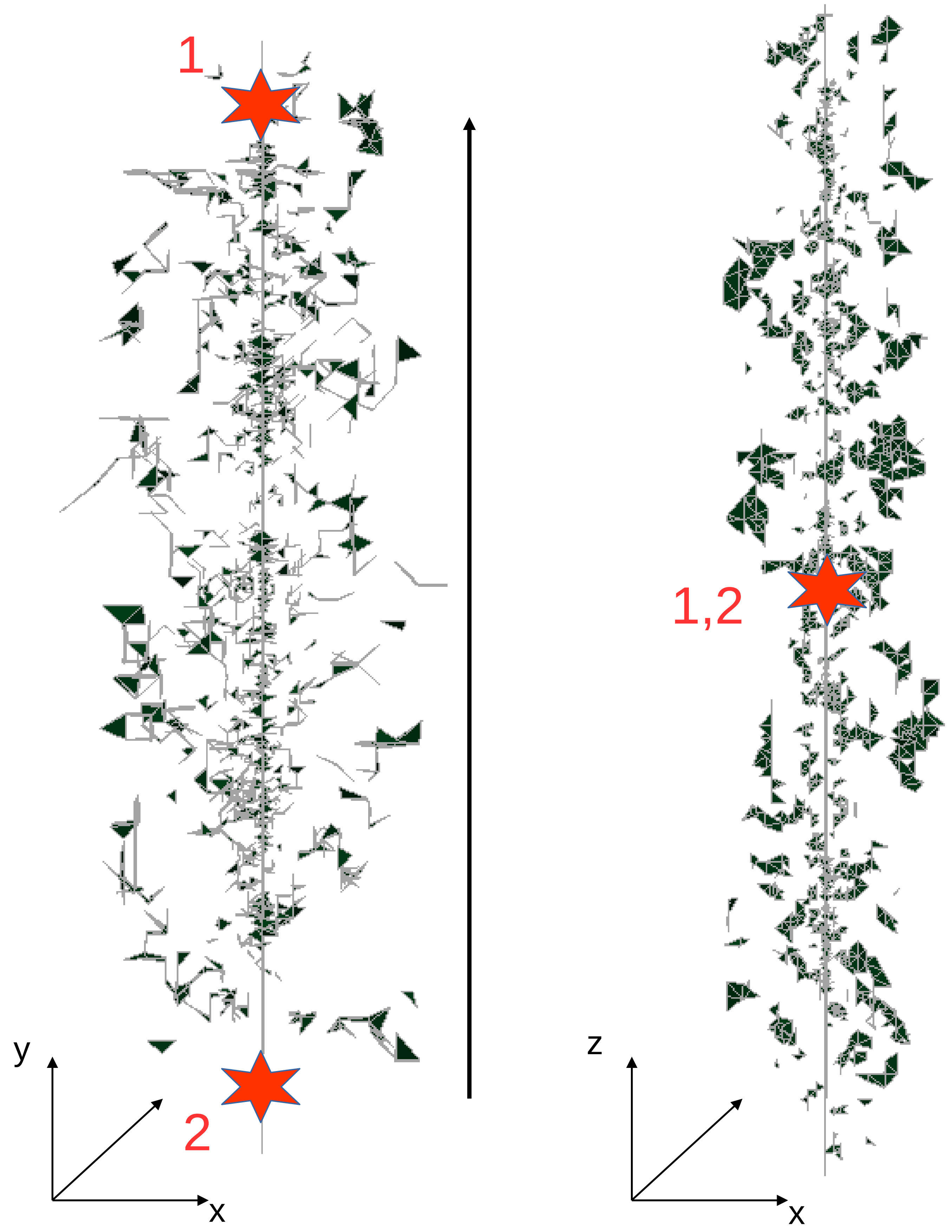
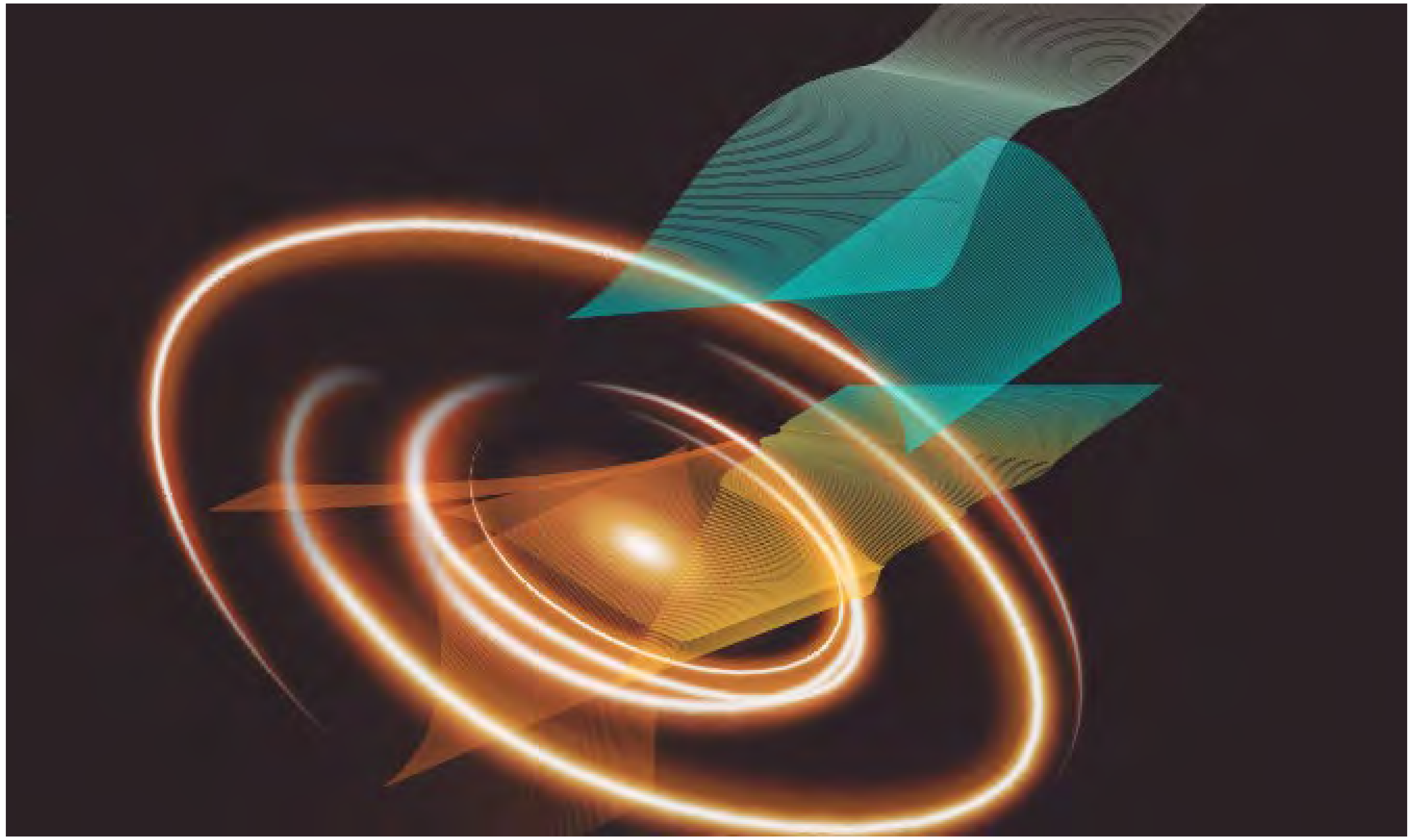
Multi-physics earthquake simulations
on complex fault networks across scales

Alice-Agnes Gabriel

T. Ulrich, S. Wollherr, S. Anger, J. A. Lopez-Comino, K. Palgunadi, M. Galis, P. M. Mai



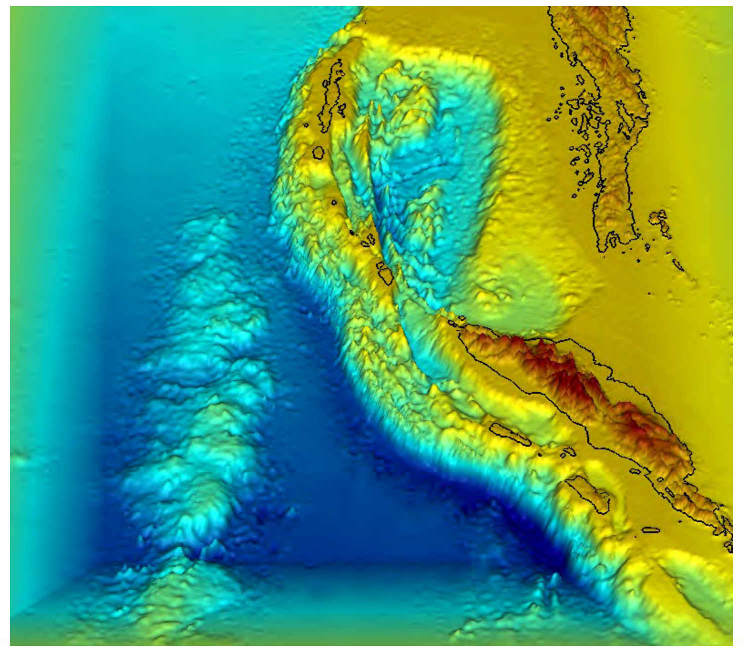
Statistical fracture network for dynamic rupture simulations from physics-based Markov Chain Monte Carlo approach (Sebastian Anger, POSTER P2-10 3320)



Artist impression of our complex dynamic rupture scenario of the 2016, Kaikōura Earthquake (Ulrich et al., Nature Comm. 2019)

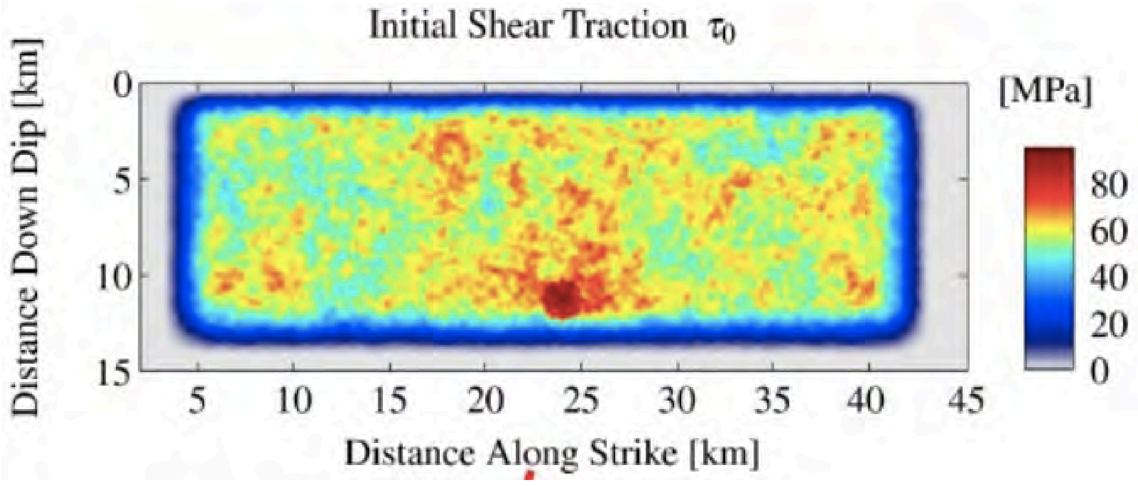
Dynamic rupture
earthquake simulation

- **Physics-based approach:** Solving for spontaneous dynamic earthquake rupture as non-linear interaction of frictional failure and seismic wave propagation

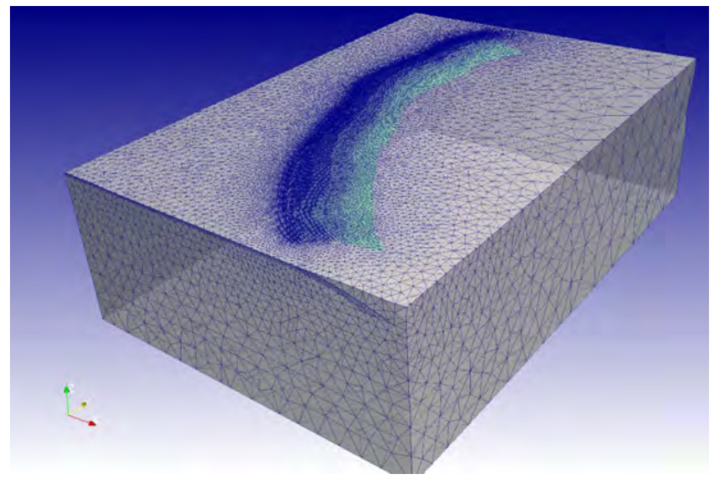


Geological structure

“Input”



Initial fault stresses



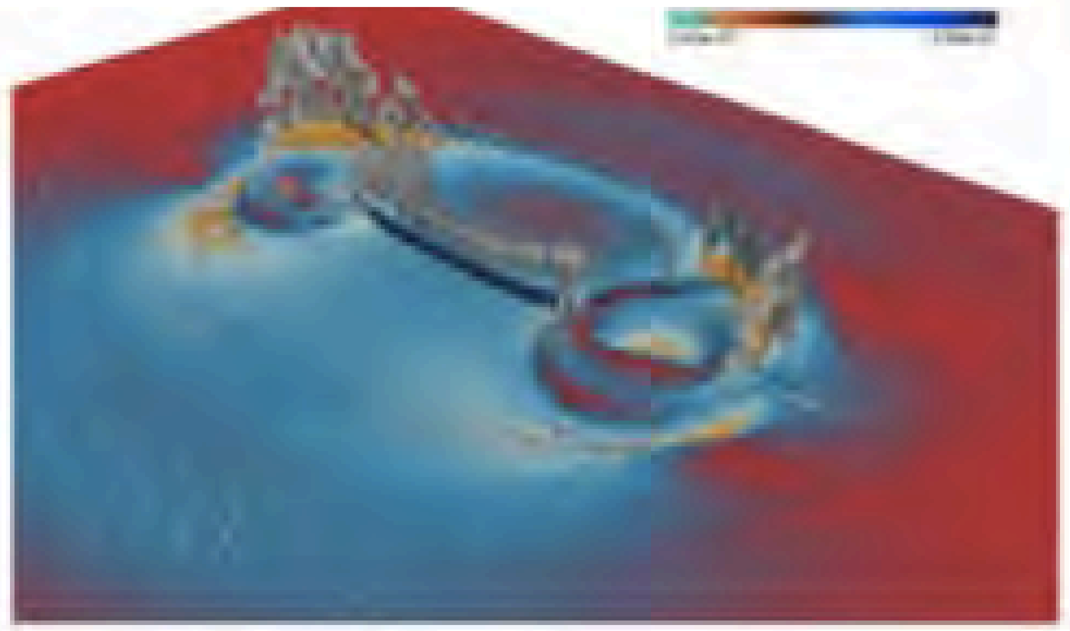
CAD & mesh generation

Failure Criterion

SOLVER

“Output”

