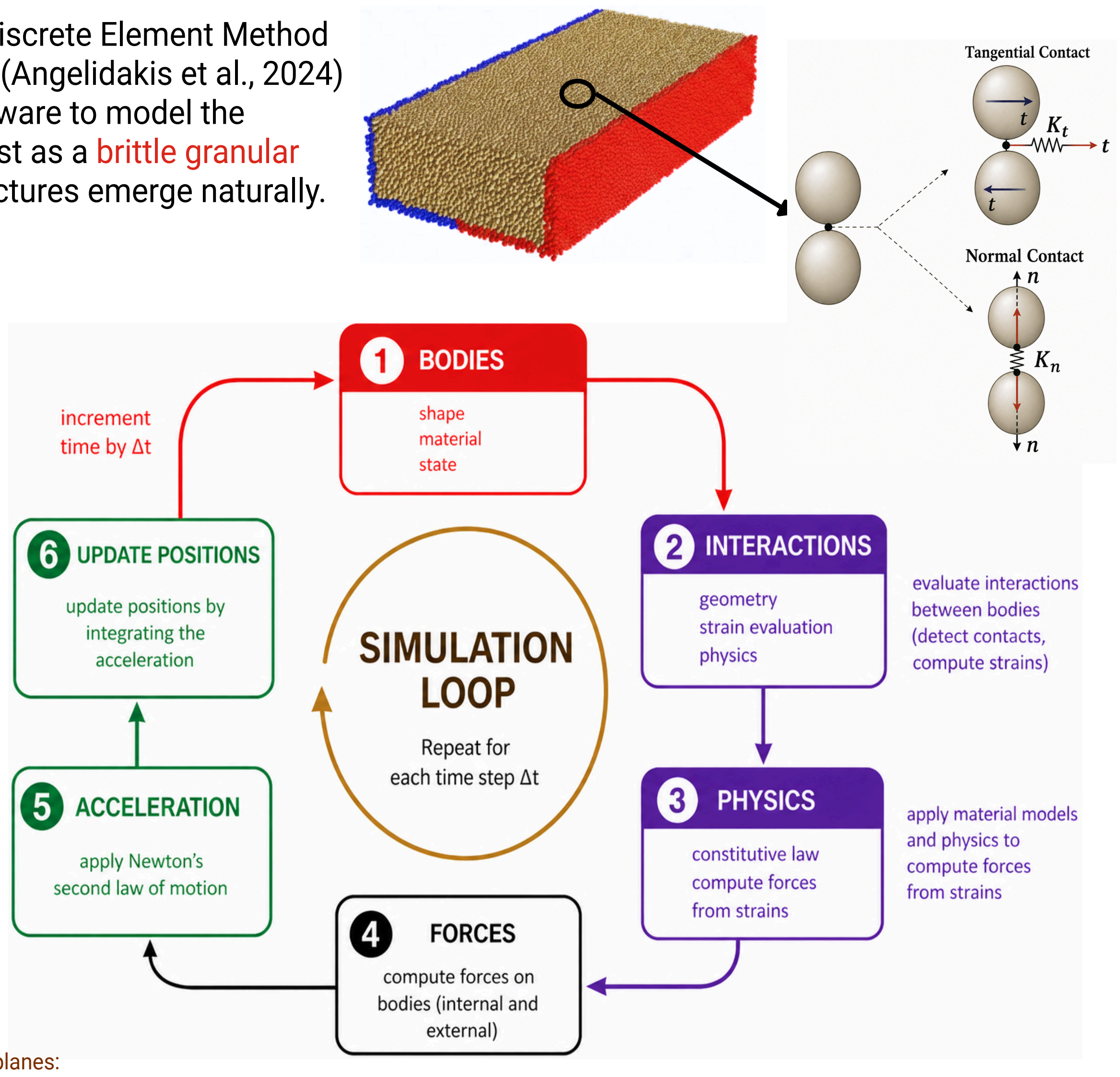
2016 Kaikōura Earthquake, New Zealand © Klinger

Key Questions

- What are the potential relationships between fault geometry and the earthquake cycle, and how does the evolution of one influence the behavior of the other over time?
- How does the transtensional obliquity control the evolution of complex fault geometry to a mature fault?
- How does the transtensional obliquity affect the seismic cycle behavior?

