

Importance of mixed flux in dynamic rupture modeling

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A Mixed-Flux-Based Nodal Discontinuous Galerkin Method for 3D Dynamic Rupture Modeling

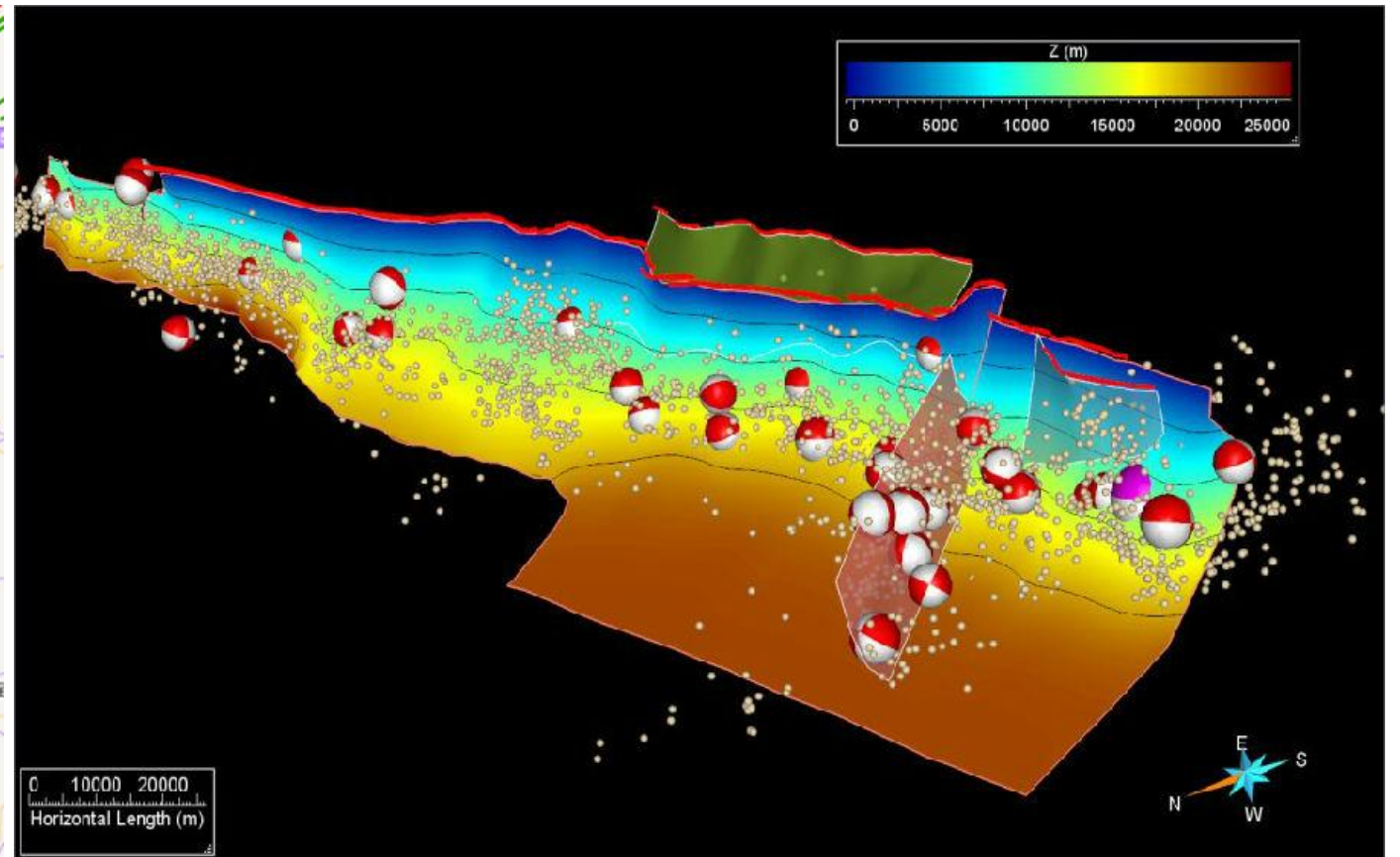
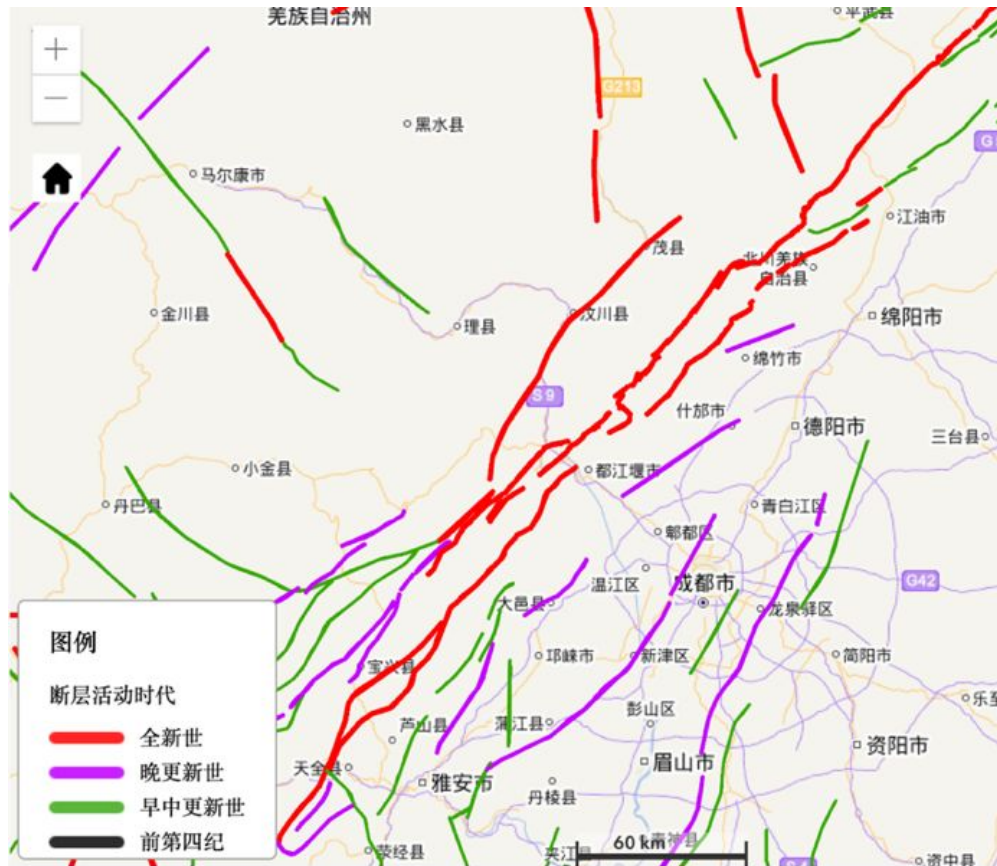
Wenqiang Zhang , Yajing Liu, Xiaofei Chen

<https://doi.org/10.1029/2022JB025817>

<https://github.com/wqseis/drdg3d>

<https://github.com/wenqiang-geophys/drdg3dv2>

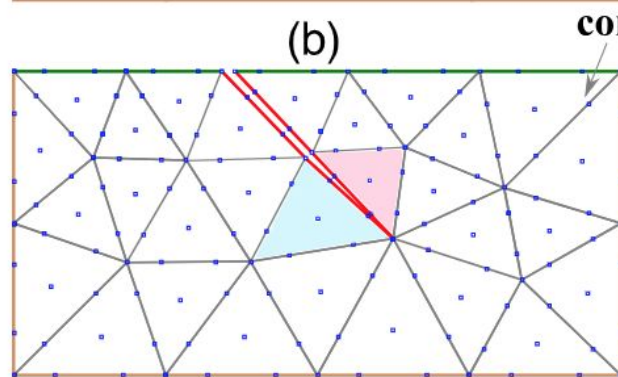
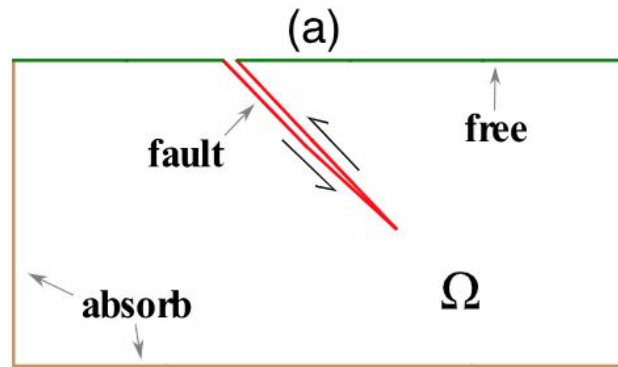
Challenges of earthquake modeling on complex faults



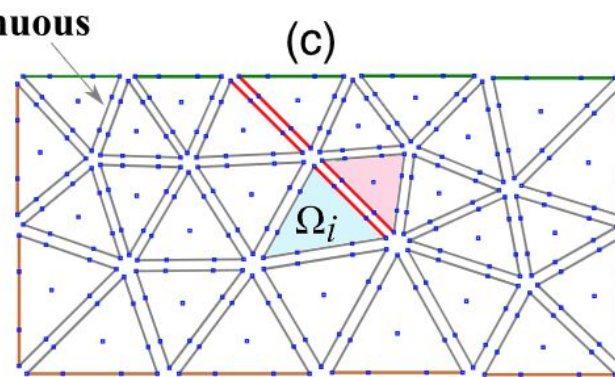
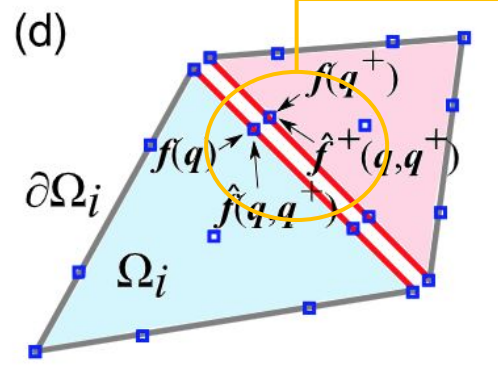
<https://activefault-datacenter.cn/>

Longmenshan 3D fault model of the 2008 Wenchuan earthquake (Institute of Geology, China Earthquake Administration)