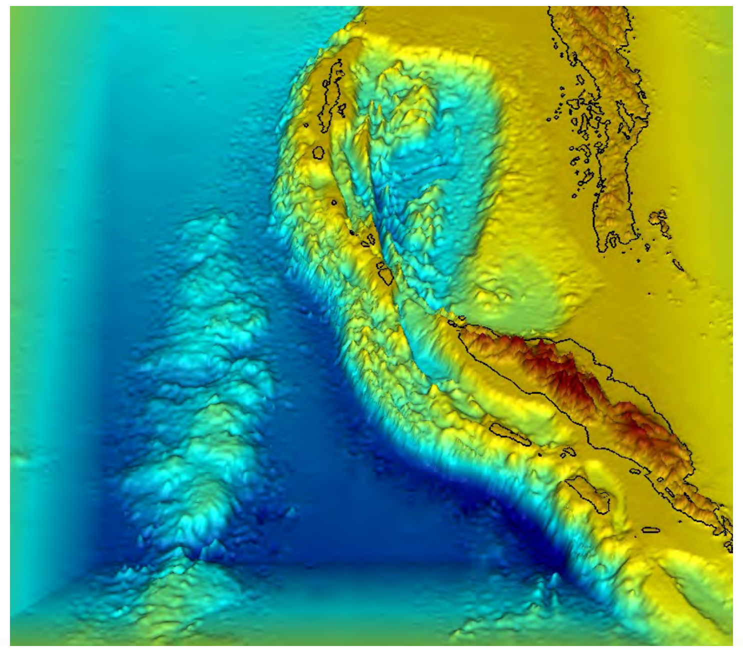
Ground motion



Synthetic seismograms

Dynamic rupture
earthquake simulation

- **Physics-based approach:** Solving for spontaneous dynamic earthquake rupture as non-linear interaction of frictional failure and seismic wave propagation



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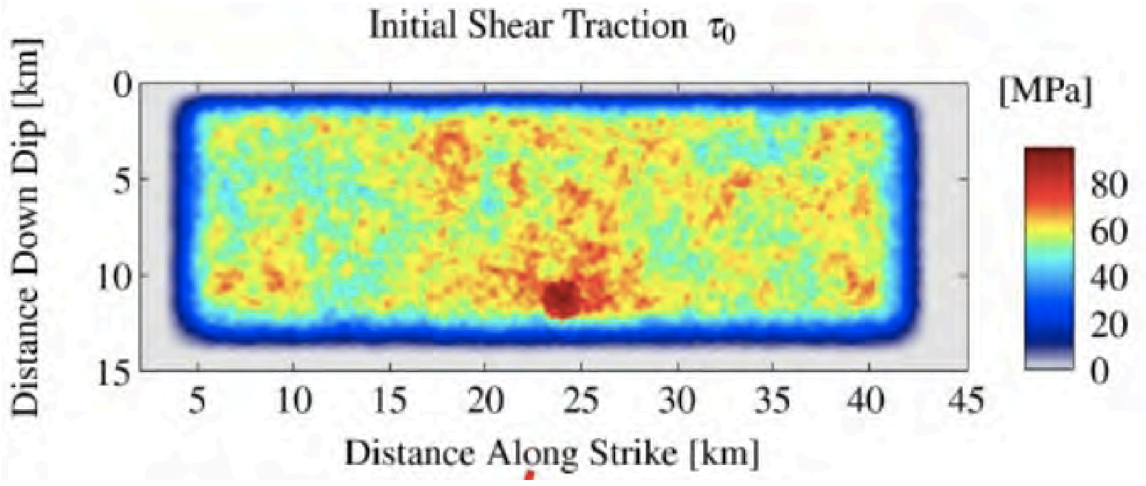
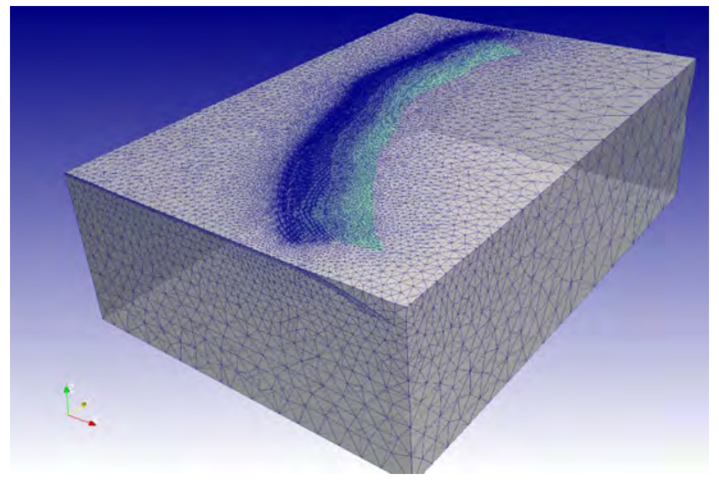


Initial fault stresses



CAD & mesh generation

Failure Criterion

SOLVER

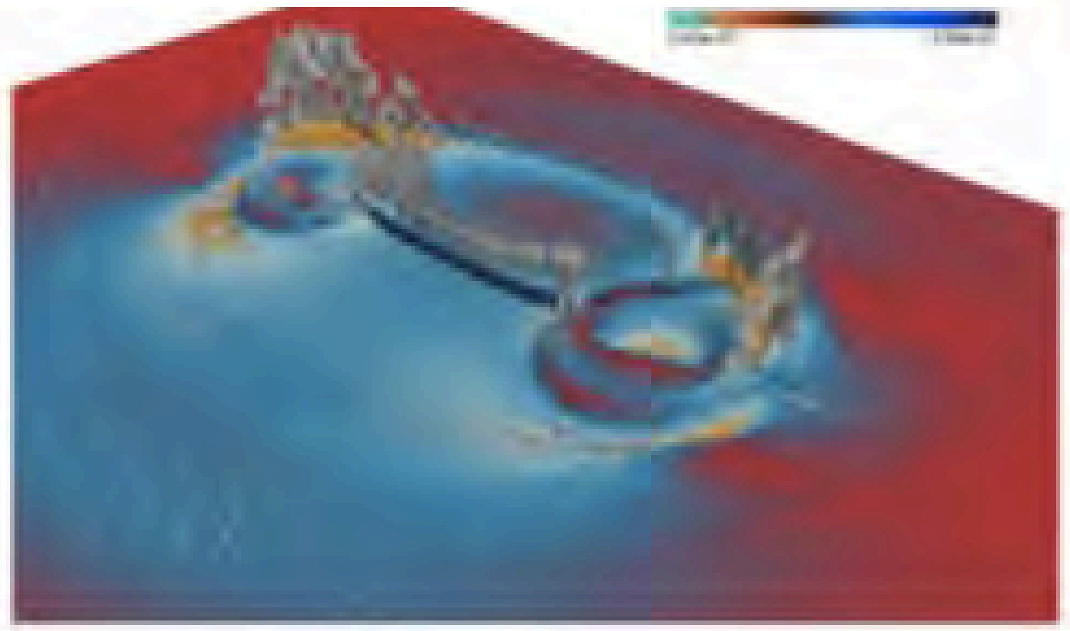
- **Requires:** Integrative view of multi-scale physics of **rock fracture**, **dynamic rupture** propagation, and emanated **seismic radiation** in complex 3D environments

- **Enables:** In-scale analysis of **which physical processes are dominant and relevant at a given spatio-temporal scale** (and in real earthquakes)?

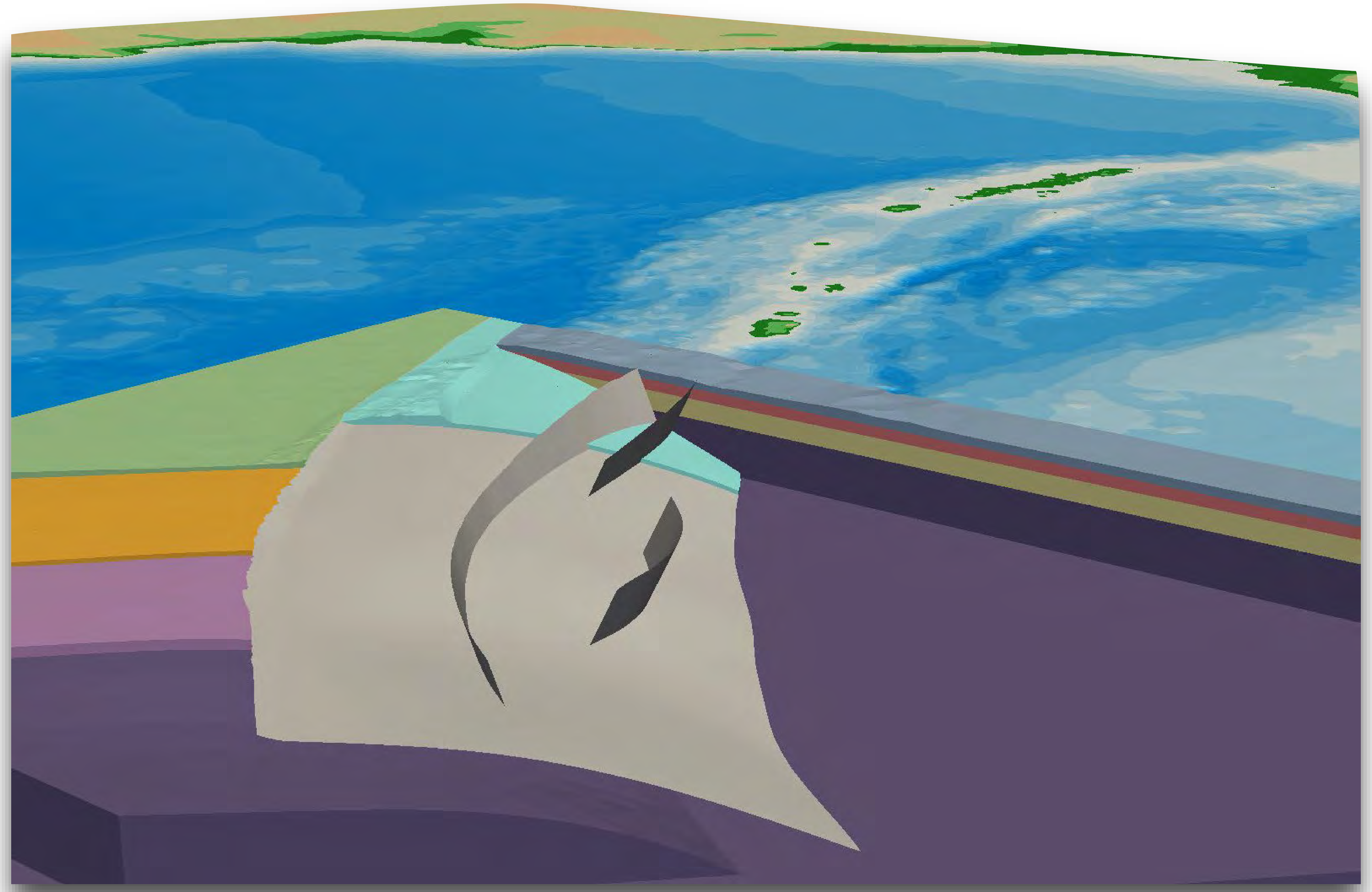
Ground motion

Synthetic seismograms

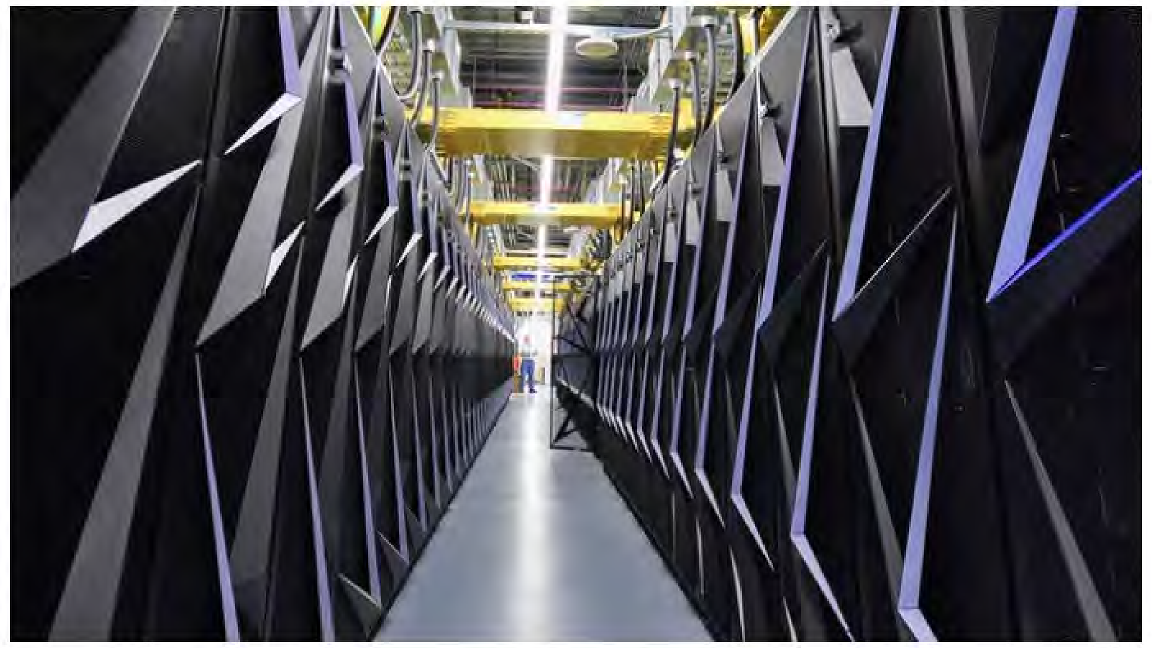
“Output”



Large-scale dynamic rupture earthquake scenarios
shedding light on the physical conditions that allow rupture cascades on complex fault systems



Computational model for **large-scale megathrust, splay faults and tsunami scenarios of the 2004 Sumatra-Andaman event** (Uphoff et al., Best Paper, SC 2017). **High-performance computing empowered simulations,** 1500 km of fault zones and 2,5 Hz wave propagation, 111 billion Degrees of Freedom, 3,300,000 time steps



Nearly complete, the 200-petaflop Summit will be a prelude to A21, the first U.S. exaflop computer. LYNN FREENY/DEPARTMENT OF ENERGY VIA FLICKR

Racing to match China's growing computer power, U.S. outlines design for exascale computer