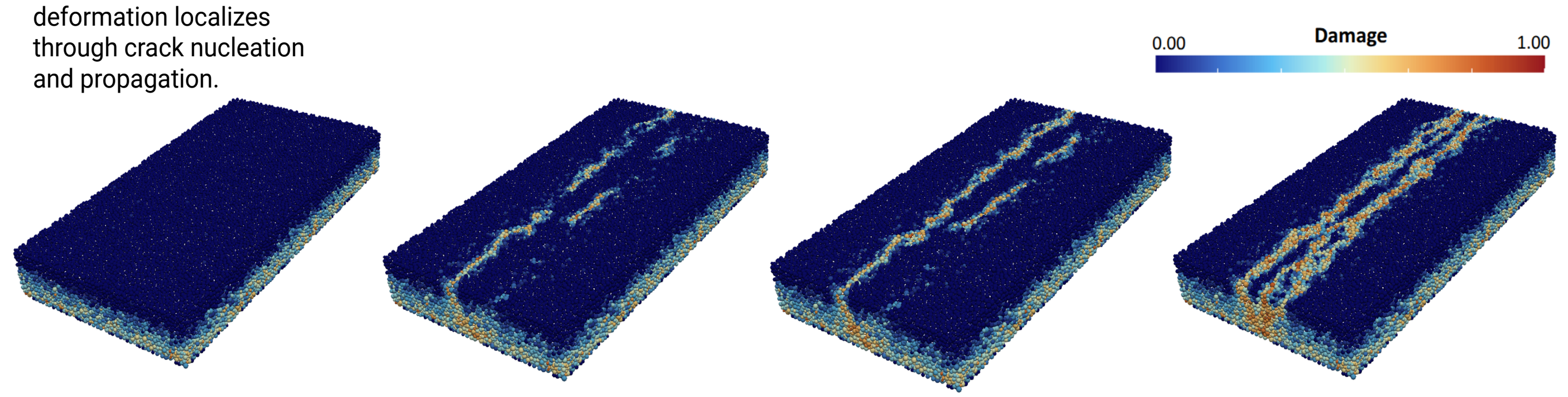
2. Method and Model

We use a 3-D Discrete Element Method (DEM) in **YADE** (Angelidakis et al., 2024) open DEM software to model the continental crust as a brittle granular layer where fractures emerge naturally.



Surface displacement, internal damage, and stress evolution are tracked through time.

No predefined fault planes: deformation localizes through crack nucleation and propagation.