Key point: dealing with fault intersections



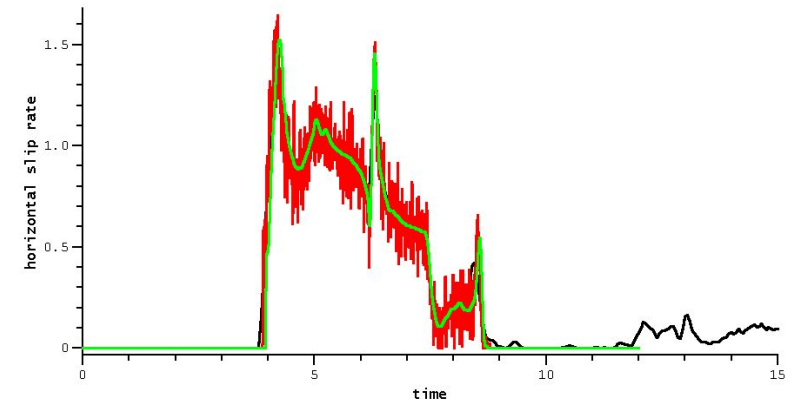
Continuous Galerkin (CG)



Discontinuous Galerkin (DG)

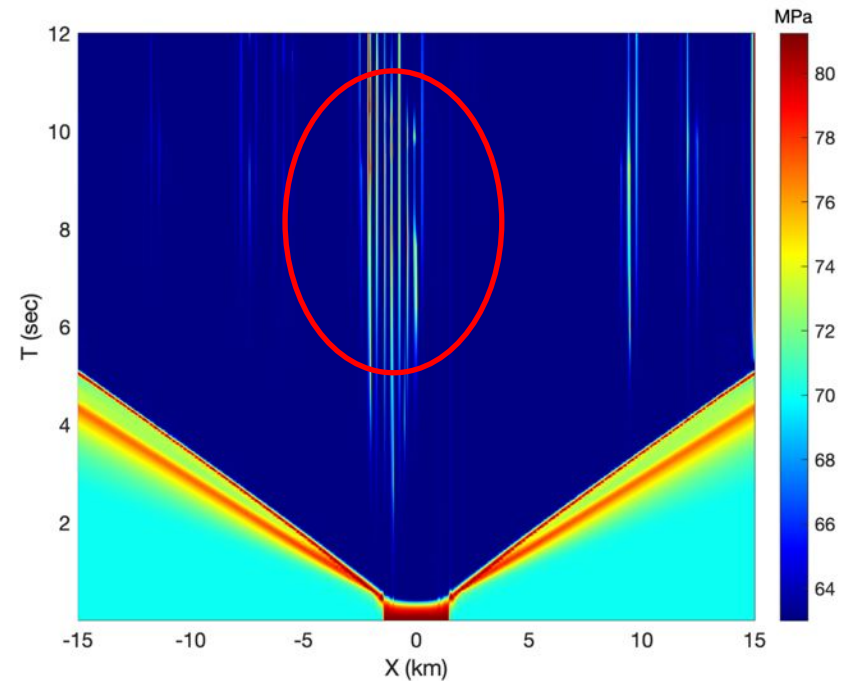
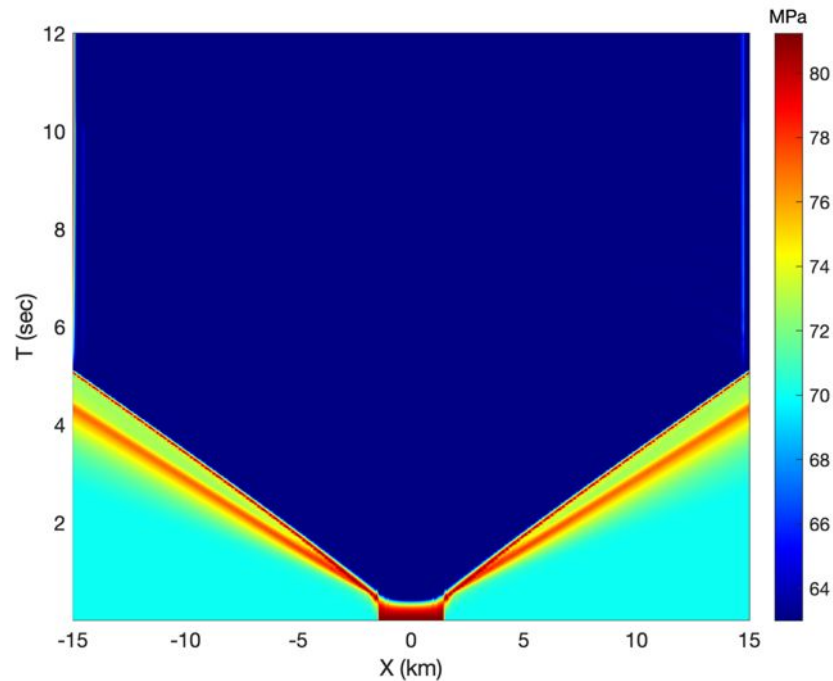
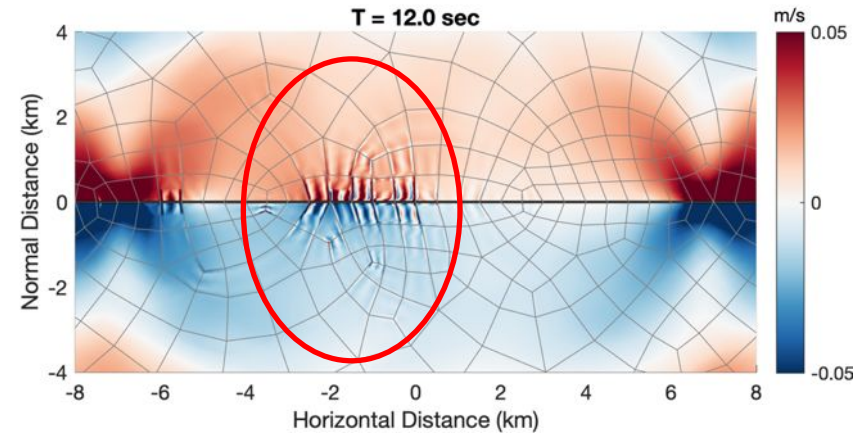
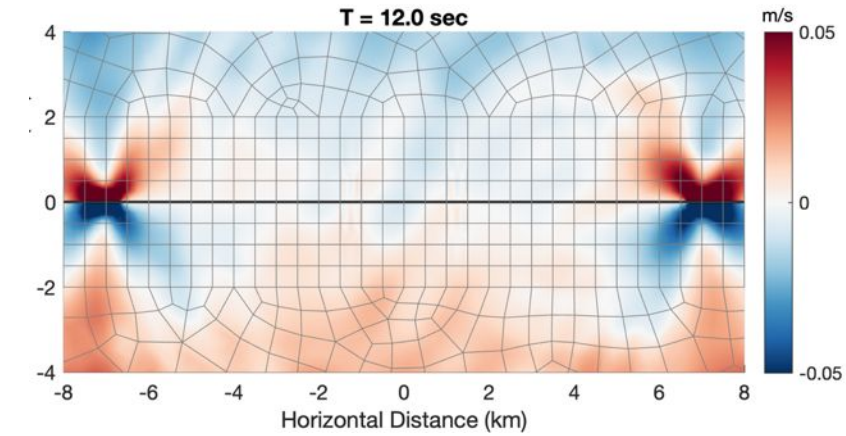
Upwind flux: for BCs

- ✓ Intrinsic dissipation
- ✓ Flexible on fault interactions
- ✓ Provable stable

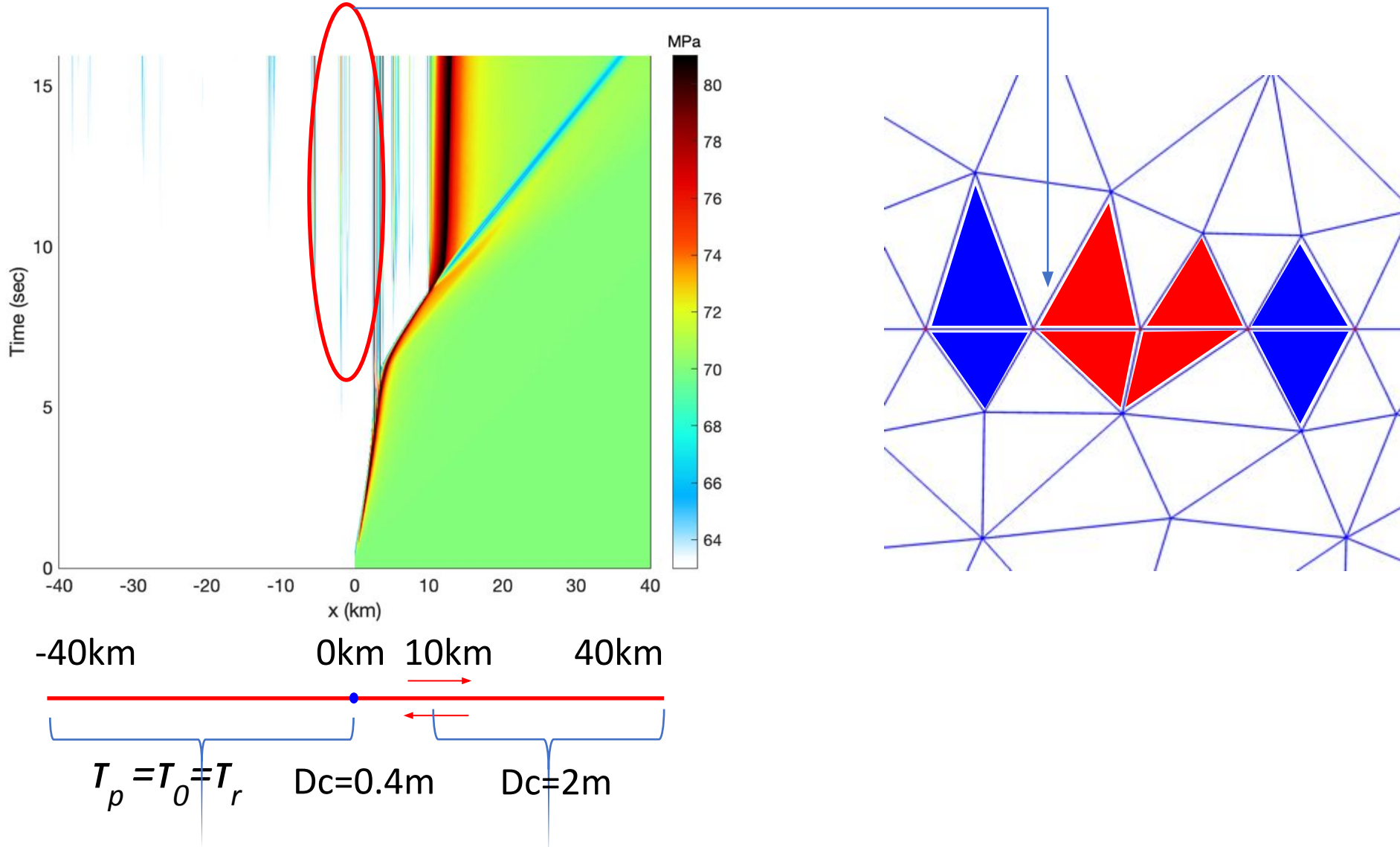


— aagaard (Brad Aagaard - Finite Element - EqSim)
 — kaneko (Yoshihiro Kaneko - Spectral Element - SPECFEM3D)
 — pelties (Christian Pelties - Discontinuous Galerkin)