By **Robert F. Service** | Feb. 7, 2018 , 11:00 AM

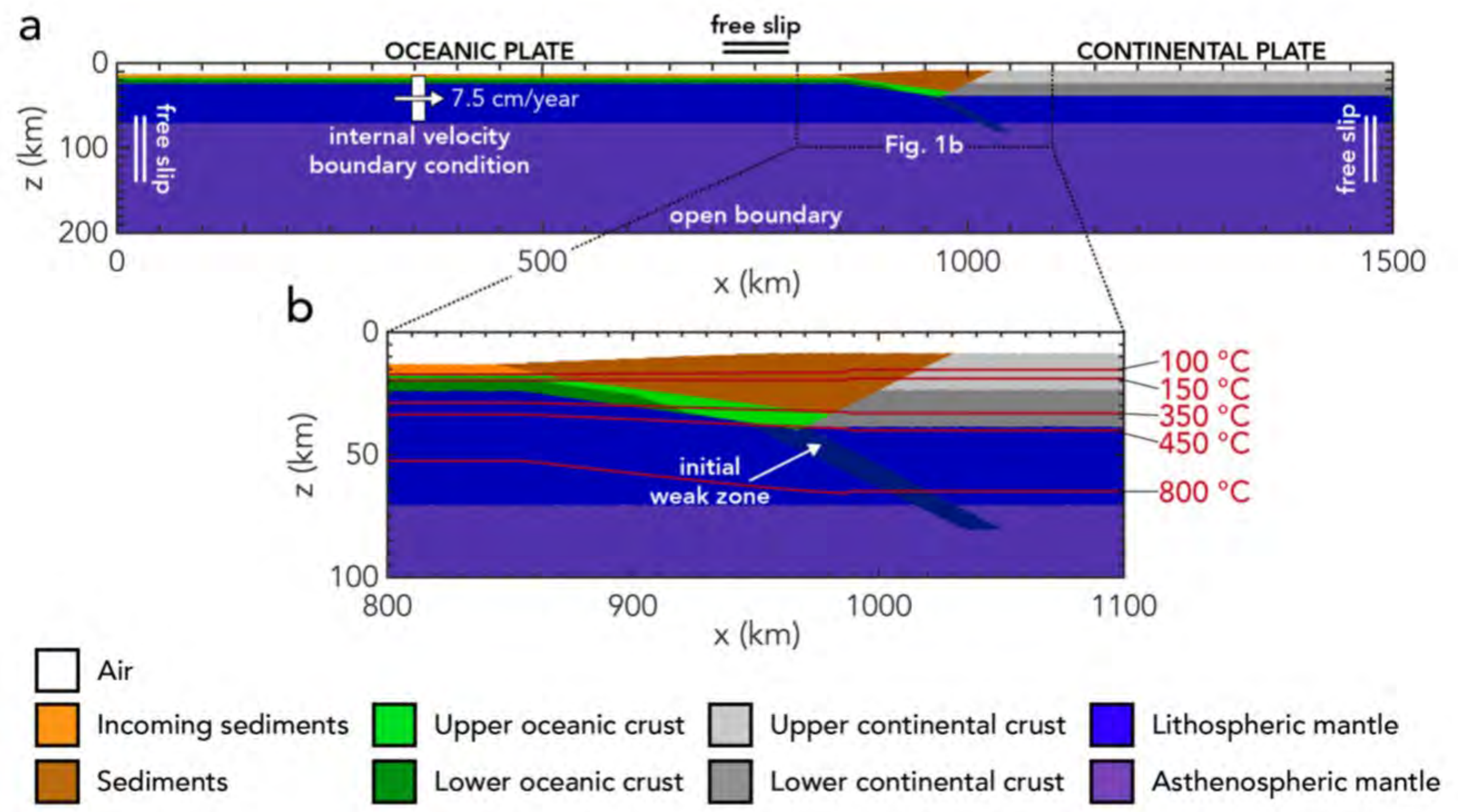


Figure 1. Complete (a) and zoomed (b) model setup of the geodynamic seismic cycle model with lithology (in colour, see key), isotherms (red), and boundary conditions (white).

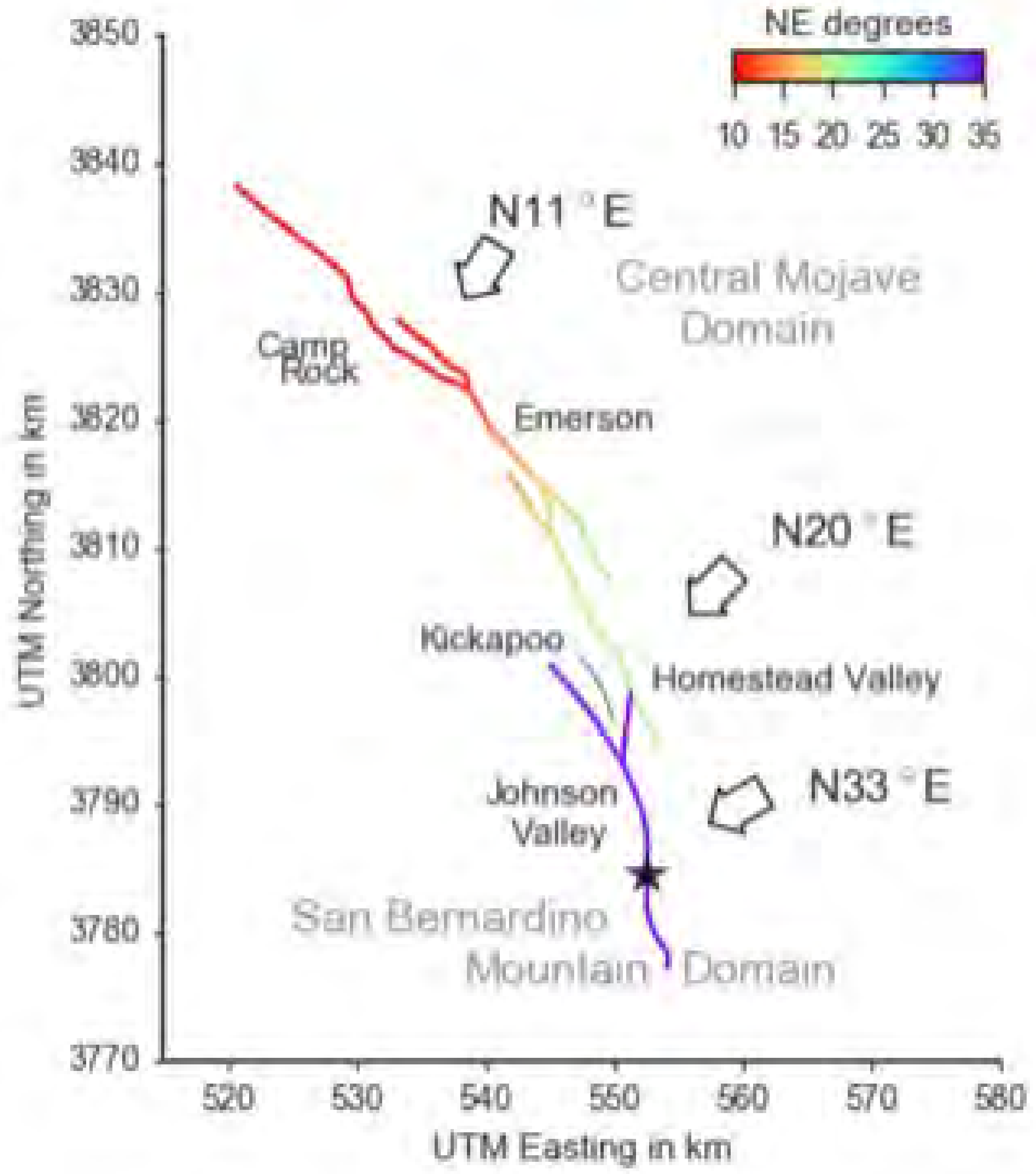
Coupling with geodynamic thermo-mechanical models to provide constraints on fault rheology and the state of stress for subduction zones, Van Zelst et al., 2019, eartharxiv.org/f6ng5

The 1992 Mw 7.3 Landers earthquake "reloaded" (Wollherr et al., preprint doi:10.31223/osf.io/kh6j9)

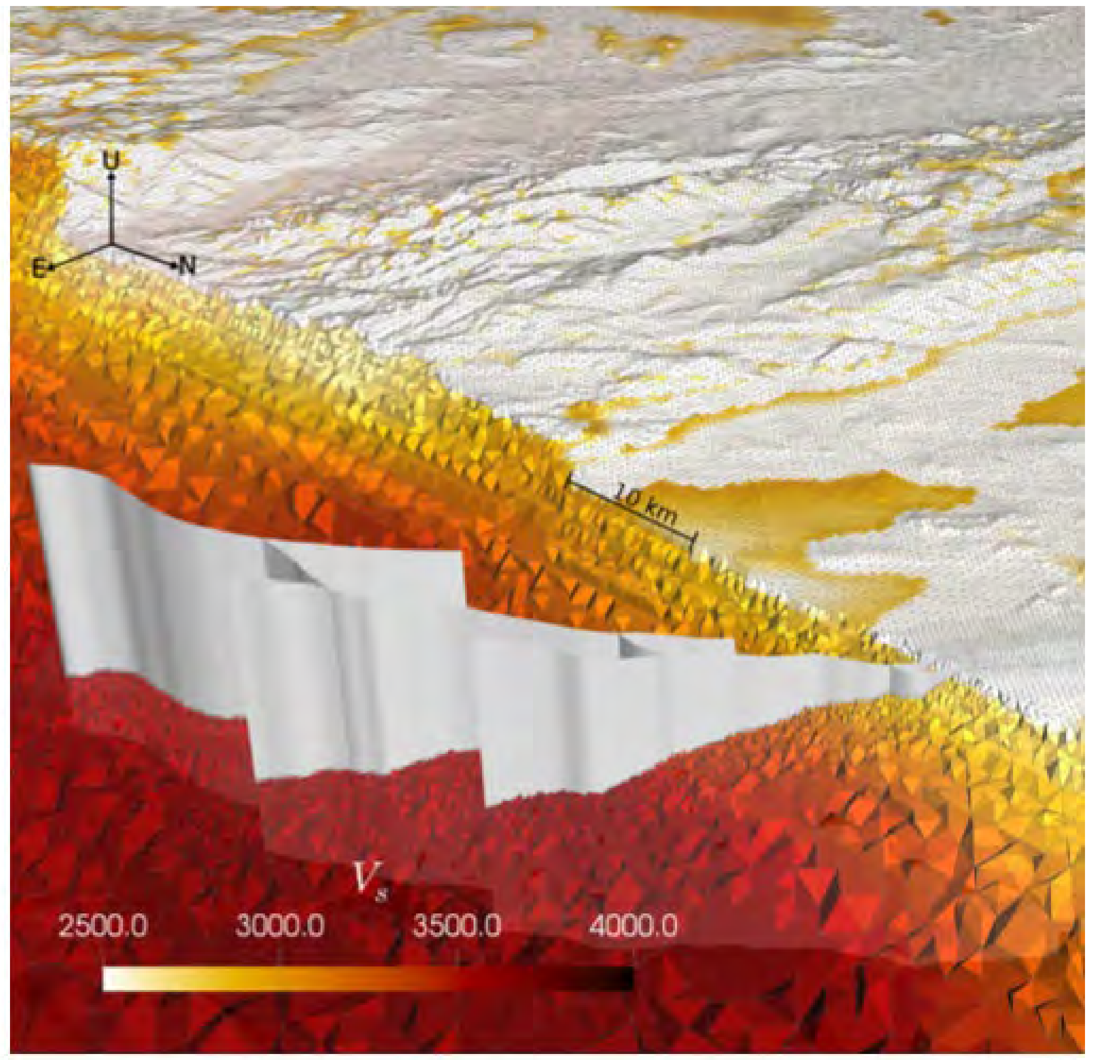
Geometry (fault morphology) matters!

- **Large-scale dynamic rupture simulation** aiming to understand on "natural-scale" which of the earthquake source "complexities" provides **first order influences**

- **A high degree of realism** leads in turn to a **high degree of uniqueness**



Mapped fault traces (Fleming et al., 1998) and assumed orientation of maximum compressional principal stress.



Computational model feat. 3D Community Velocity Model-Harvard (CVM-H, Shaw et al., 2015). Local refinement is applied in the vicinity of the faults (200 m) and the Earth's topography (500 m) (Farr et al., 2007)

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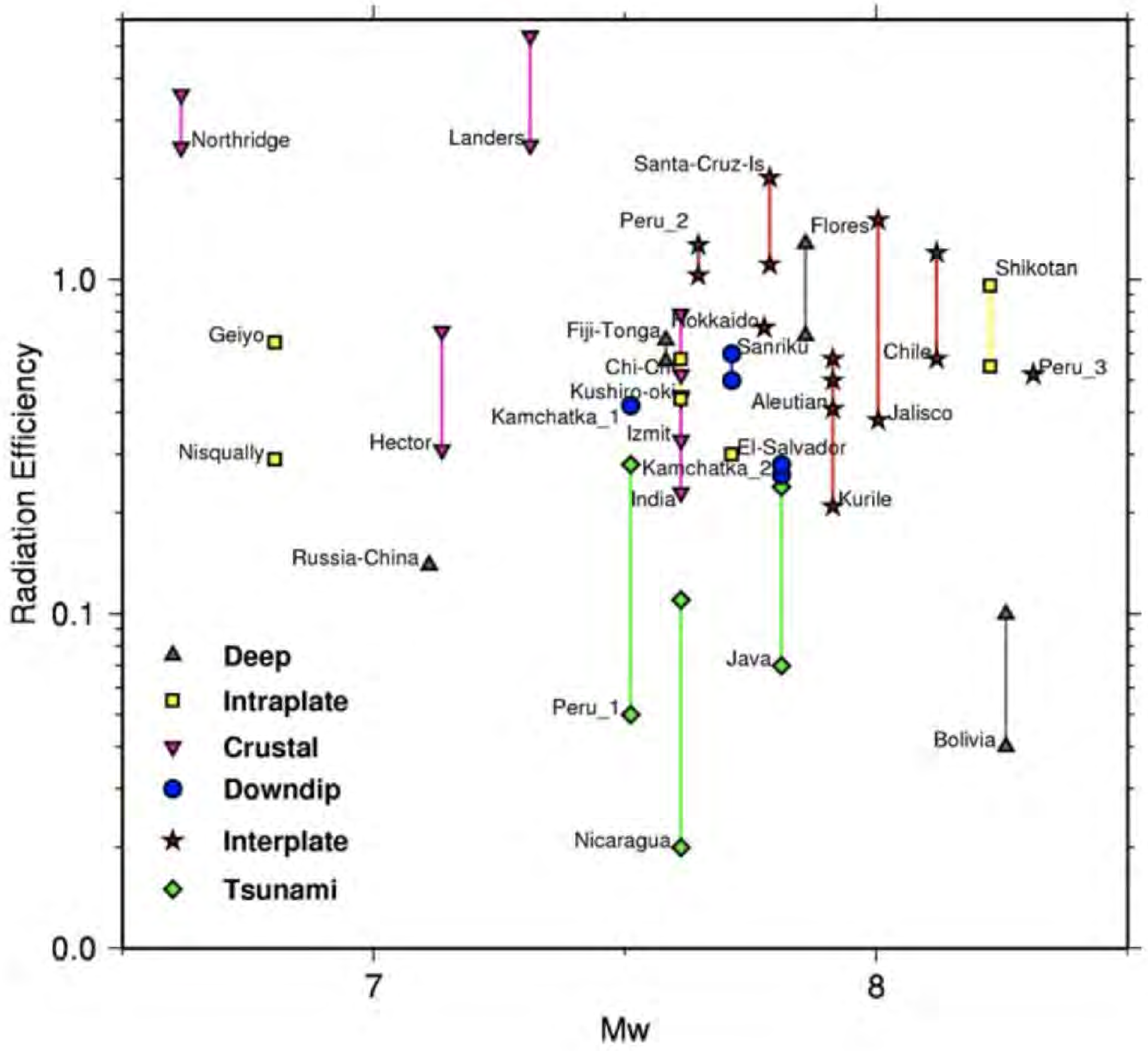

Figure 4. Radiation efficiency $\eta_R = E_R/(E_R + E_G)$ as a function of M_w. The different symbols show different types of earthquakes as described in the legend. Most

Kanamori, Hiroo. "The diversity of the physics of earthquakes." *Proceedings of the Japan Academy, Series B* 80.7 (2004): 297-316.