Total offset = 0
Total offset = 650m
Total offset = 900m
Total offset = 2000m

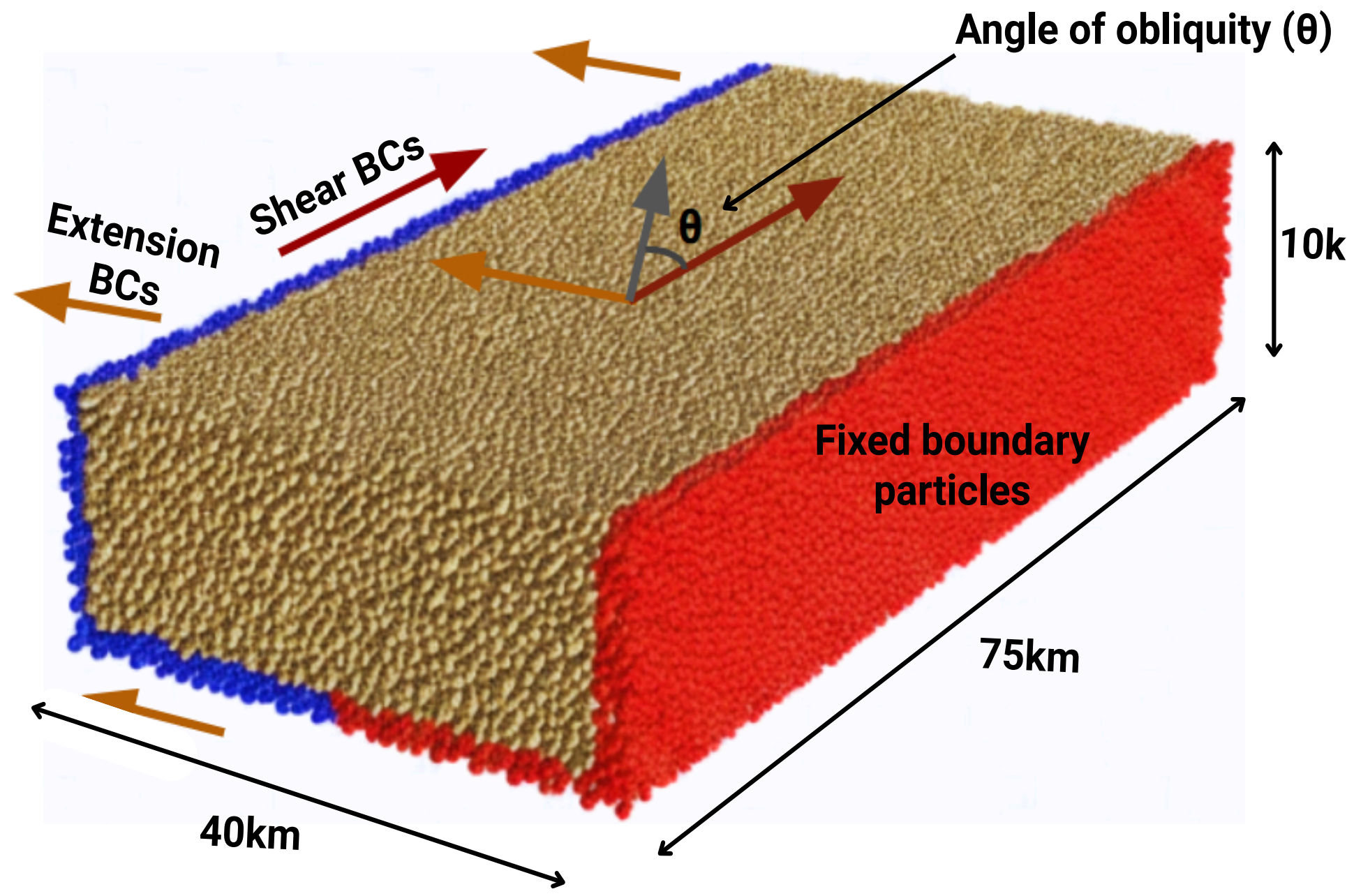
Snapshots illustrating the evolution of damage under varying offsets for pure extension at different stages of the simulation.