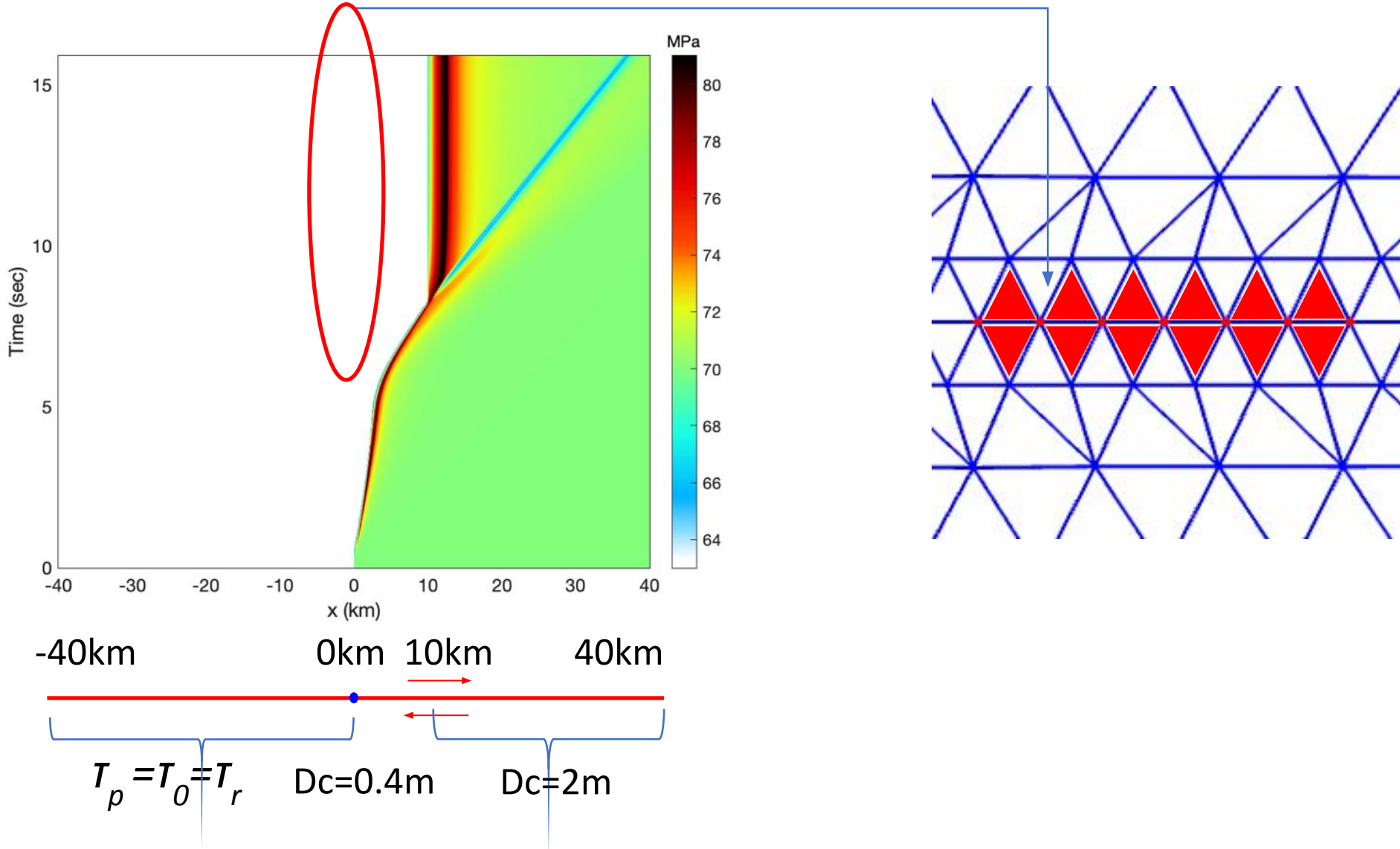
But... Mesh dependency (2D Quadrilateral)



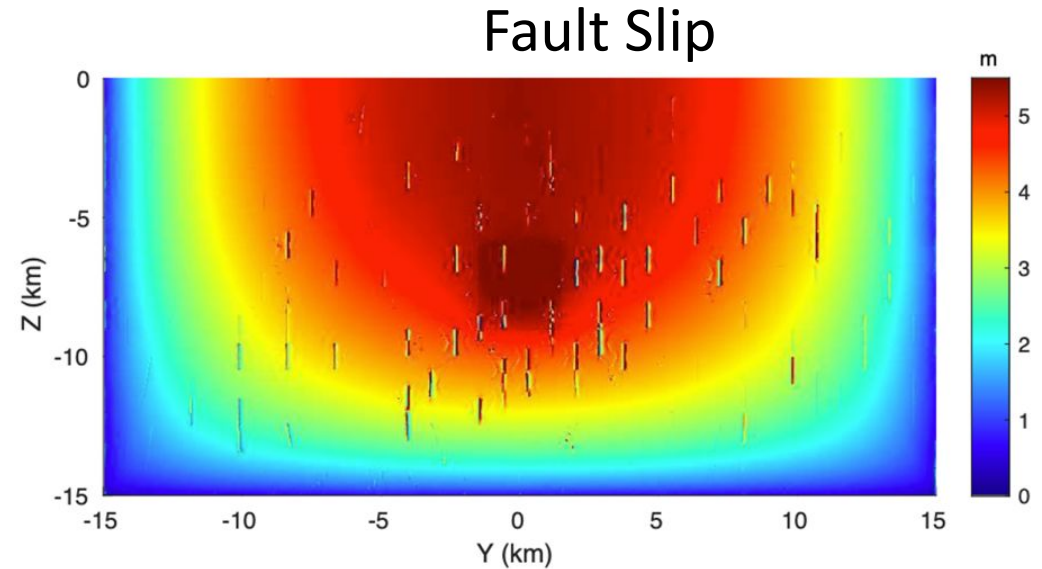
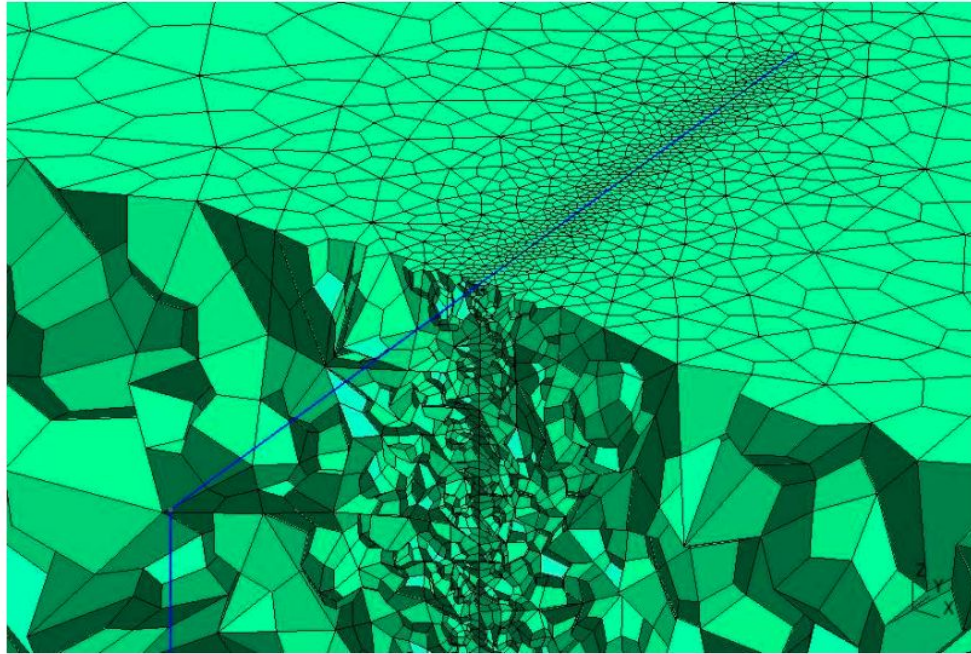
But... Mesh dependency (2D Triangular)



But... Mesh dependency (2D Triangular)