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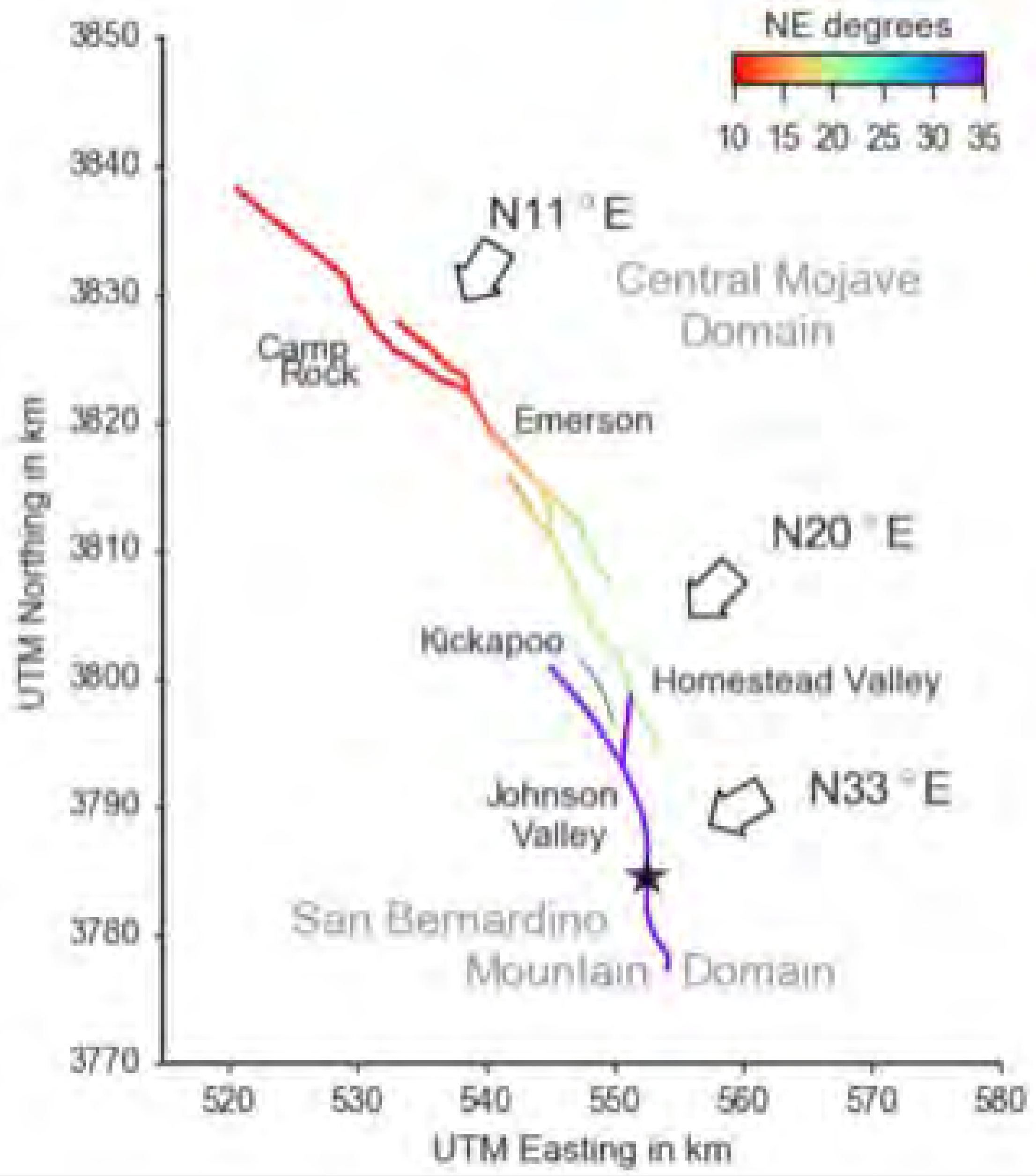
Geometry (fault morphology) matters!

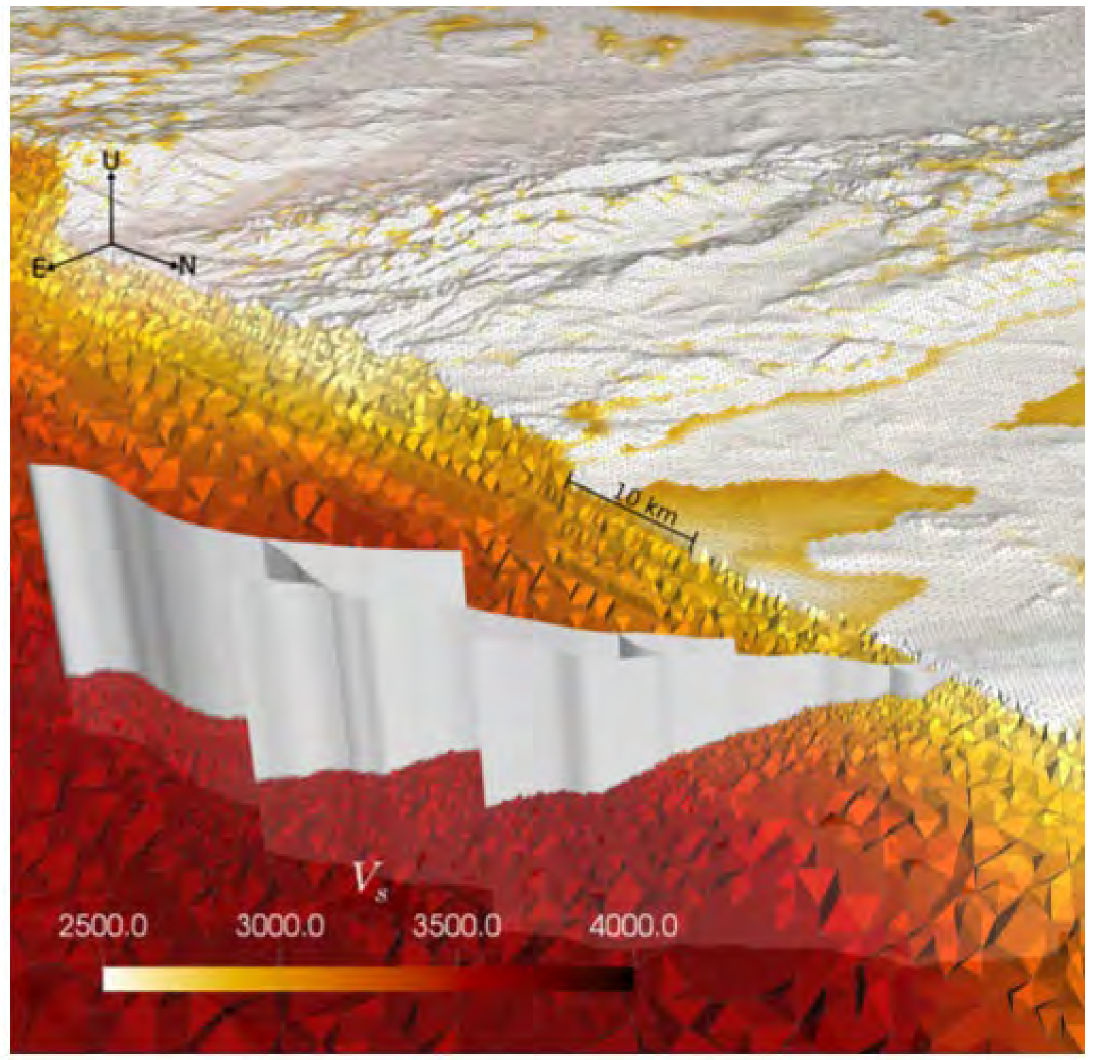
- Large-scale dynamic rupture simulation aiming to understand on "natural-scale" which of the earthquake source "complexities" provides first order influences

- A high degree of realism leads in turn to a high degree of uniqueness

- **Sustained** dynamic rupture interconnecting fault segments **constraints pre-stress and fault strength**

- Complex rupture transfers as combination of direct branching and dynamic triggering over **large distances** due to simultaneous failure of segments and **affected by viscoelastic wave attenuation**





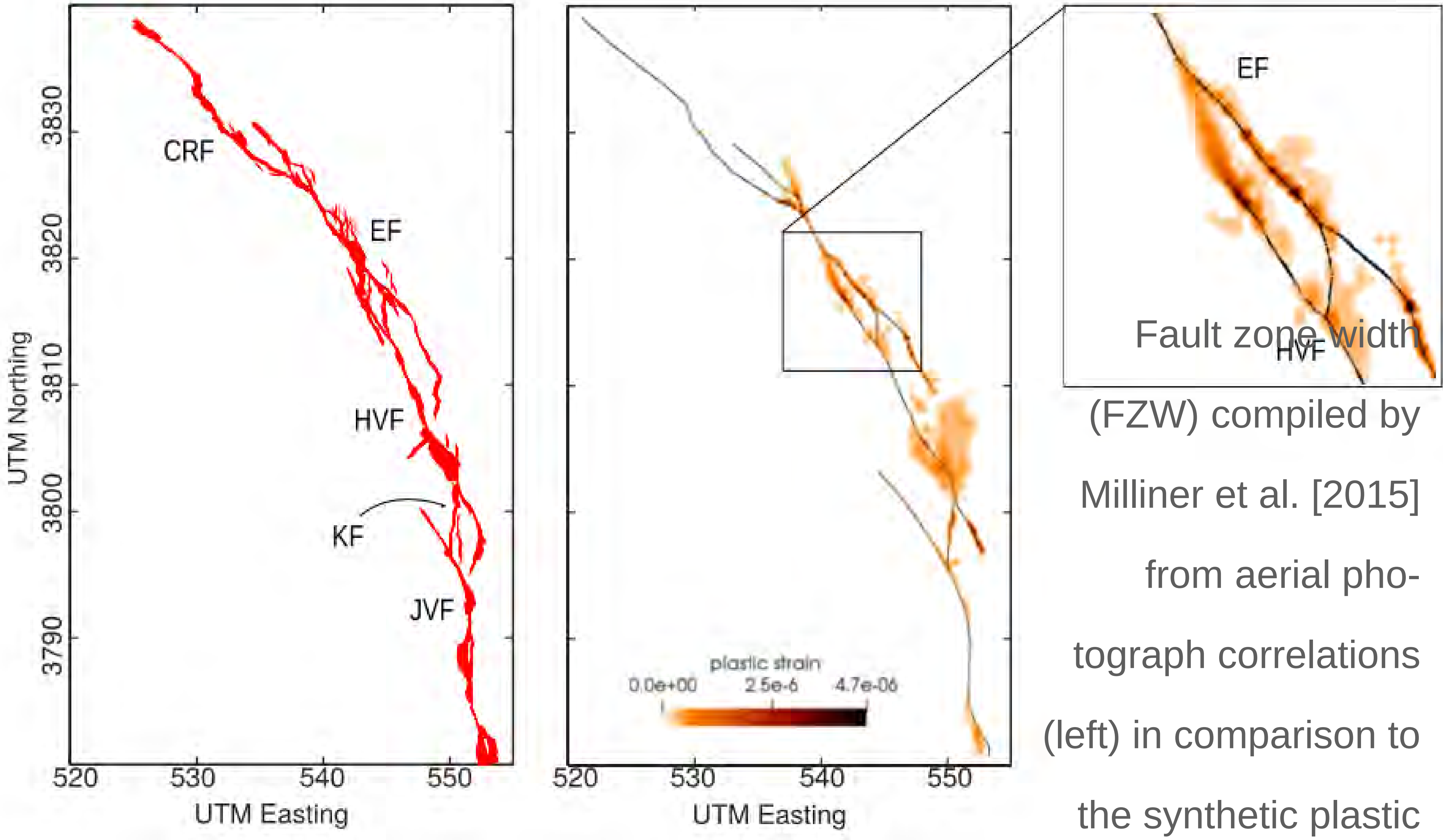
failure on-fault coupled to seismic wave propagation accounting for off-fault plasticity

The 1992 Mw 7.3 Landers earthquake "reloaded" (Wollherr et al., preprint doi:10.31223/osf.io/kh6j9)

➡ Multi-physics, such as off-fault plasticity, matters!

- **Drastic increase** of **off-fault deformation** in **geometrically complex fault regions** enhancing geometric barriers, hindering rupture transfers and matching newly available mapping

- **Strain localisation** forming non-prescribed 'faults'



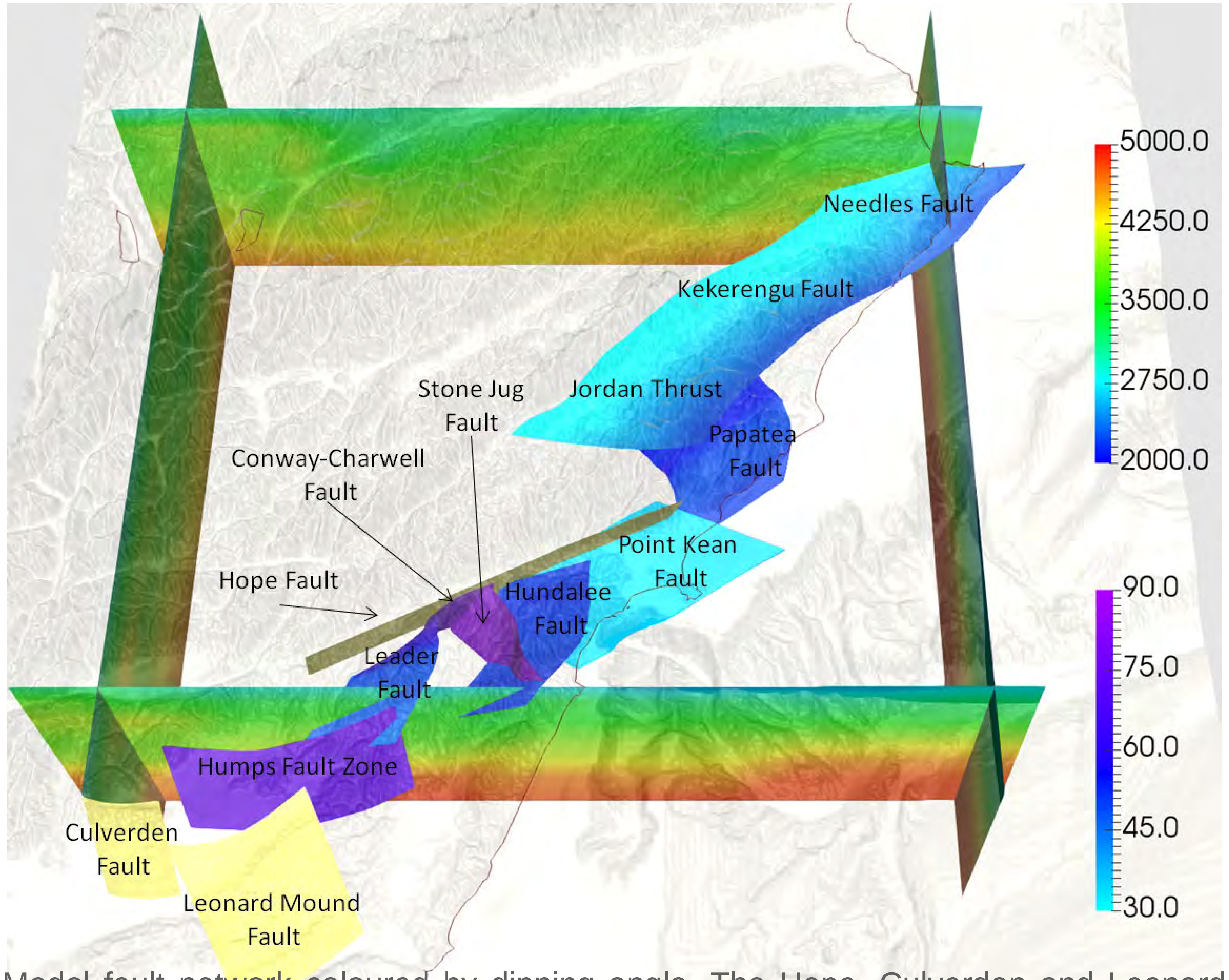
Fault zone width (FZW) compiled by Milliner et al. [2015] from aerial photograph correlations (left) in comparison to the synthetic plastic strain