3. Emerging fault geometry

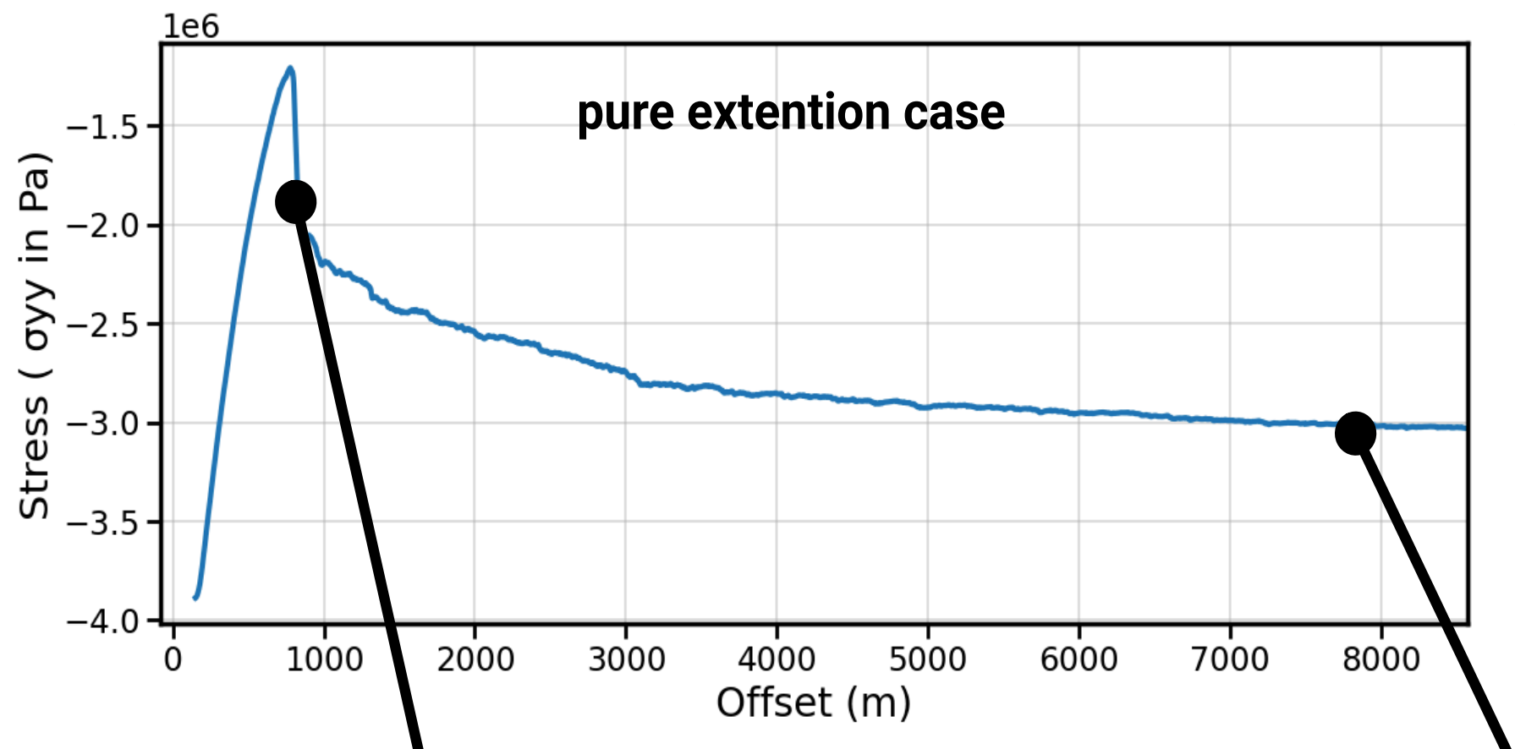
Combined shear and extension are imposed at model boundaries to simulate transtensional tectonic regimes.