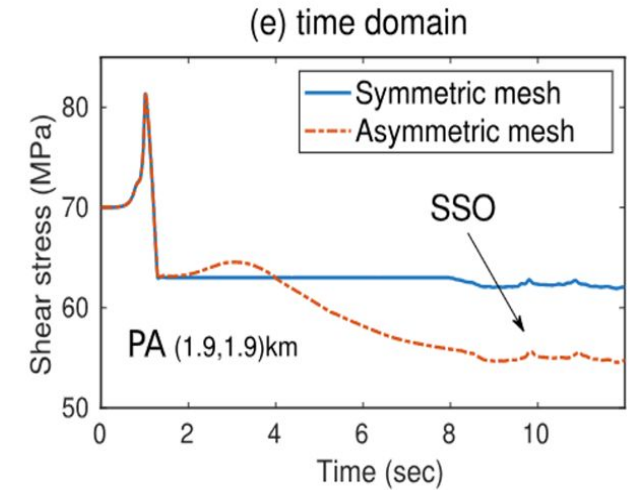
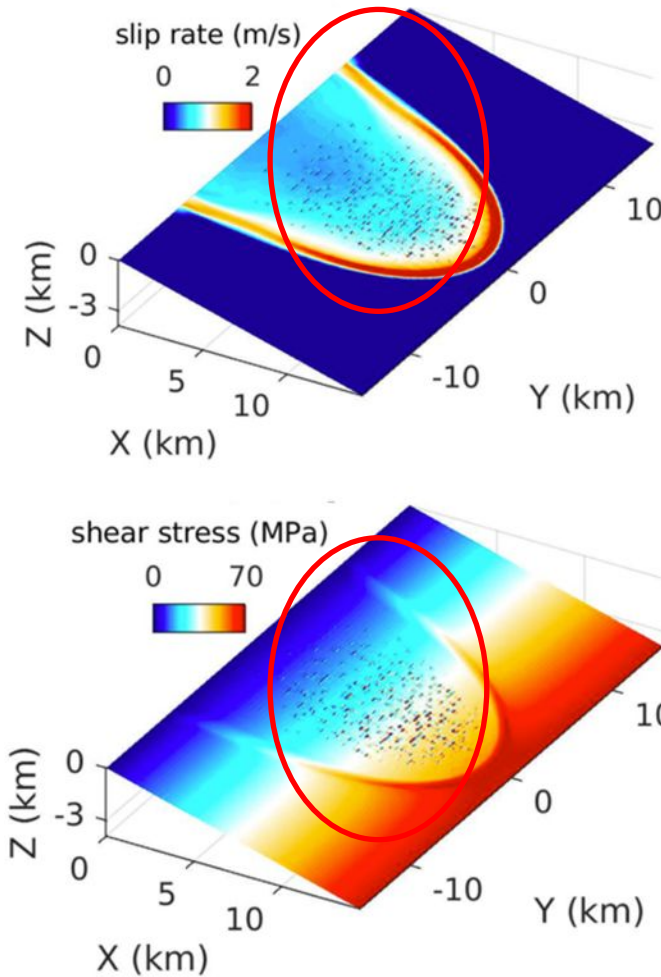
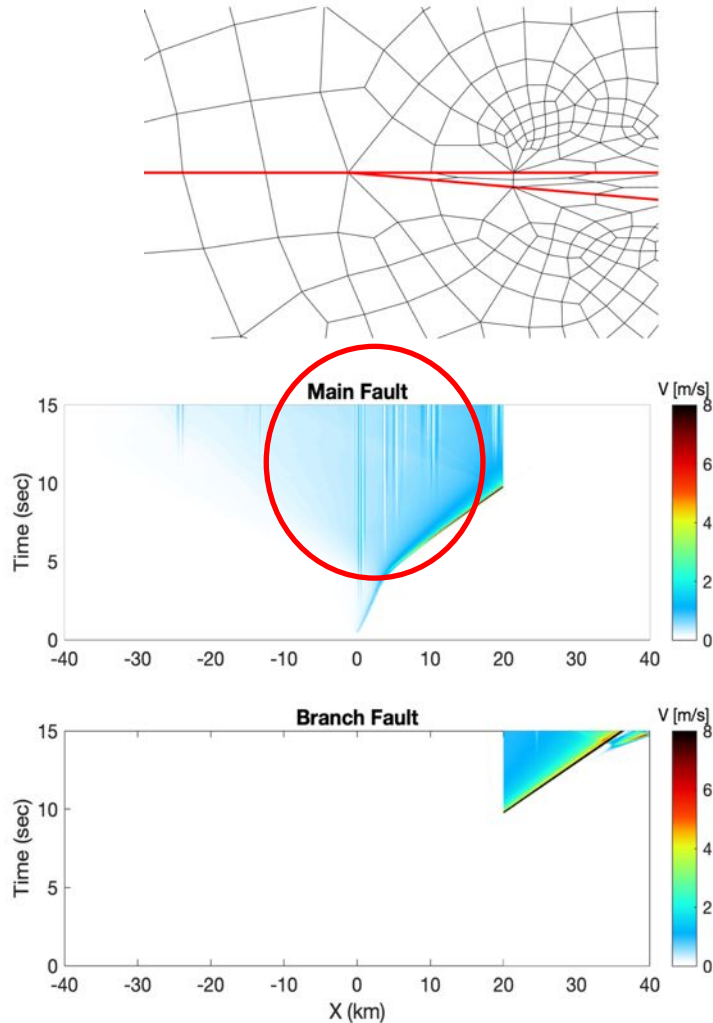


But... Mesh dependency (3D Hexahedral)



For 3D cases, generating a high-quality mesh can be very challenging, depending on the complexity of the fault geometry.

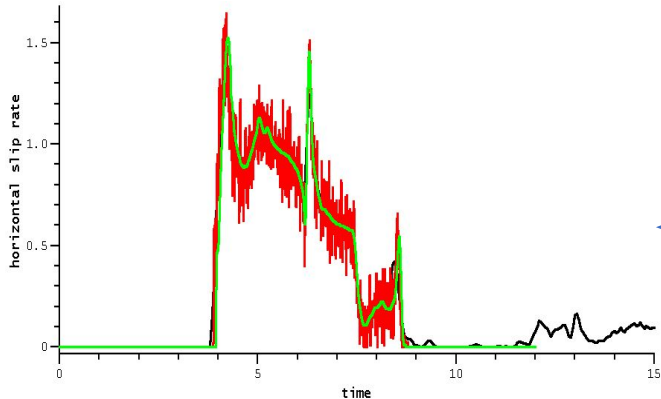
Generating high-quality meshes can be very challenging!



Spatial spike oscillations (SSO) in time domain cause by **upwind flux**

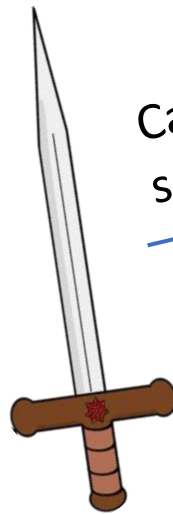
Summary

- Upwind-flux method can be problematic, depending on the mesh quality, but regardless of the mesh type (Tri, Quad, Tet, Hexa)
- Generating high-quality mesh is sometimes impossible → Improved methods are needed!
- Upwind flux is a “**double-edged sword**”



— aagaard (Brad Aagaard - Finite Element - EqSim)
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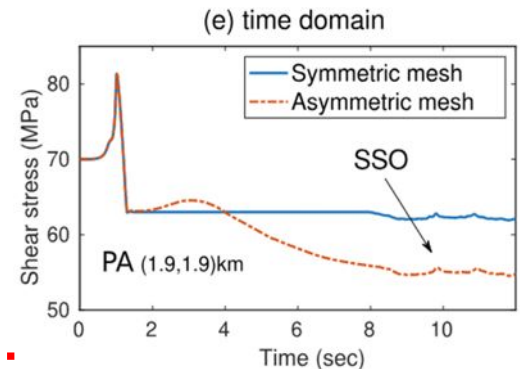
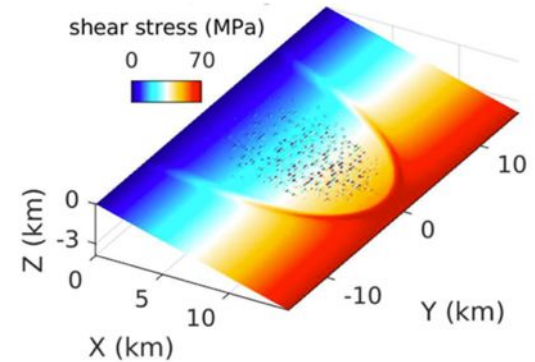
Suppress high frequency oscillations



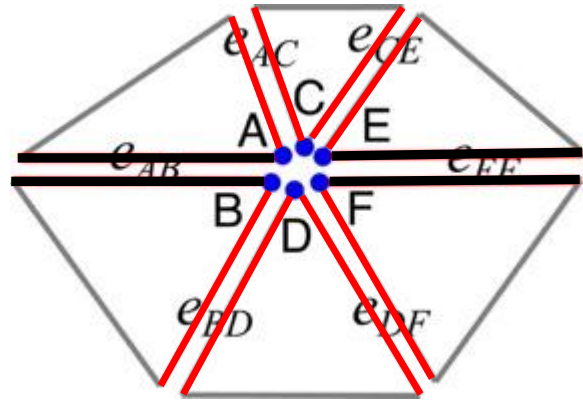
Cause spatial spike oscillations



We want upwind flux, but not too much ...

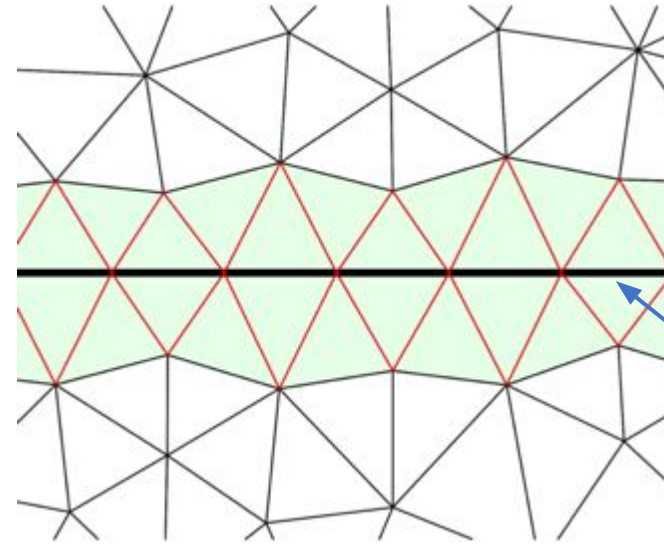


Introduce the “mixed flux”