The 2016 Mw 7.8 Kaikōura earthquake
- a rupture cascade on weak crustal faults

(Ulrich et al., 2019, https://eartharxiv.org/aed4b/)

➞ Mechanical viability of a complex rupture cascade linking the crustal fault system only when operating at low apparent friction

- Rupture propagation across **highly segmented fault system with diverse orientations and faulting mechanisms** (strike-slip, thrusting)
- Most of the modeled faults are relatively **well oriented with respect to the regional stress field**

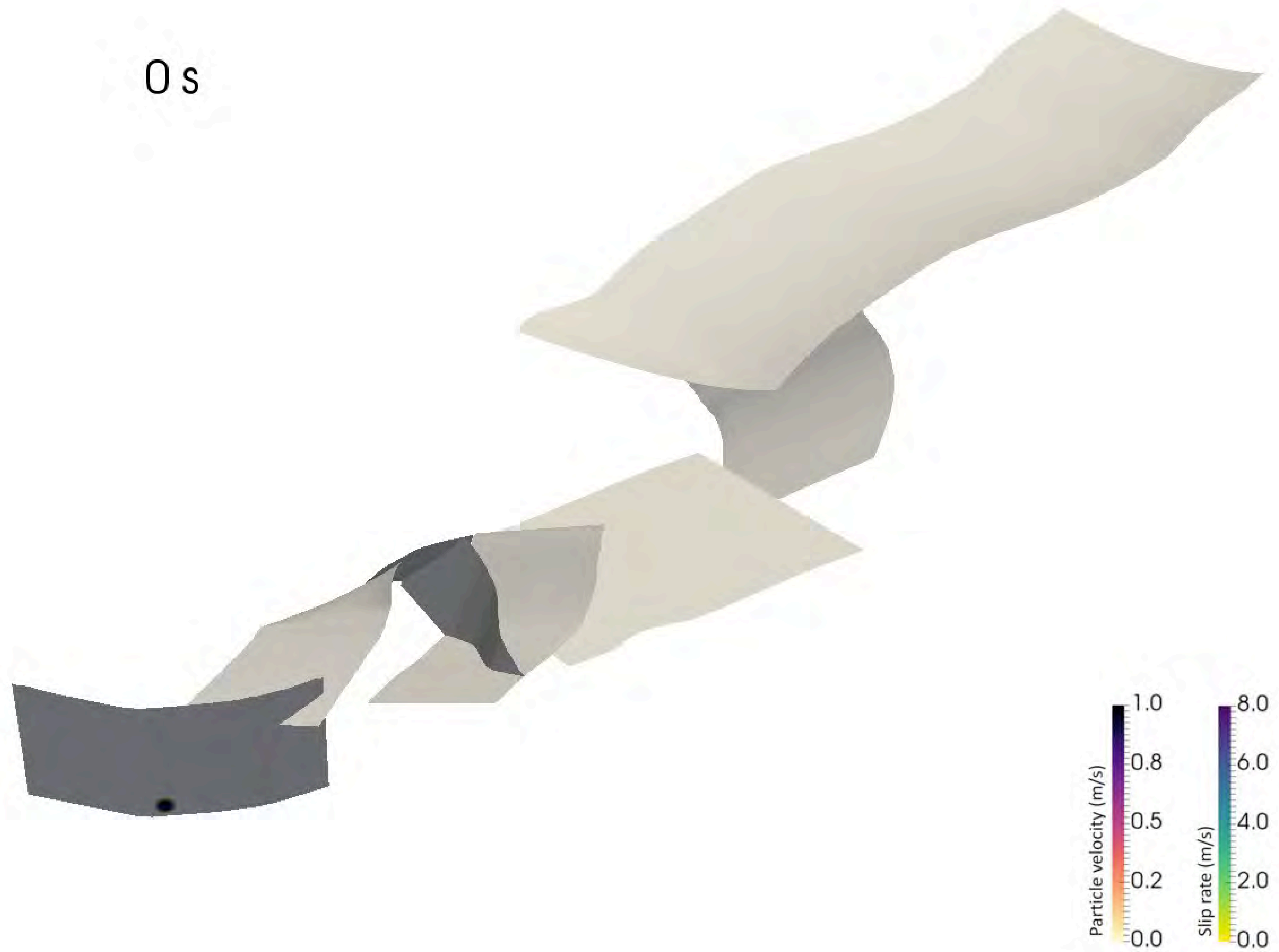


Model fault network coloured by dipping angle. The Hope, Culverden and Leonard Mound faults are included but do not rupture. Faults are embedded in high-resolution topography and bathymetry (Mitchell et al., 2012) and 3D subsurface structure

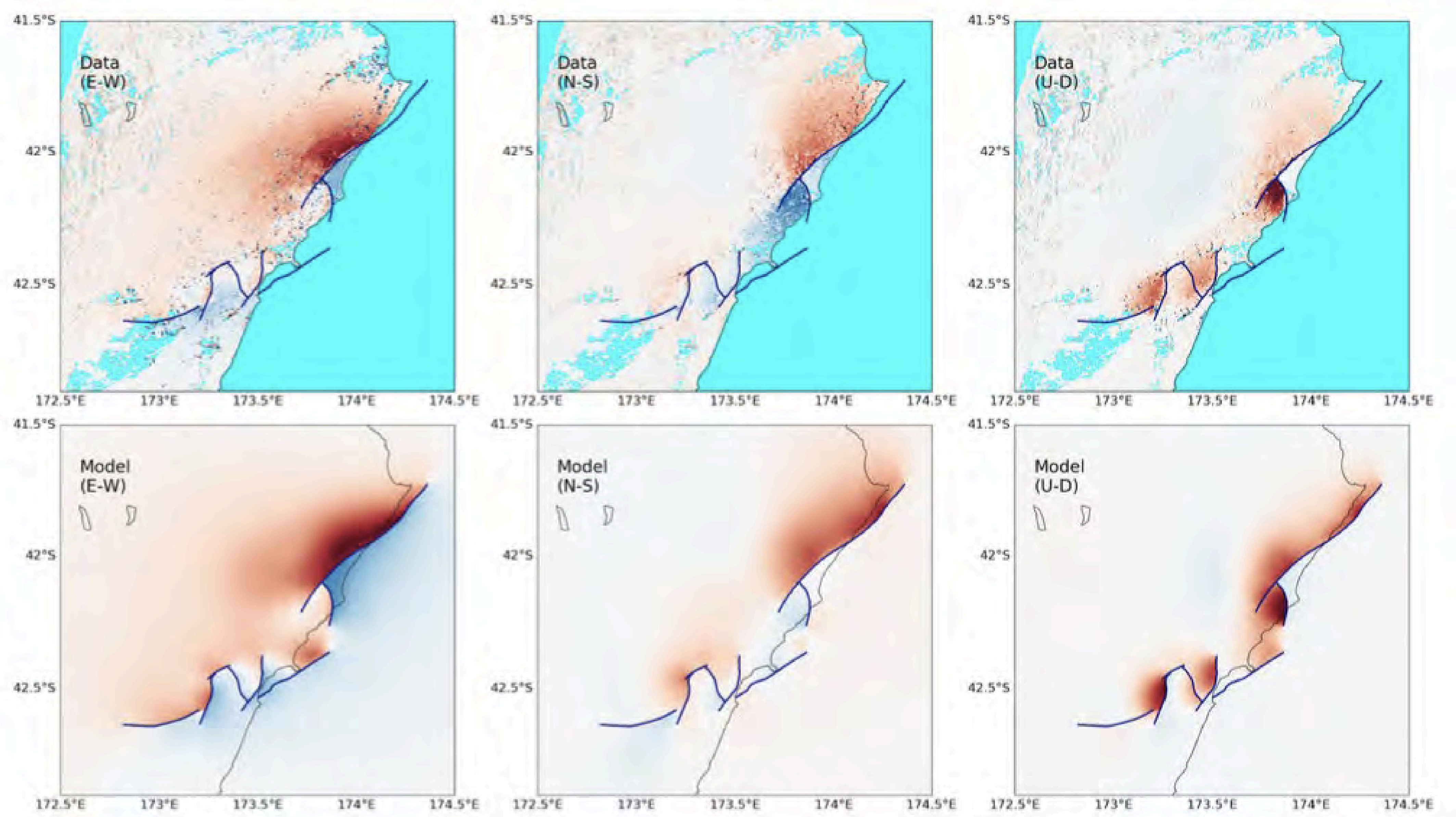
The 2016 Mw 7.8 Kaikōura earthquake - a rupture cascade on weak crustal faults

→ Reproducing observations and constraining competing views

- Rupture propagation across fault segments with diverse orientations and faulting mechanisms does **not require slip on the underlying subduction interface**
- **Slow** apparent rupture velocity from **zigzagging rupture** path
- **Point Kean fault** (Clark et al., 2017) acted as a **crucial link** between the Hundalee fault and the Northern faults
- **Non-rupture of the Hope fault** due to unfavourable dynamic stresses on the restraining step-over formed by the Conway-Charwell and Hope faults



On-fault slip rate and wave speed. Multiple rupture fronts, Point Kean, Papatea and Kekerengu segments slip more than once.



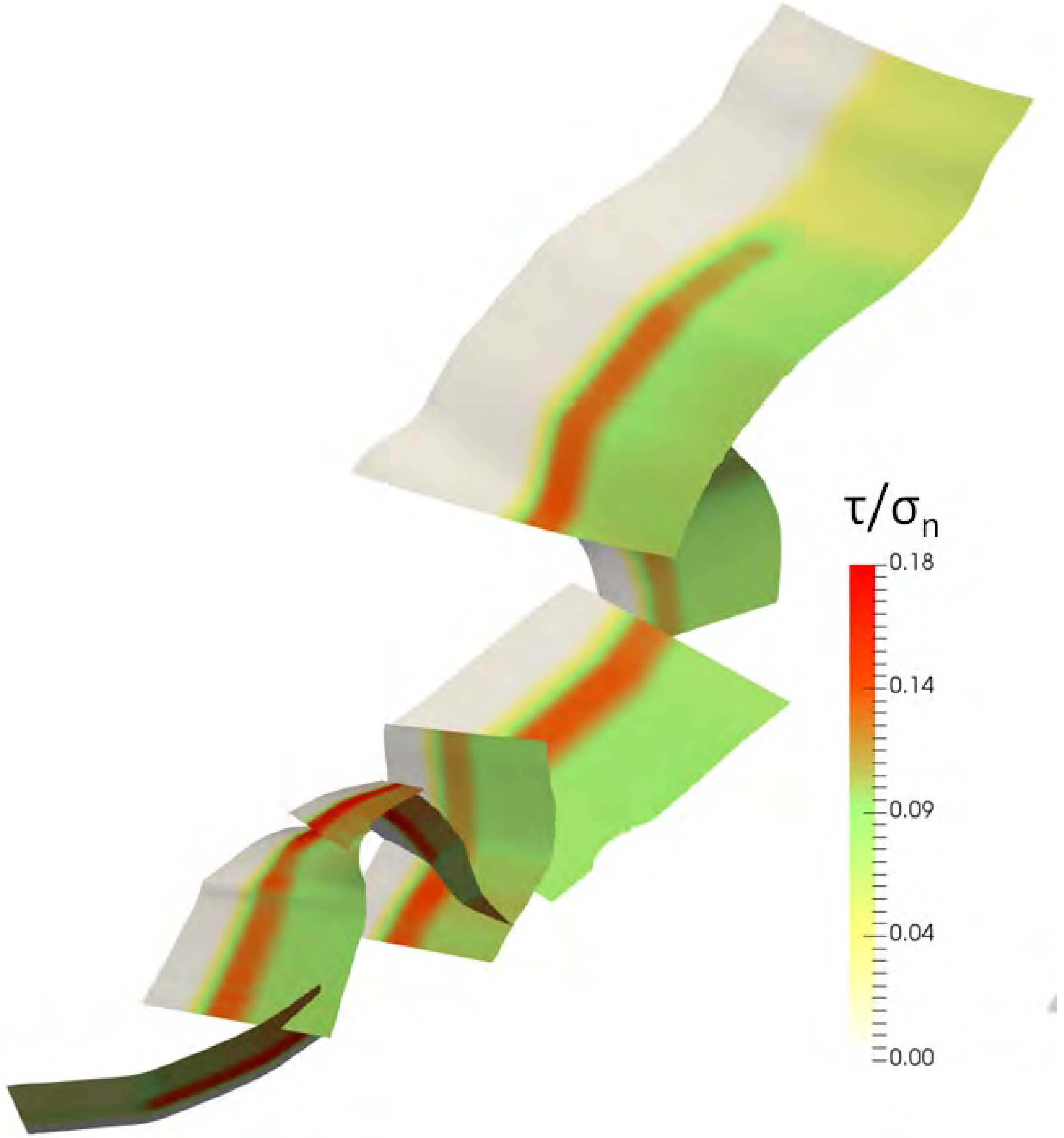
3D ground displacement cf. inferred by space geodetic data (Xu et al. 2018)

The 2016 Mw 7.8 Kaikōura earthquake
- a rupture cascade on weak crustal faults

(Ulrich et al., preprint https://eartharxiv.org/aed4b/)

→ Fault weakness across time scales restores dynamic triggering potential

- Fault weakness (I) - **low dynamic friction**
- Fault weakness (II) - **overpressurized fluids**
- Fault weakness (III) - **deep stress concentration induced by deep fault creep**