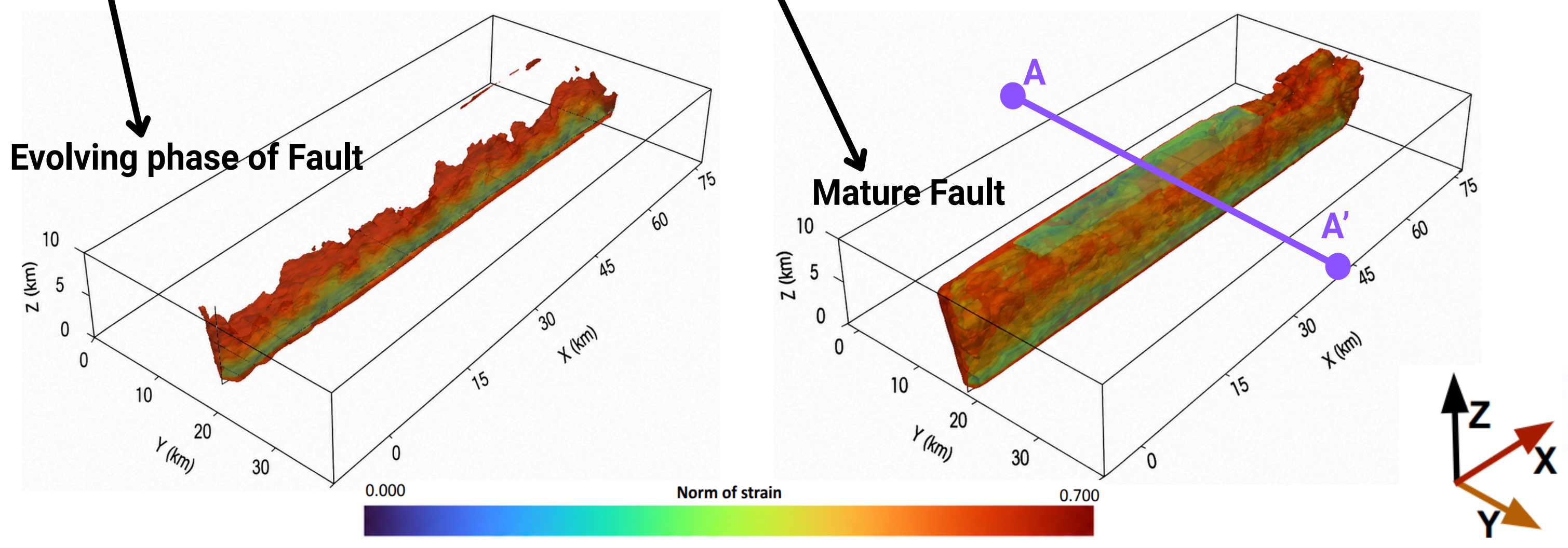
Five obliquity cases are investigated: 0°, 22.5°, 45°, 67.5°, and 90°.