Edge e_{CE} and e_{DF} have different dissipations

Remove
dissipations
on red edges



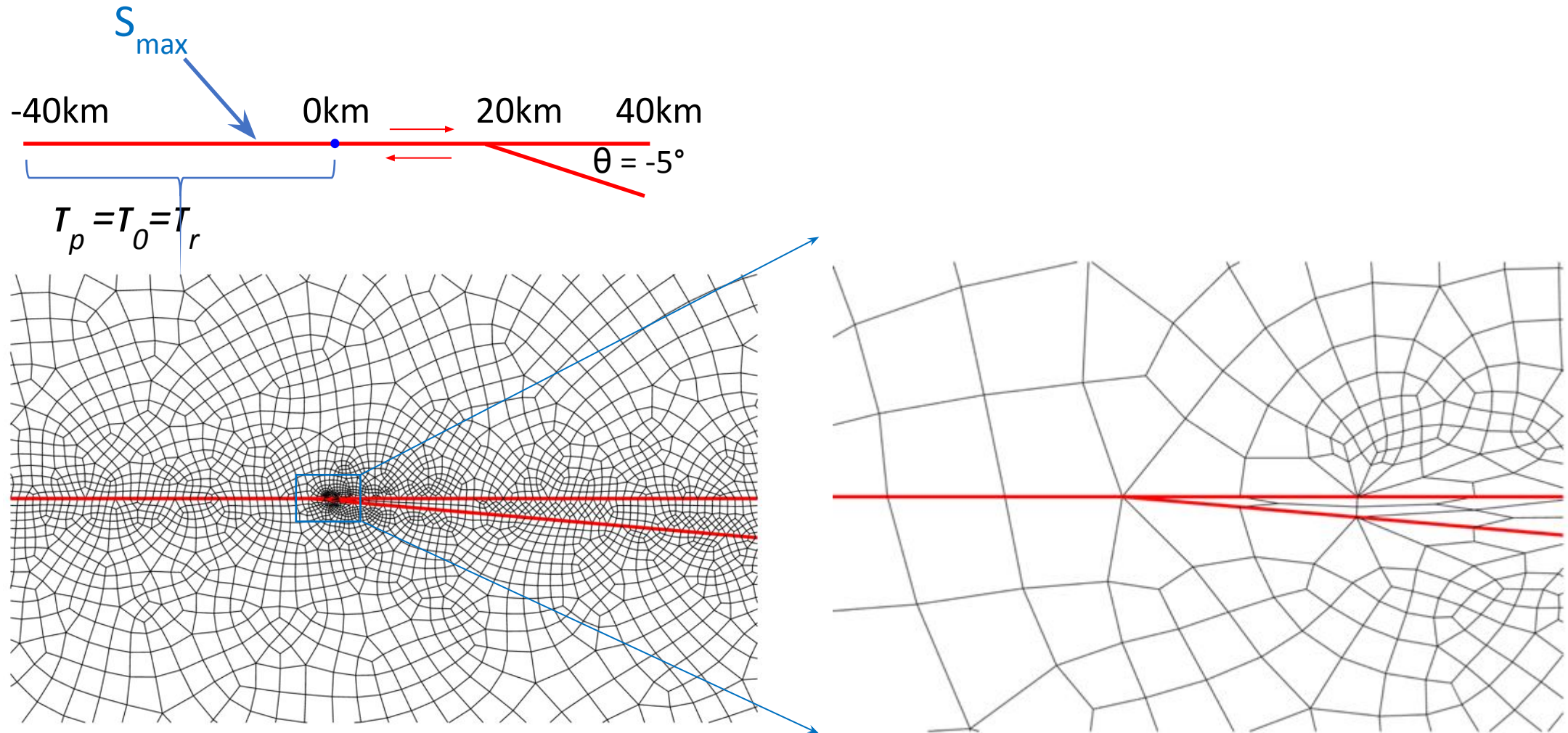
Mixed flux
— upwind flux
— central flux
Fault surface

Old scheme: **upwind** flux for all boundaries

New scheme: Mixed **upwind/central** flux

(**central** flux is only used on continuous boundaries attached to faults)

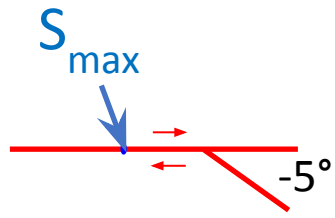
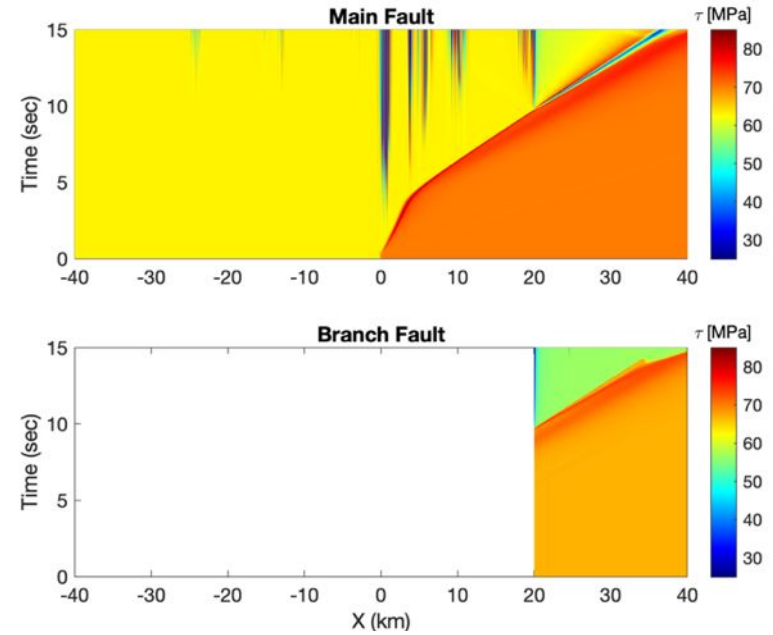
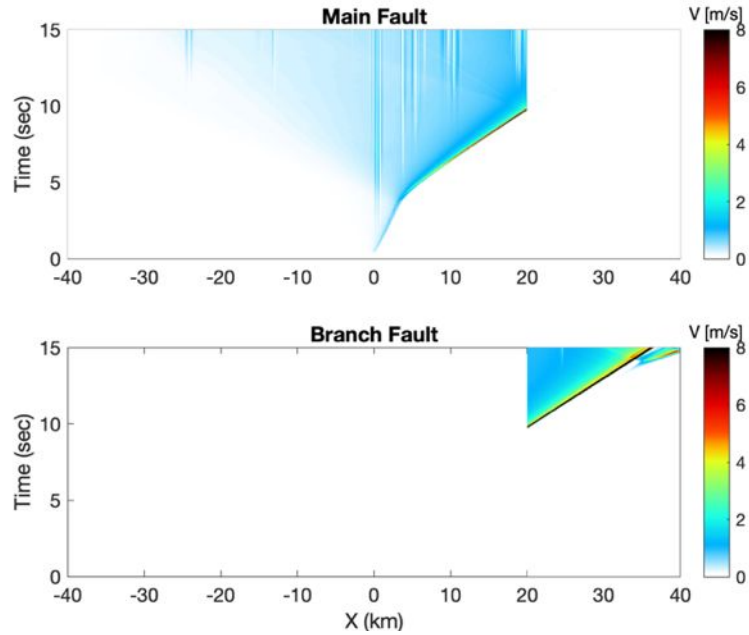
Mixed flux reduces mesh dependency



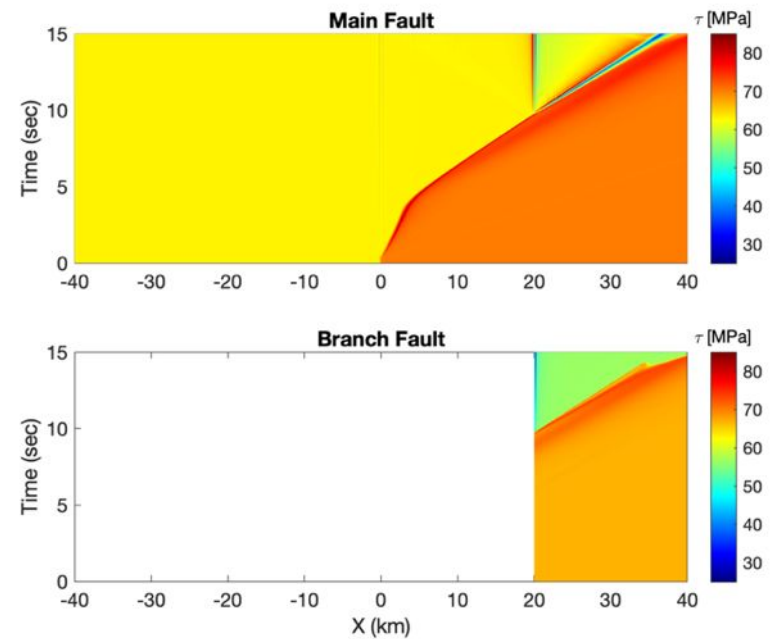
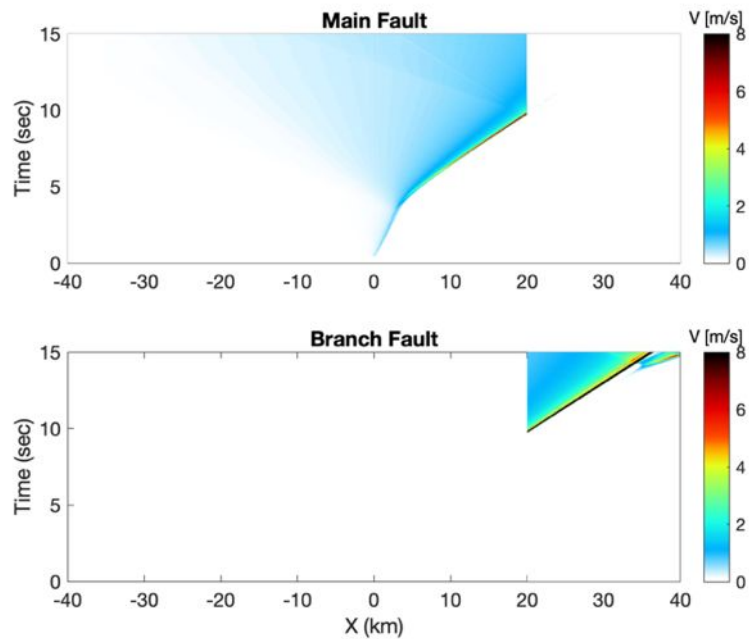
Slip rate