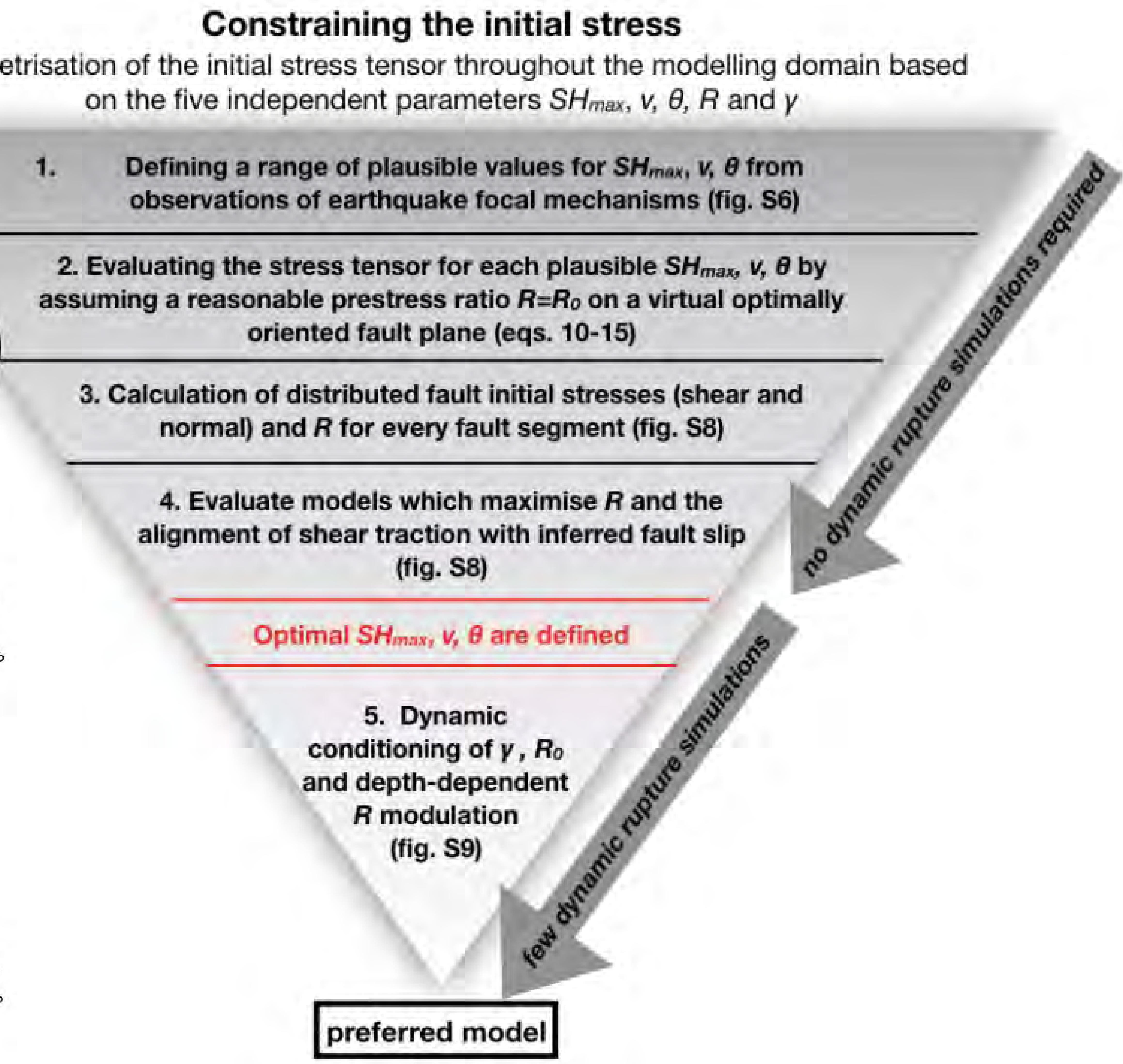


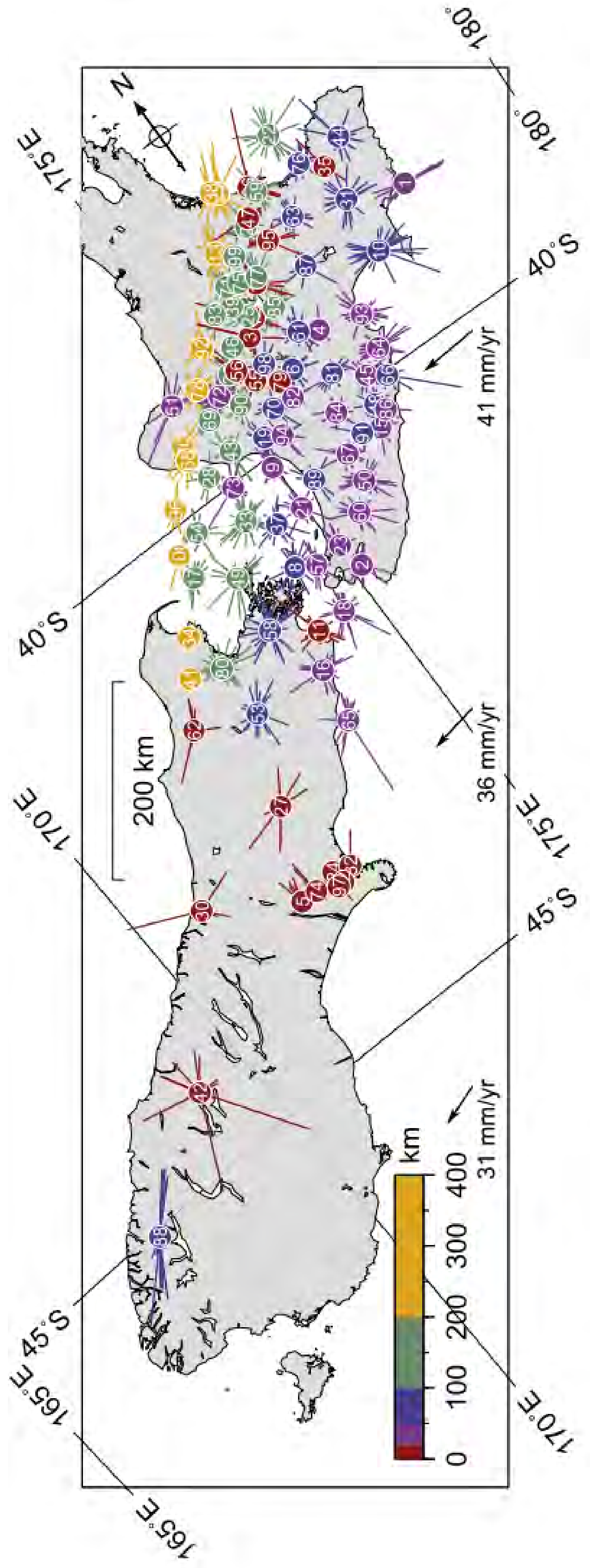
“Optimal stress algorithm” - all faults are overall stressed well below failure and yet break spontaneously.

Initial fault stress and strength

We systematically search for a **smoothly varying regional stress** parametrized by:

- **3 angles (principal stress orientations)**
- **Deviatoric stress** given by relative fault strength and the ratio between fluid-pressure and lithostatic confining stress
- Of those 7 parameters, 4 are directly constrained by regional stress and seismogenic depth, **3 are unkown: fluid pressure, background shear stress and intensity of deep stress concentration**



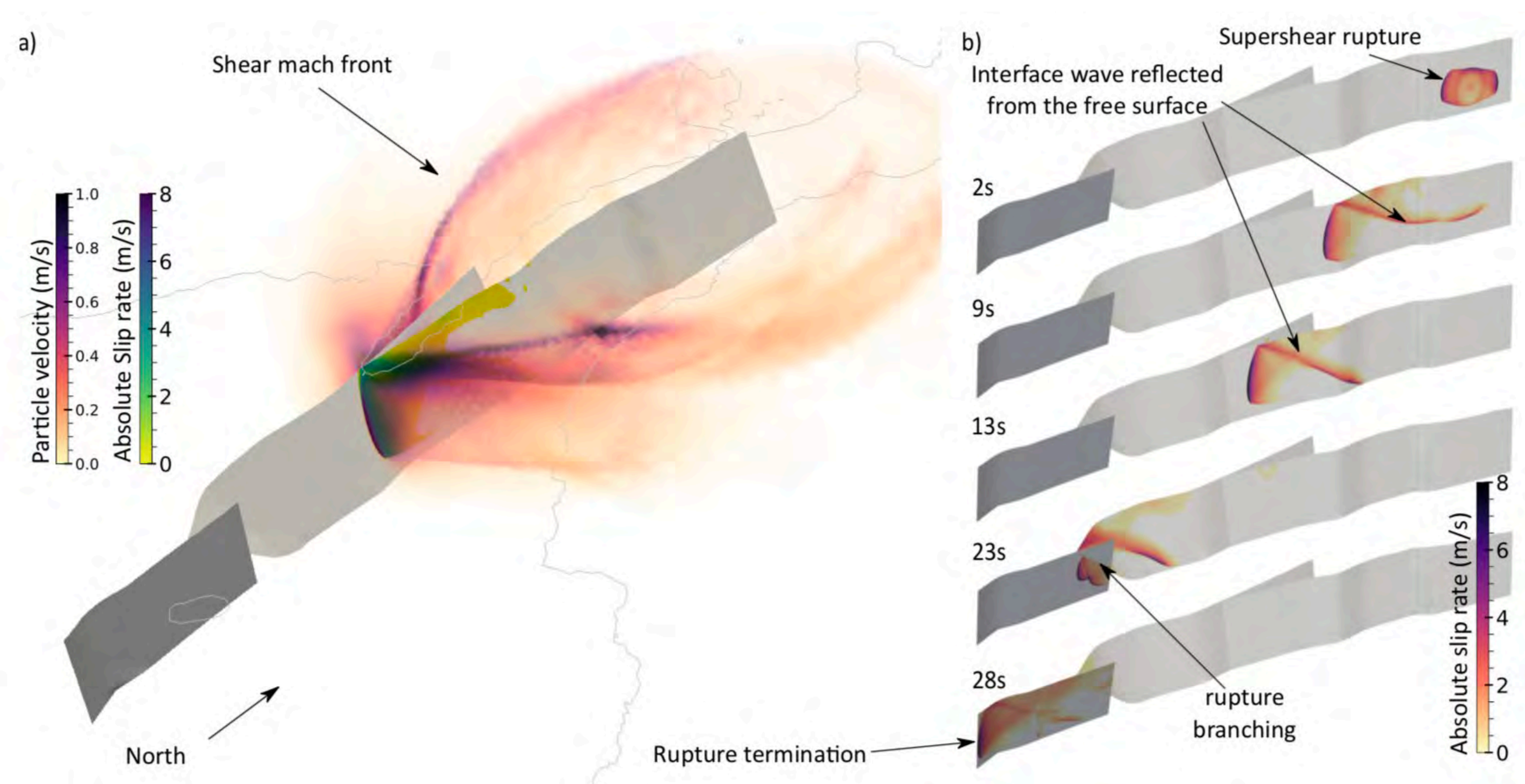


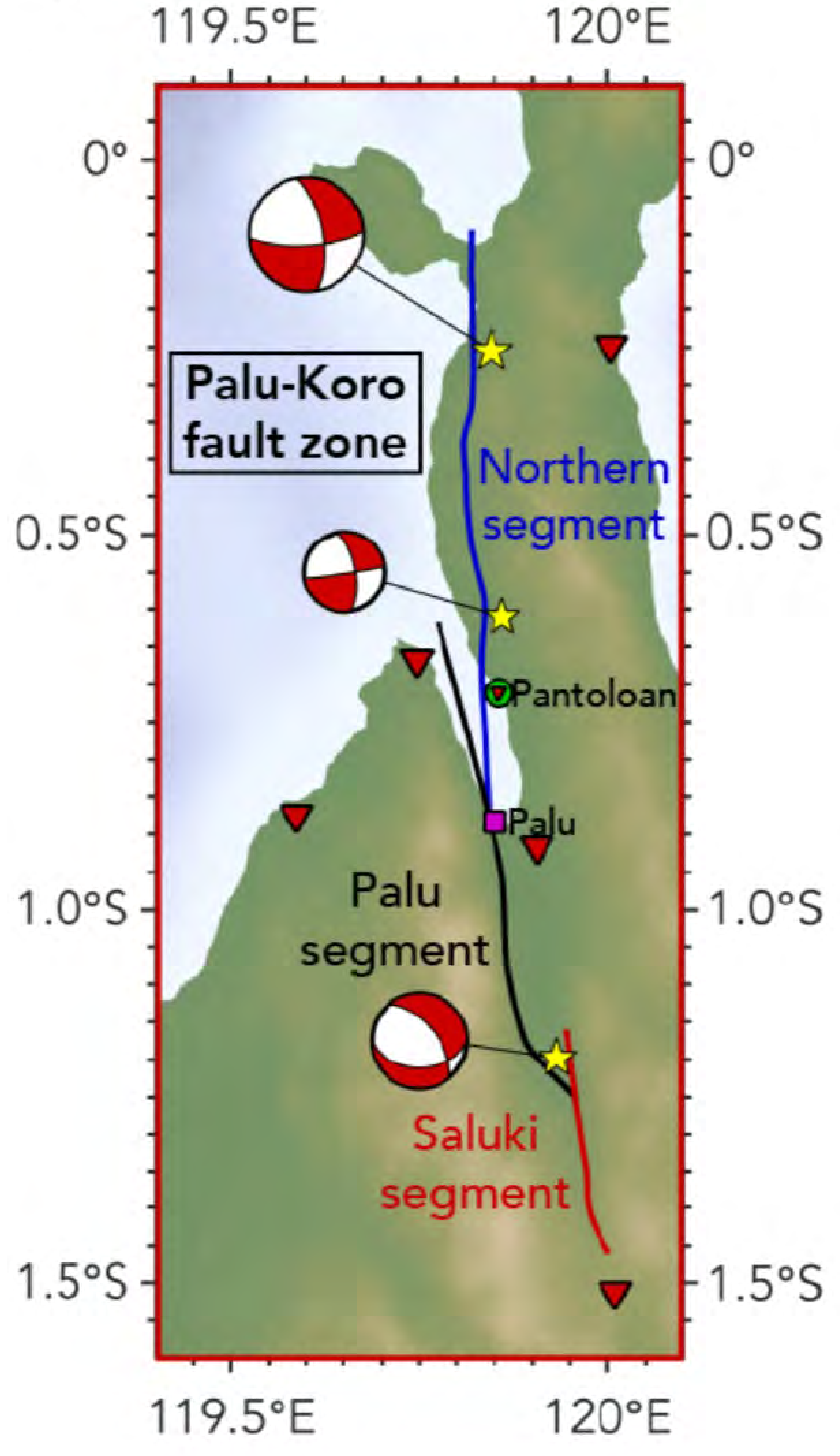
Townend et al., 2012

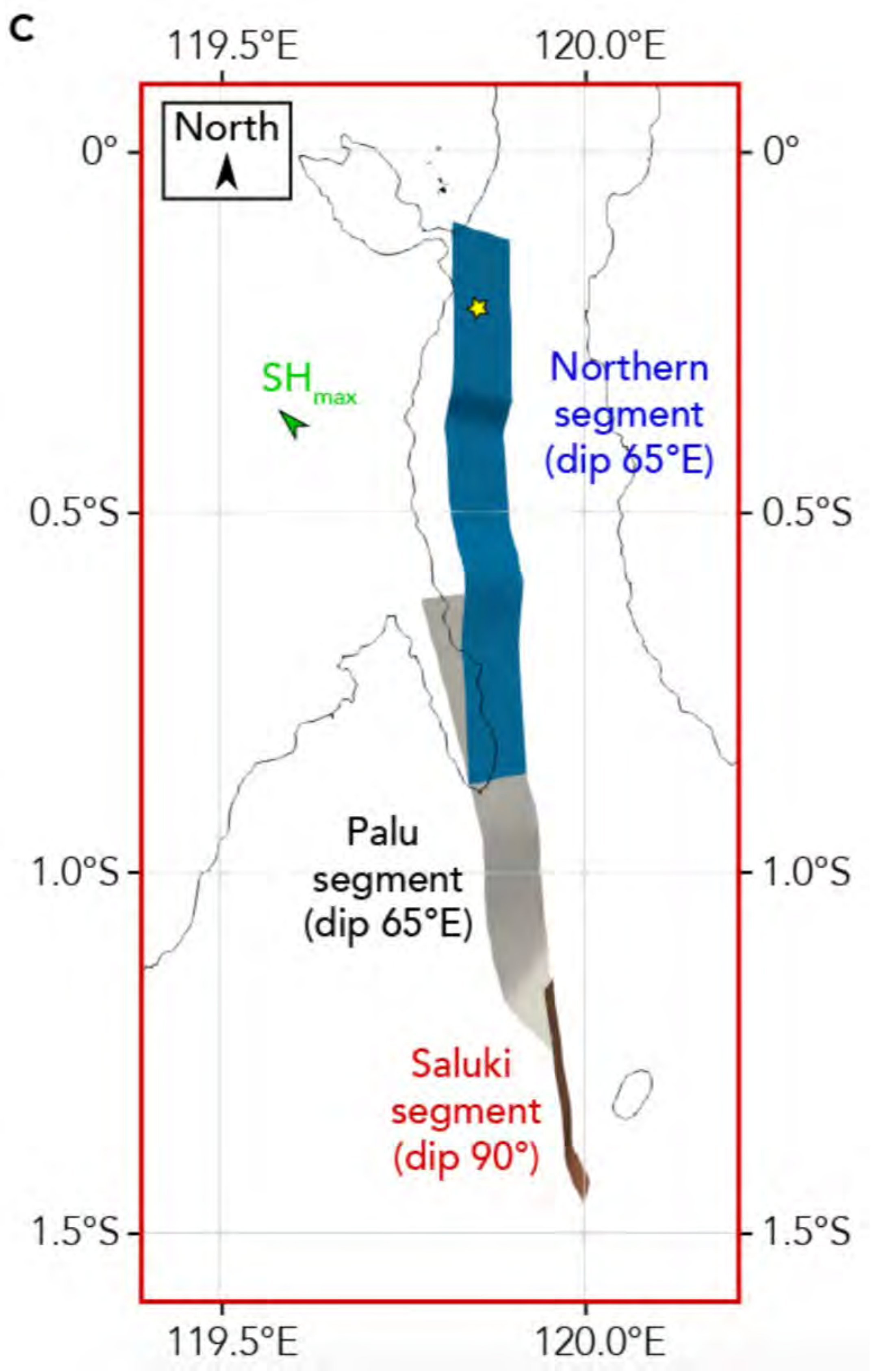
Dynamic rupture **earthquake simulation**