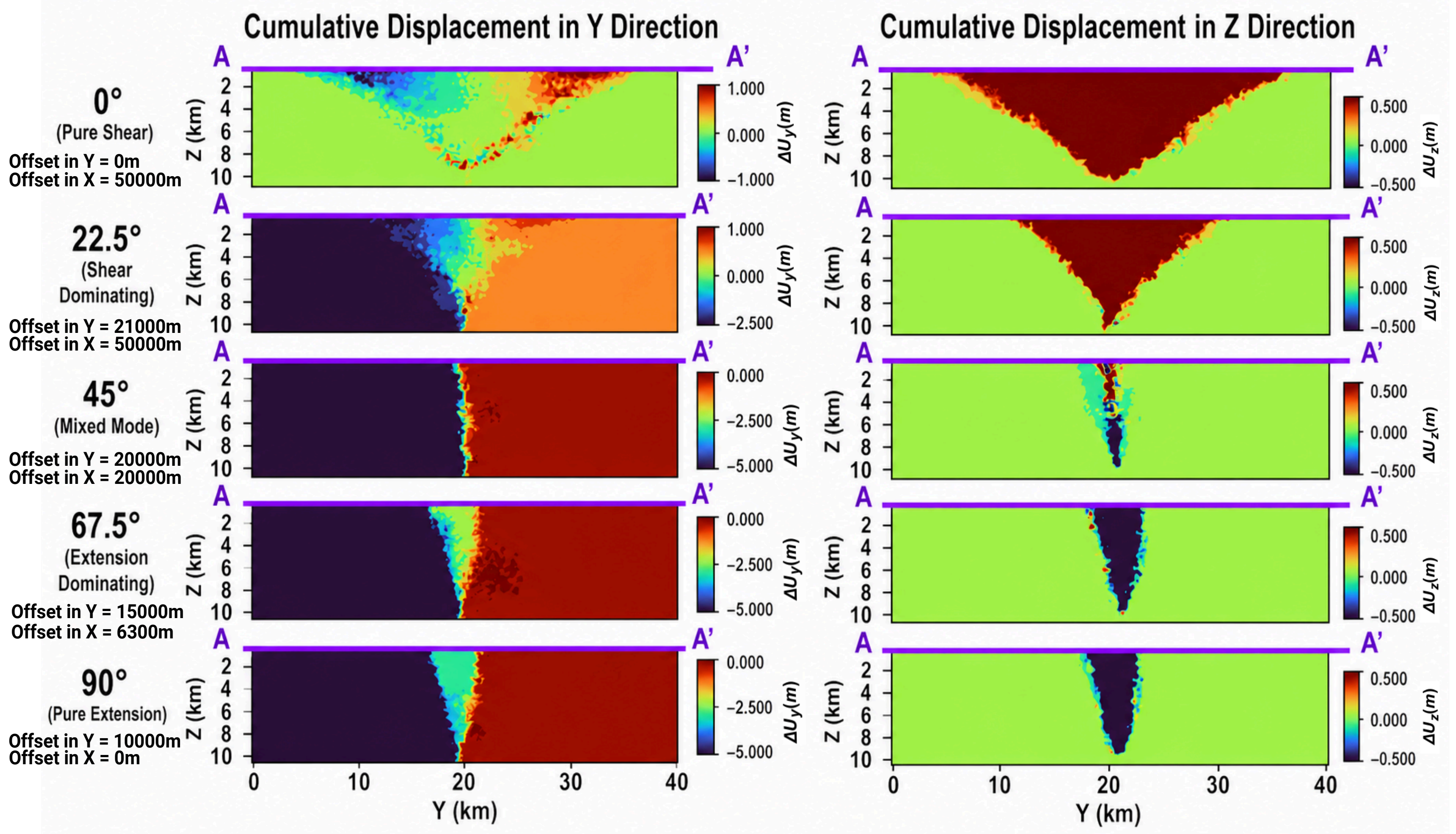
0° corresponds to pure shear / strike-slip loading, while 90° corresponds to pure extension/tension.



A combined extension and shear displacement rate is imposed on one half of the model boundary particles (blue particles), while the opposite half of the boundary particles remains fixed (red particles).