Shear stress

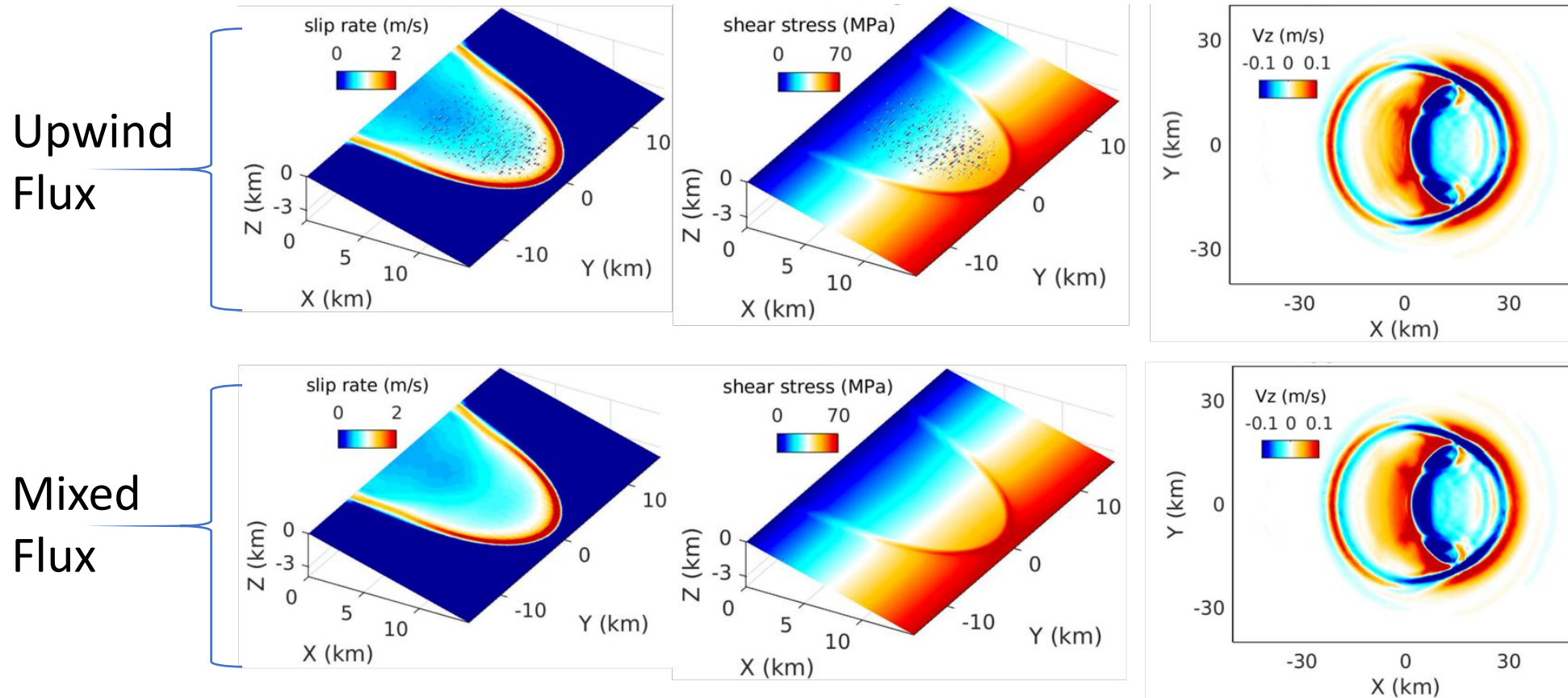
Upwind
Flux



Mixed
Flux



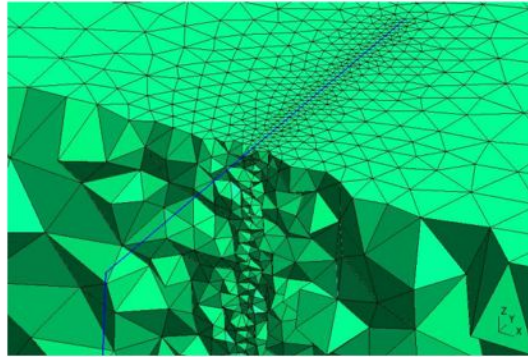
Mixed flux reduces mesh dependency



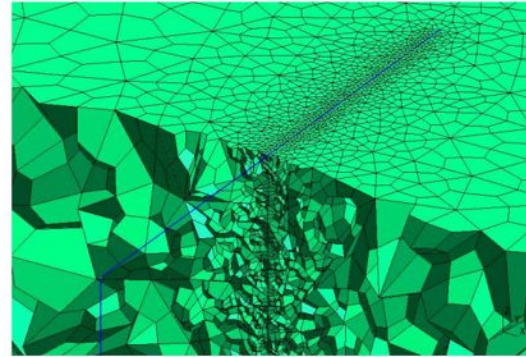
The meshes on two sides of the fault do not need to be nearly symmetrical by using the mixed flux method

Mixed flux reduces mesh dependency

(a) Tetrahedral mesh

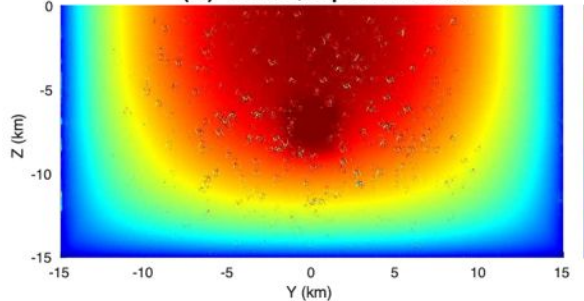


(d) Hexahedral mesh

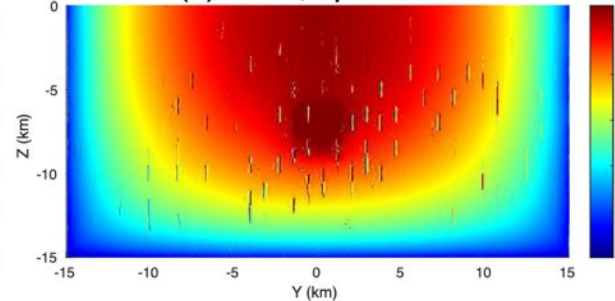


Tetrahedral/Hexahedral meshes

(b) Tetra, upwind flux

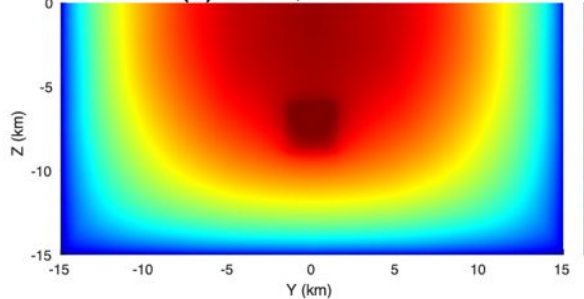


(e) Hexa, upwind flux

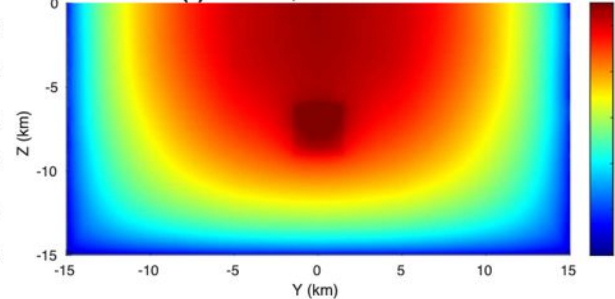


Upwind-flux is problematic

(c) Tetra, mixed flux

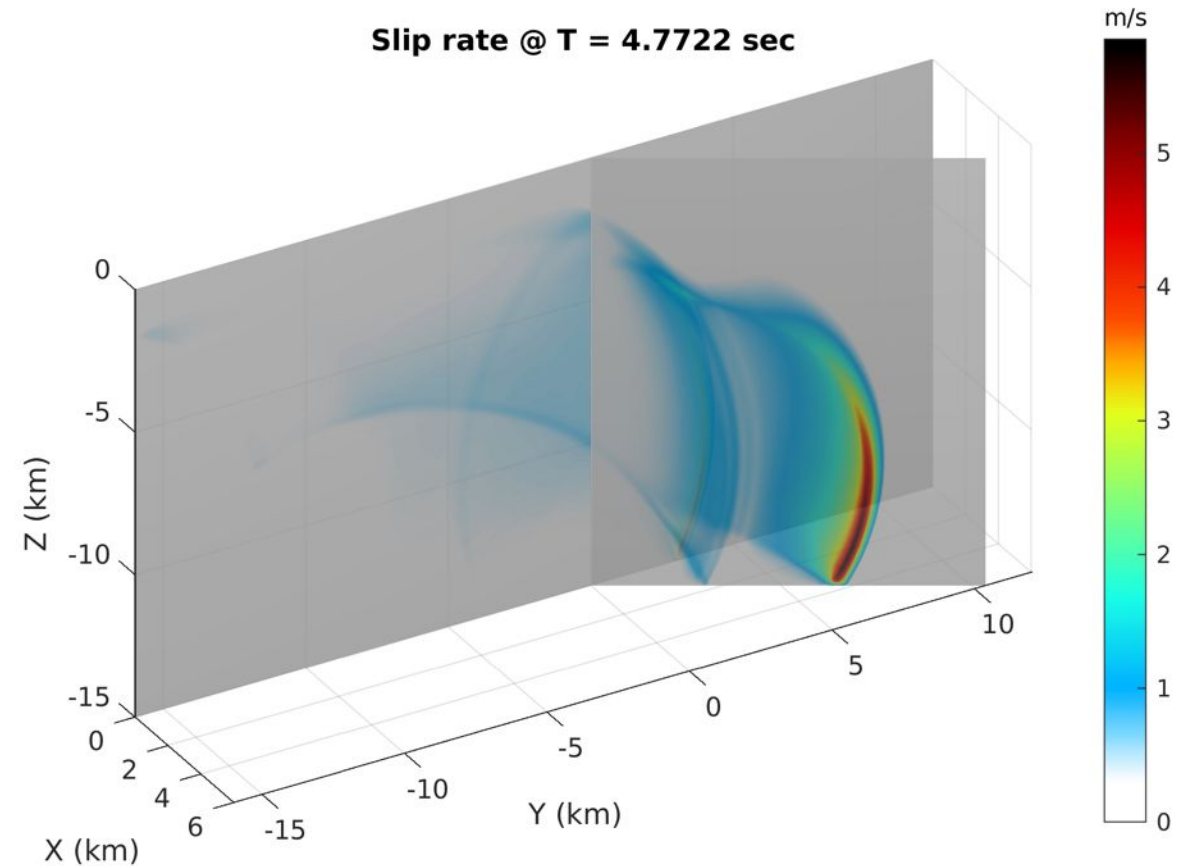
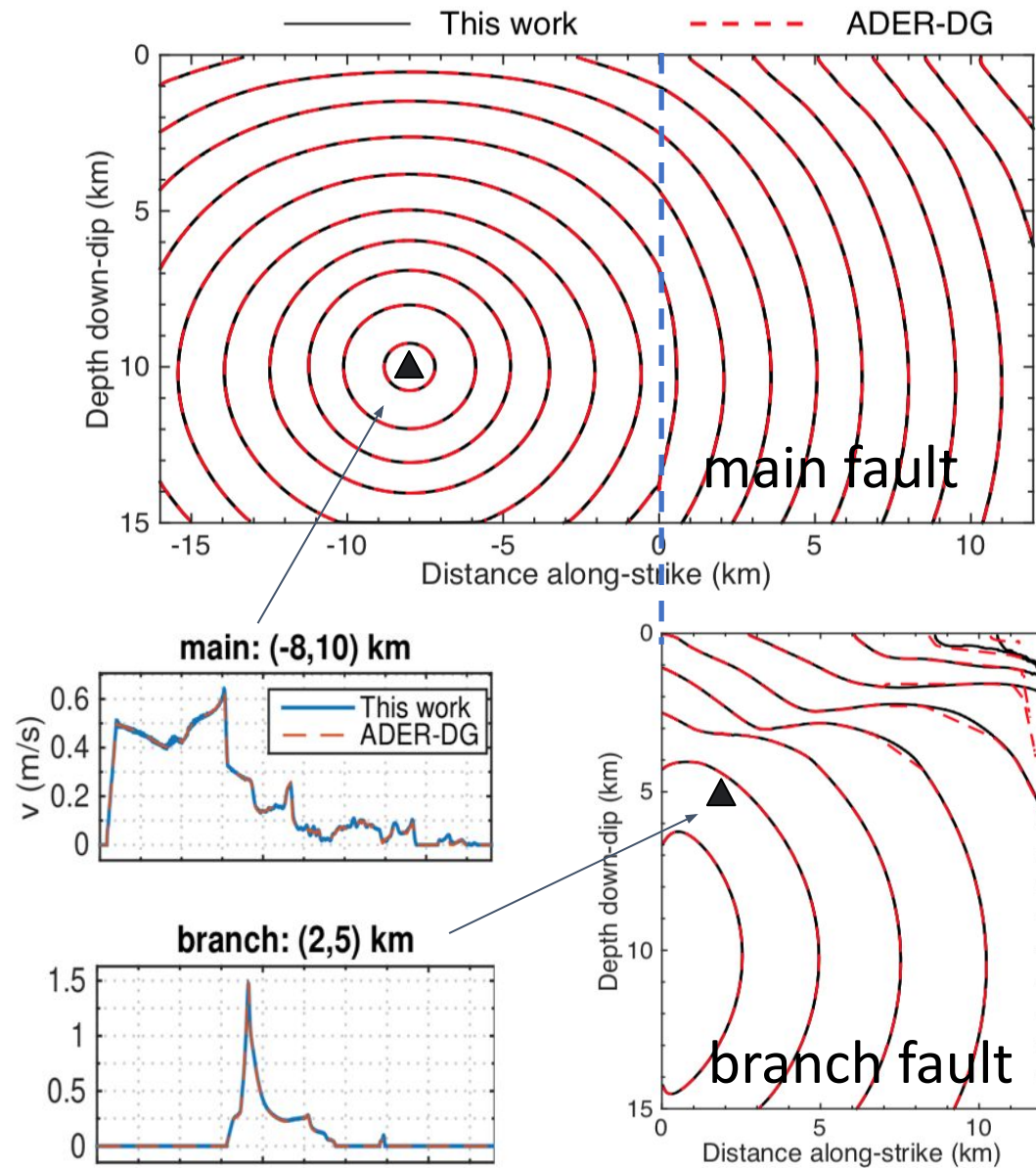