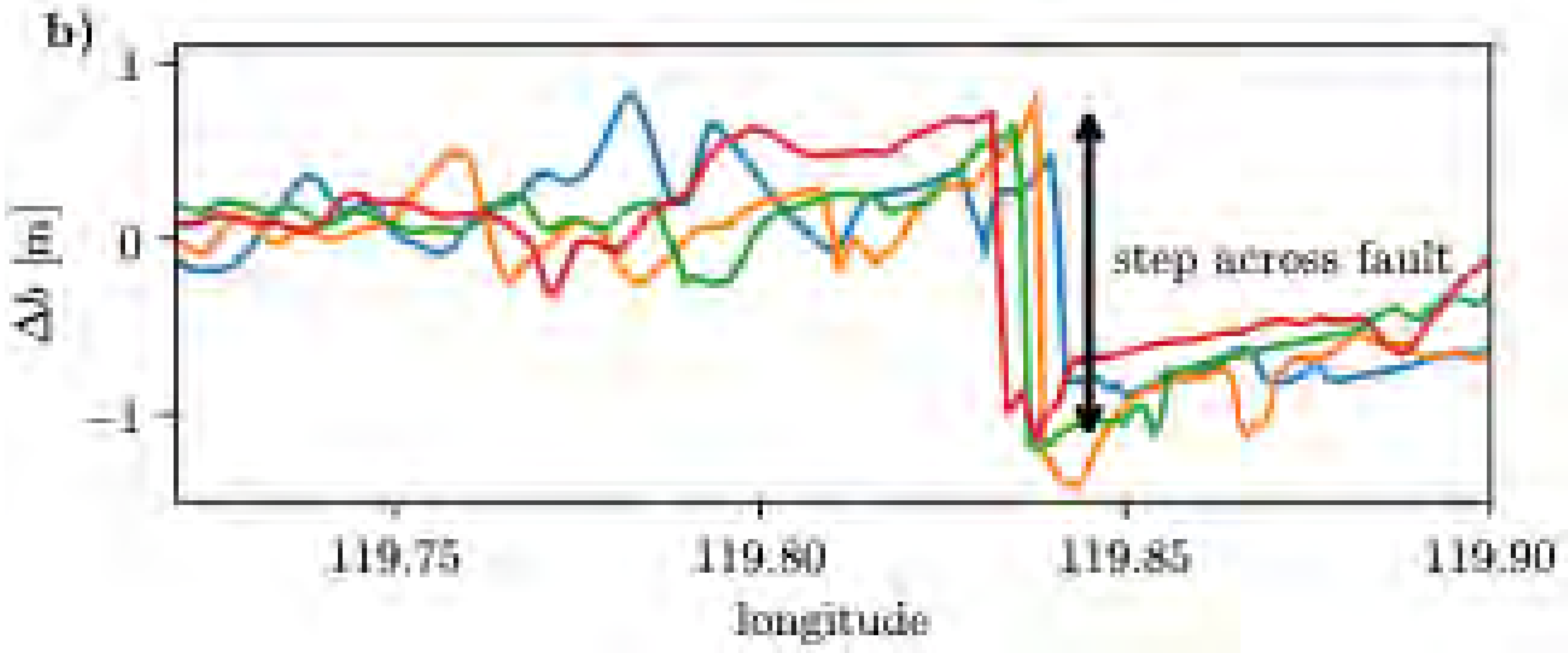
Physics-based complement to empirical seismic hazard assessment

For example: Few weeks after the Sept. 2018 Palu-Koro earthquake and tsunami dynamic rupture earthquake ground displacements alone are shown to be sufficient to generate the observed tsunami within Palu Bay, Sulawesi, Indonesia









(Ulrich et al., 2019, https://eartharxiv.org/3bwqa/)

Dynamic rupture
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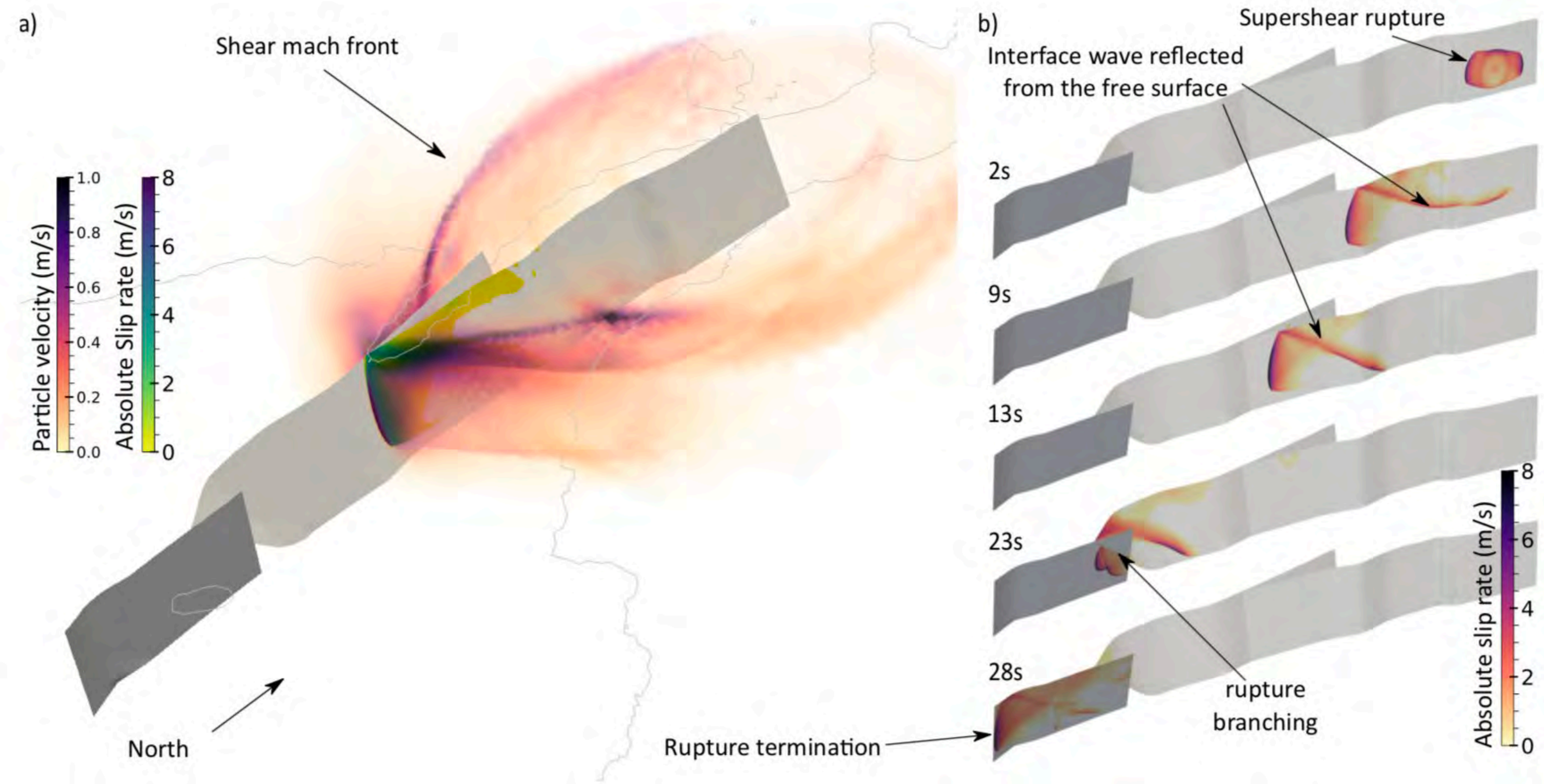
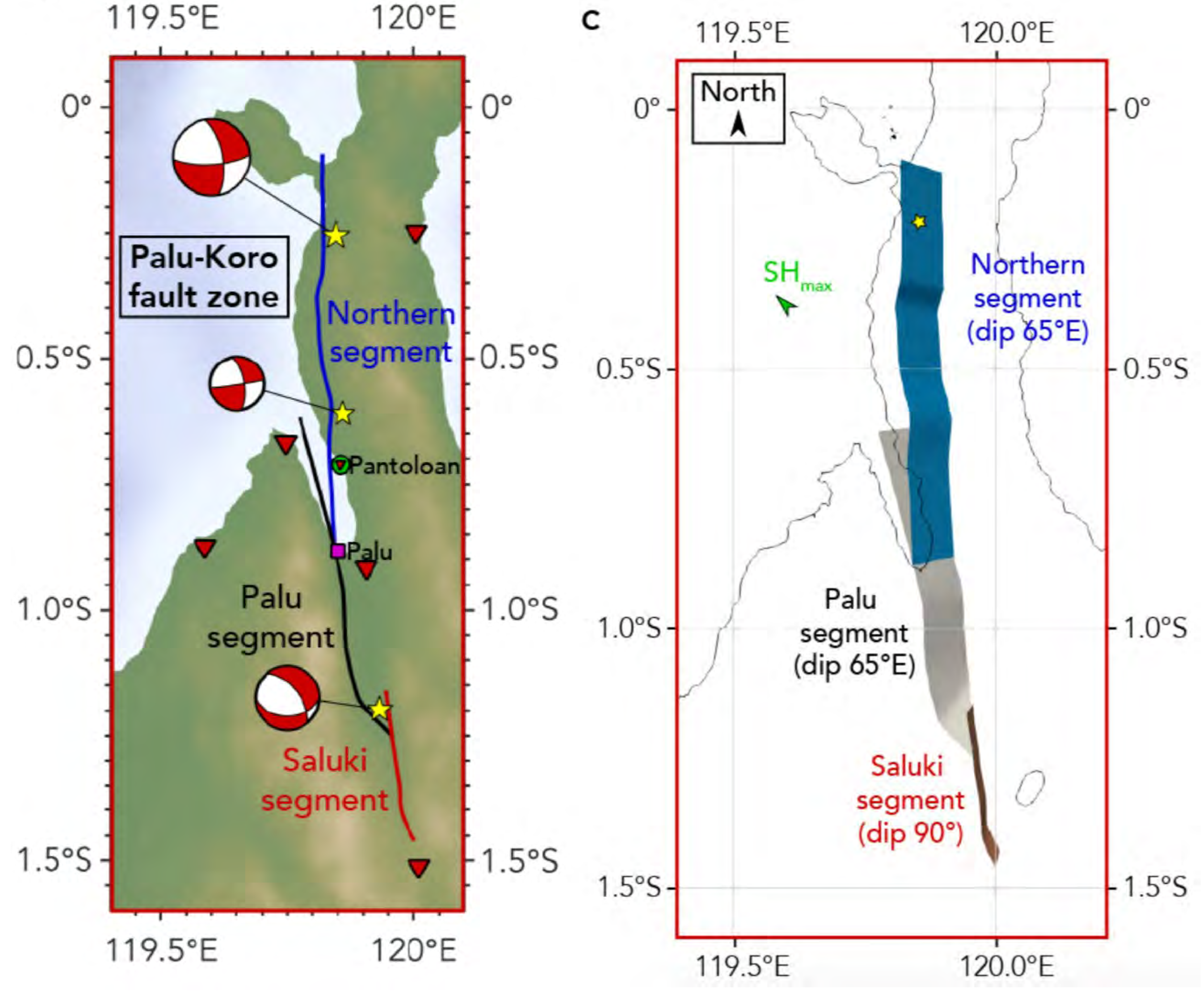