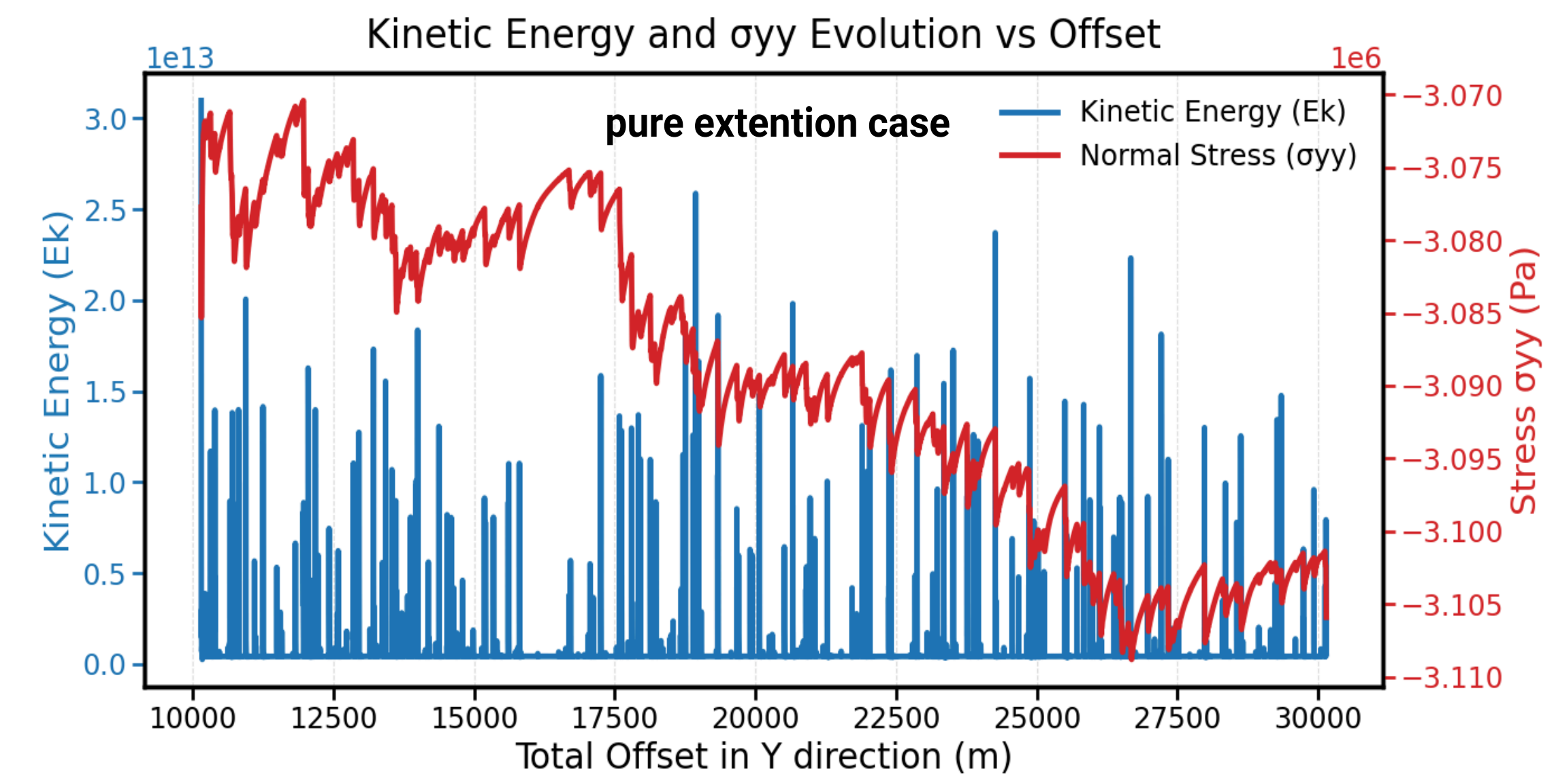


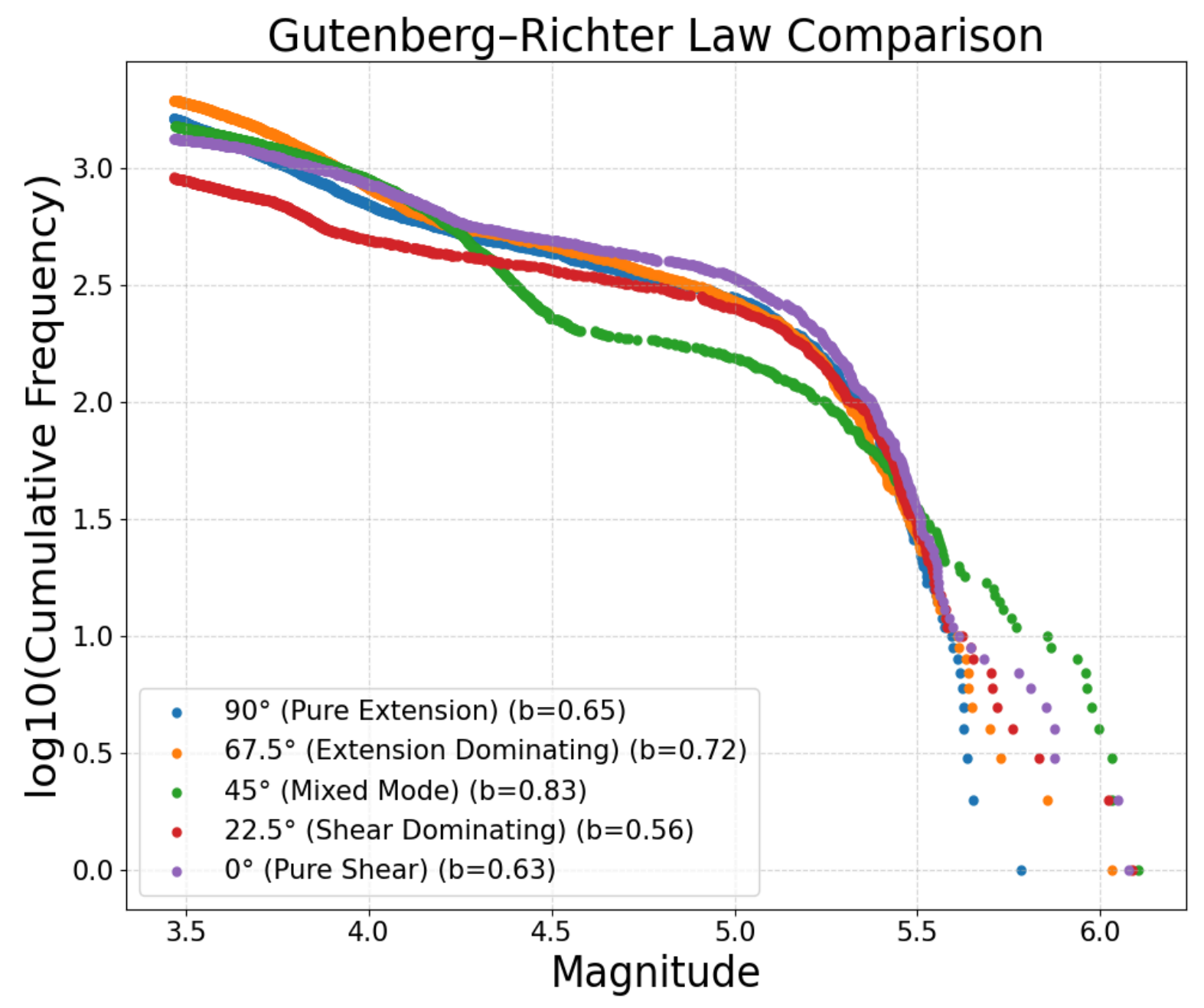




This figure presents cumulative displacement in the Y-direction (left column) and Z-direction (right column) at the mature stage of deformation. Each row corresponds to increasing obliquity angles (0°, 22.5°, 45°, 67.5°, 90°), illustrating the transition from pure shear to pure extension.
Purple lines mark the reference section A–A', representing a cross-section through the mid Z–Y plane.

4. Earthquake cycles





Simulations produce cyclic stick-slip behavior analogous to earthquake cycles, as shown in the above figure; each earthquake corresponds to a stress drop that correlates to the release of kinetic energy.

$$M = \frac{2}{3}\log_{10}(\Delta Ek) - 3.2$$

(Kanamori, 1977; Hanks and Kanamori, 1979)

The figure compares Gutenberg−Richter frequency−magnitude distributions for different obliquity angles under transtensional boundary conditions, along with the corresponding calculated b-values for each deformation regime.

5. Conclusion

- Our 3D DEM model can reproduce both the long- and short-term evolution of a fault system under different transtensional modes.
- Stick-slip behaviors are simulated for all obliquity angles and can be studied to characterize the earthquake cycle.
- Obliquity controls both the fault system geometry and the rupture characteristics of the earthquake cycle.

Future Work

- Extend the 3D DEM framework to transpressional and other tectonic regimes to generalize the relationship between boundary conditions, fault evolution, and earthquake-cycle behavior.
- Investigate the coupled evolution of fault geometry, topography, and seismic cycle characteristics under varying obliquity conditions.

6. References

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