(f) Hexa, mixed flux

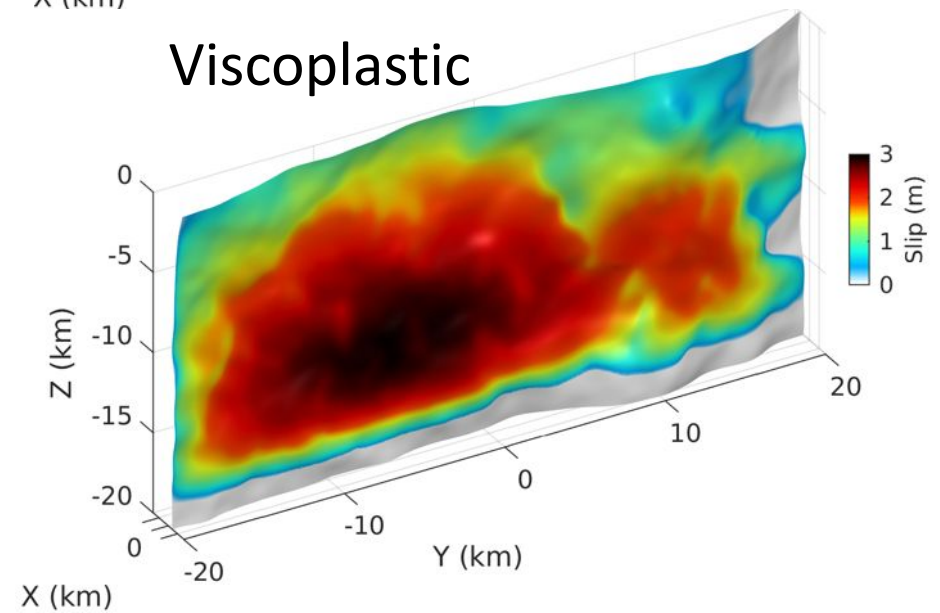
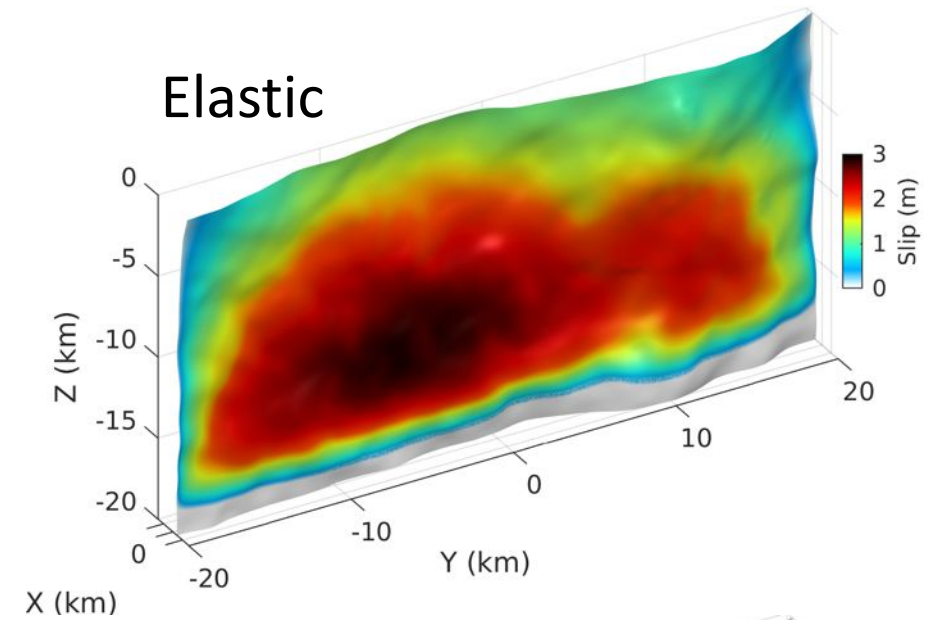
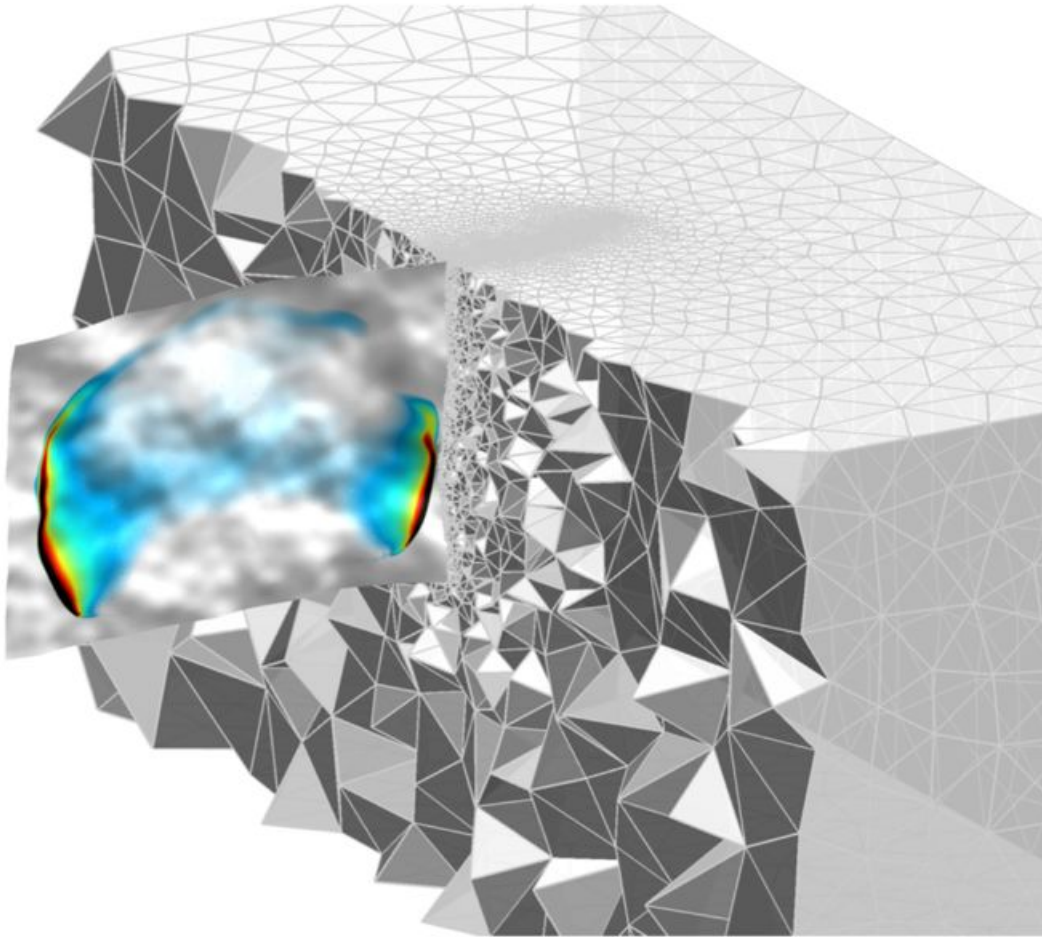


Mixed-flux works for different mesh types

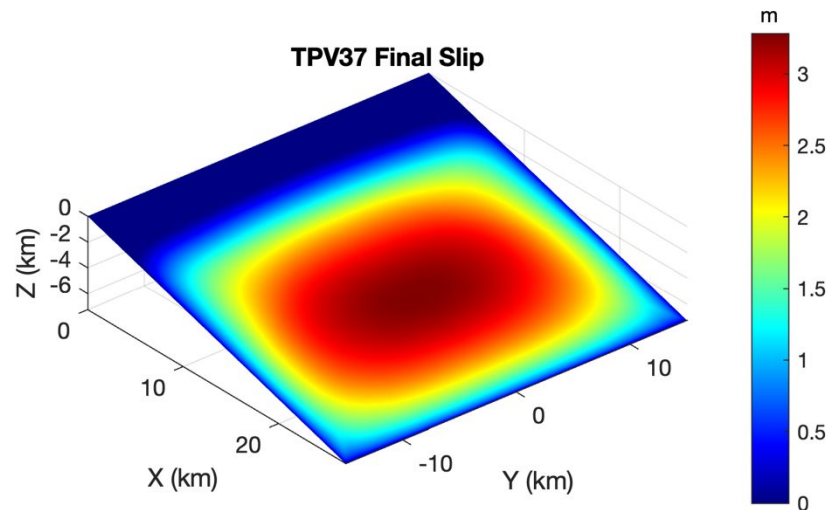
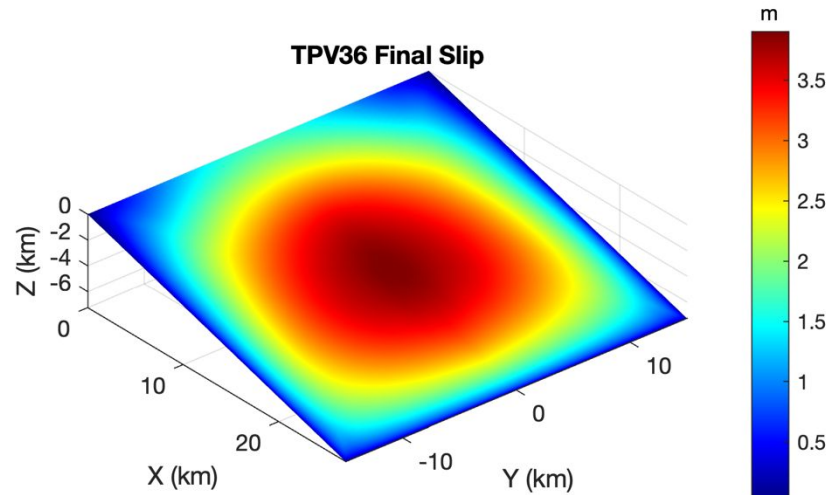
Benchmark TPV24: branch fault



Benchmark TPV29/30: rough fault

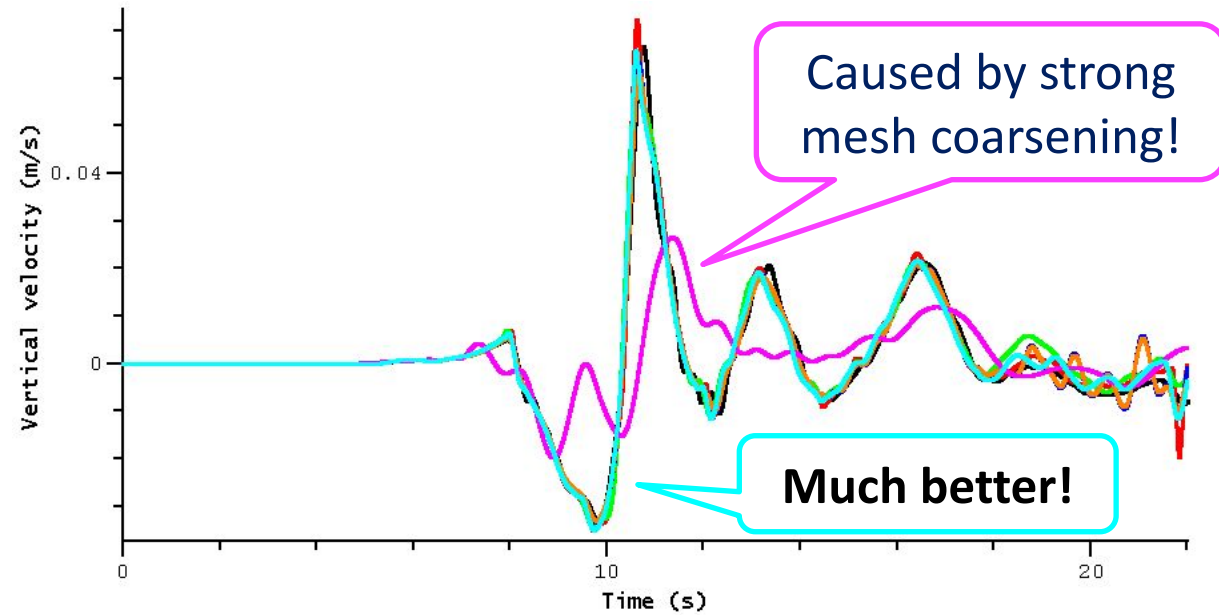


Benchmark TPV36/37: shallowly-dipping fault



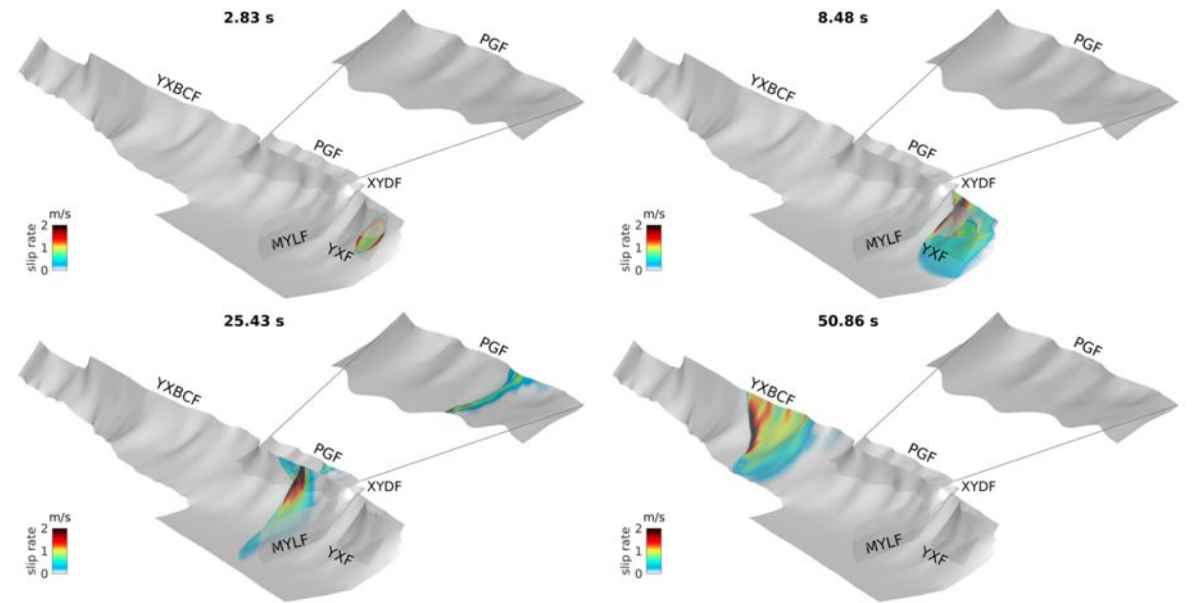
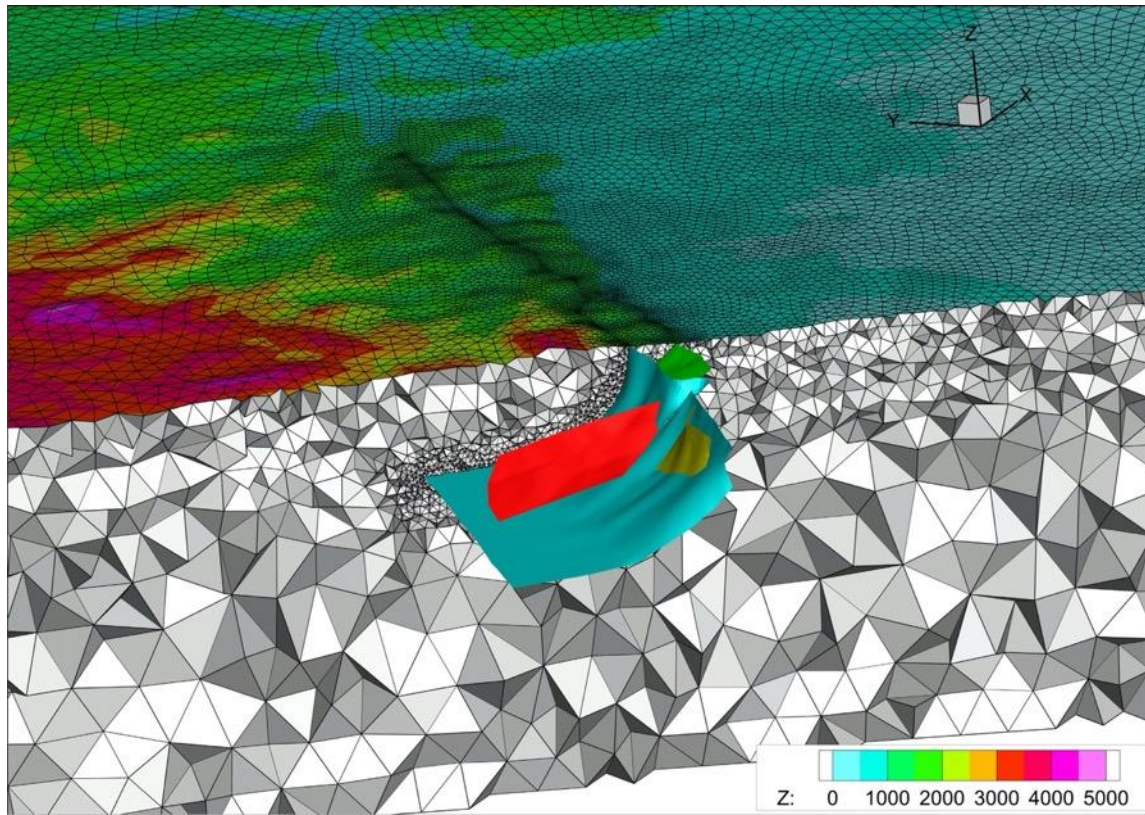
TPV36

body450st100dp000 (body 45.0 km, strike 10.0 km, depth 0.0 km)



- barall (Michael Barall - FaultMod - 50 m)
- kutschera.2 (Fabian Kutschera - DG - SeisSol v1.2.0 - fault 200 m - o4)
- li.2 (Duo Li - DG FE, h=200m, O4)
- ma (Shuo Ma - Finite Element - MAFE - 50 m on fault)
- wang (Yongfei Wang - Generalized Finite Difference - SORD)
- wzhang (Wenqiang Zhang - Mixed-Flux DG (200m-10km, O4))
- wzhang.2 (Wenqiang Zhang - Mixed-Flux DG - drdg3d - 200m, O4)

Application: 2008 Mw 7.9 Wenchuan earthquake



Conclusion

- Upwind flux can be problematic when the mesh is highly asymmetric near the fault.
- Mixed-flux method solves the problem of spatial-spike oscillations when mesh is asymmetric, thus simplifies the modeling process especially for geometric-complex faults.
- Many benchmarks and applications to real-world earthquakes modeling demonstrate the flexibility of the method.
- Open-source code ***drdg3d***