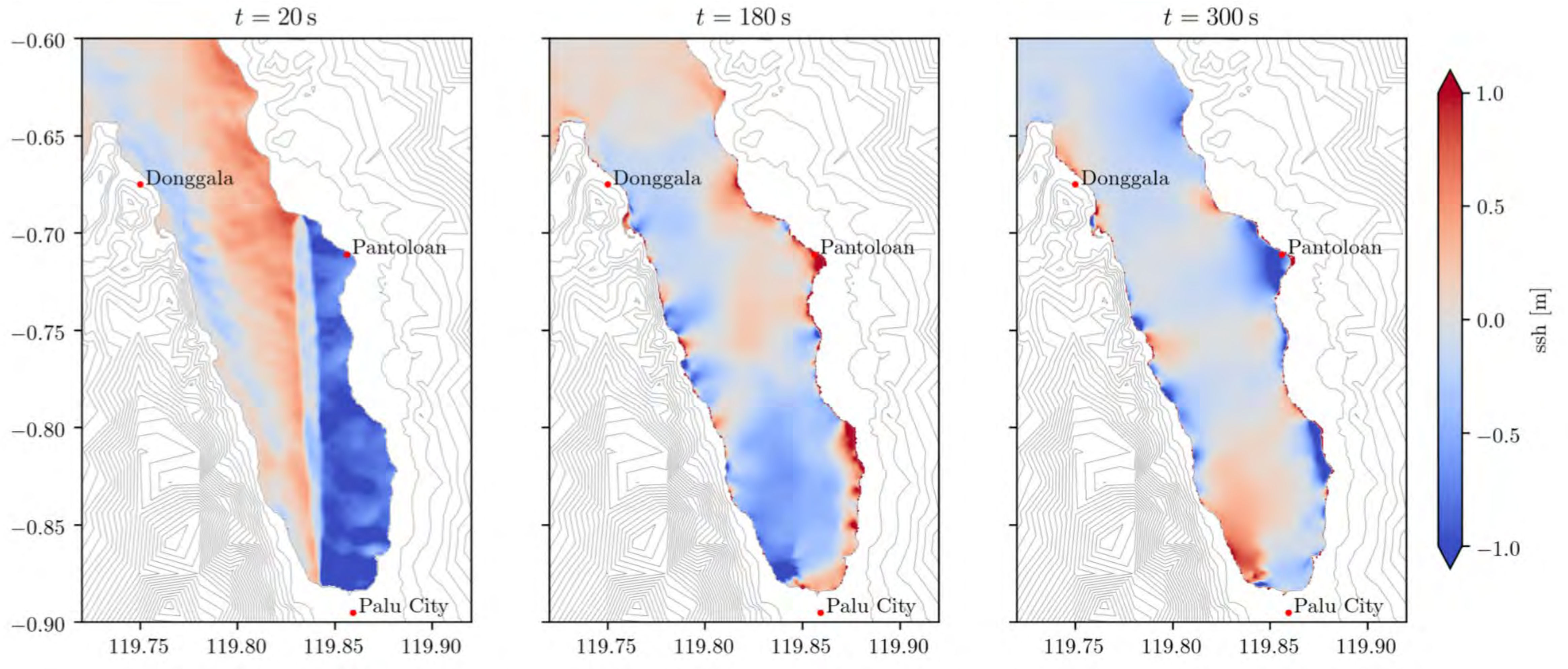
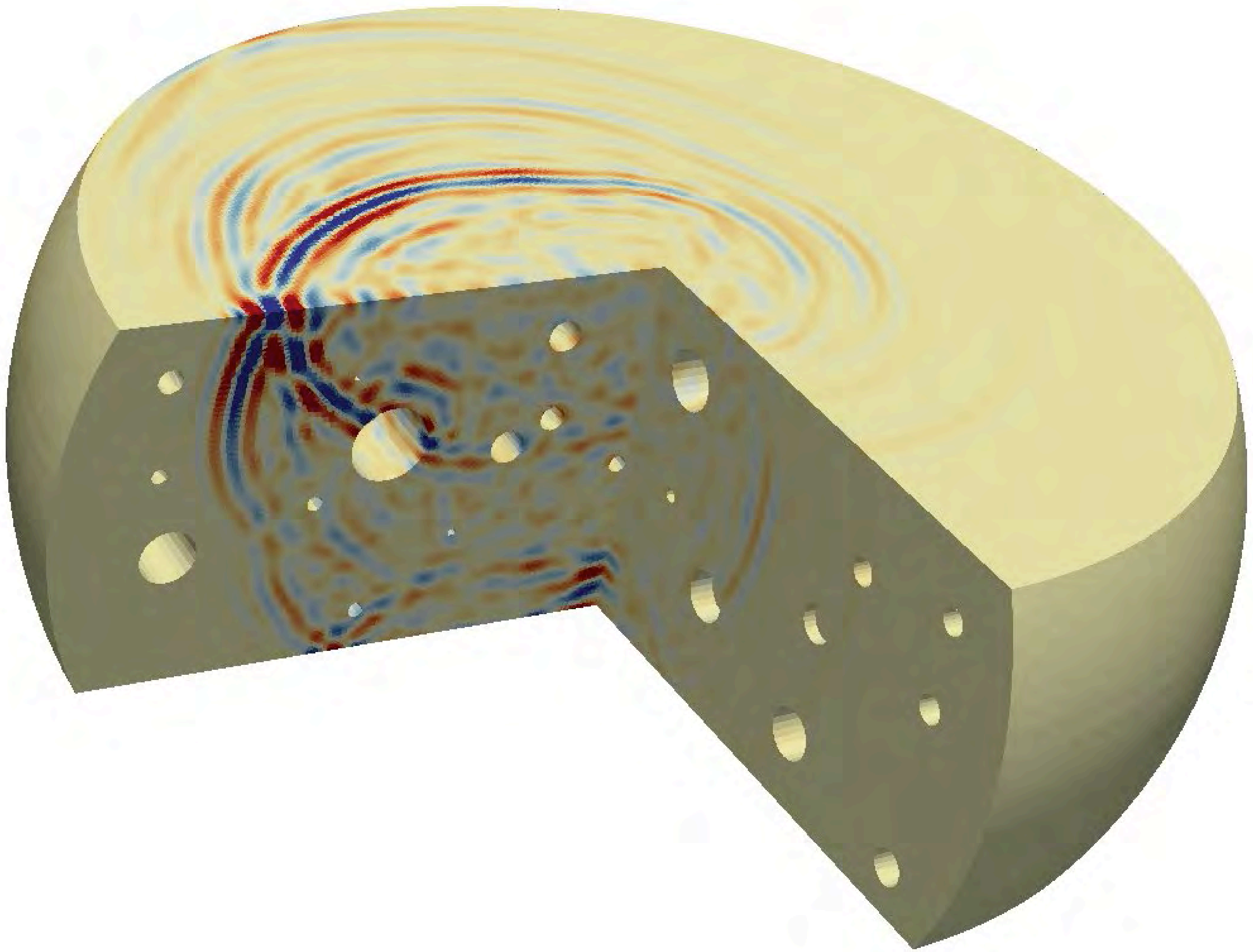
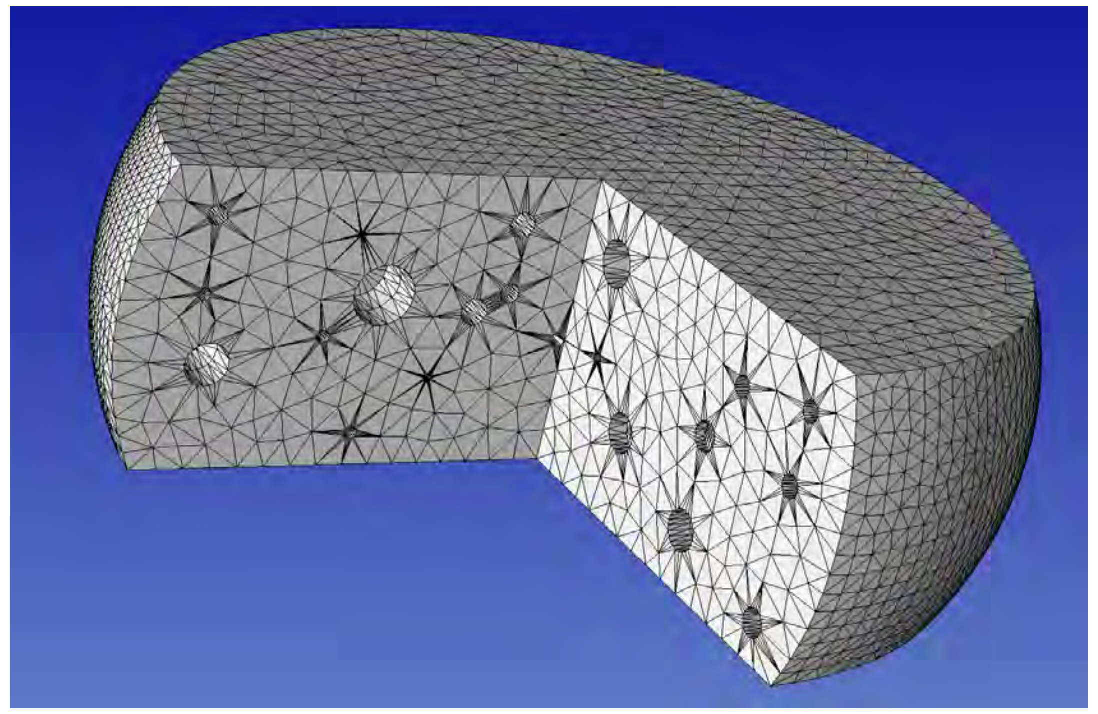


Fig. 9 Snapshots of the tsunami simulation at 20 s, 180 s and 300 s (left to right), showing only the area of Palu Bay.

(Ulrich et al., 2019, https://eartharxiv.org/3bwqa/)

Change of scales





Change of scales - Application to reservoir scales towards physics-based seismic hazard assessment (FRAGEN project)

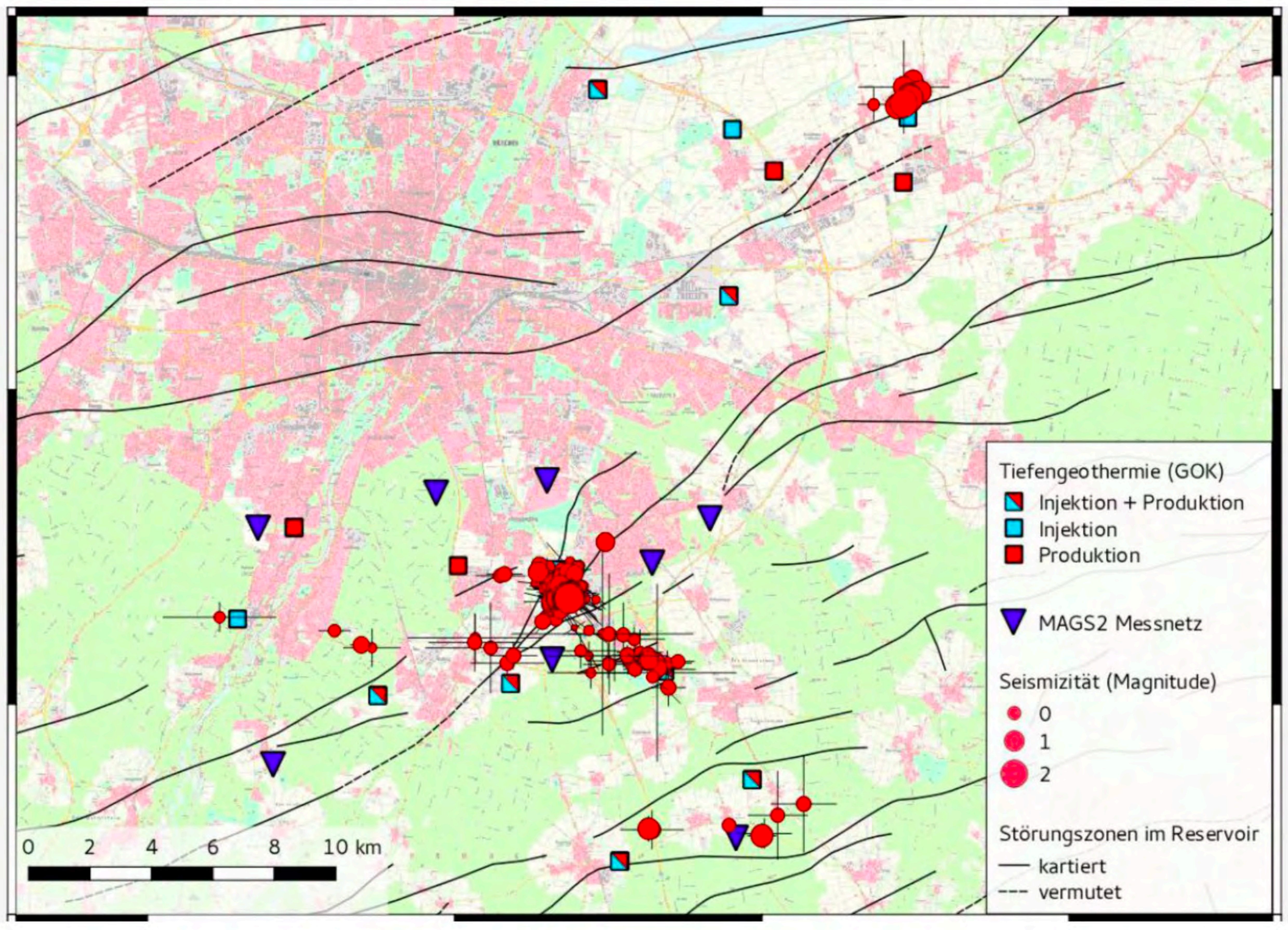


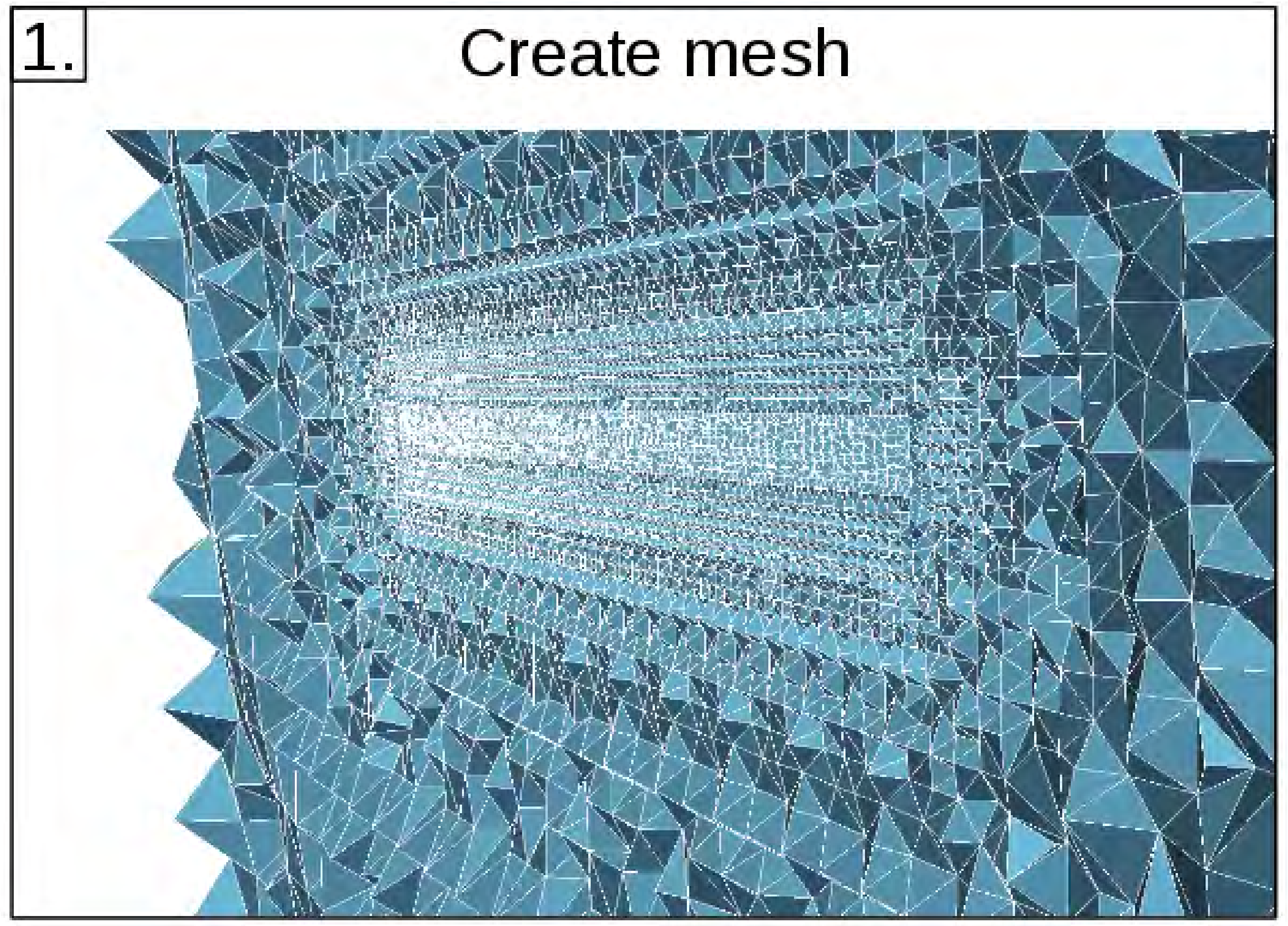
Fig. 5: Megies, Wassermann, 2016, - "Praxisforum Geothermie Bayern", Oktober 2017pers. comm. Megies 2017. Fault traces from Bayerisches Staatsministerium für Wirtschaft, Infrastruktur, Verkehr und Technologie. 2010. Bayerischer Geothermieatlas. München

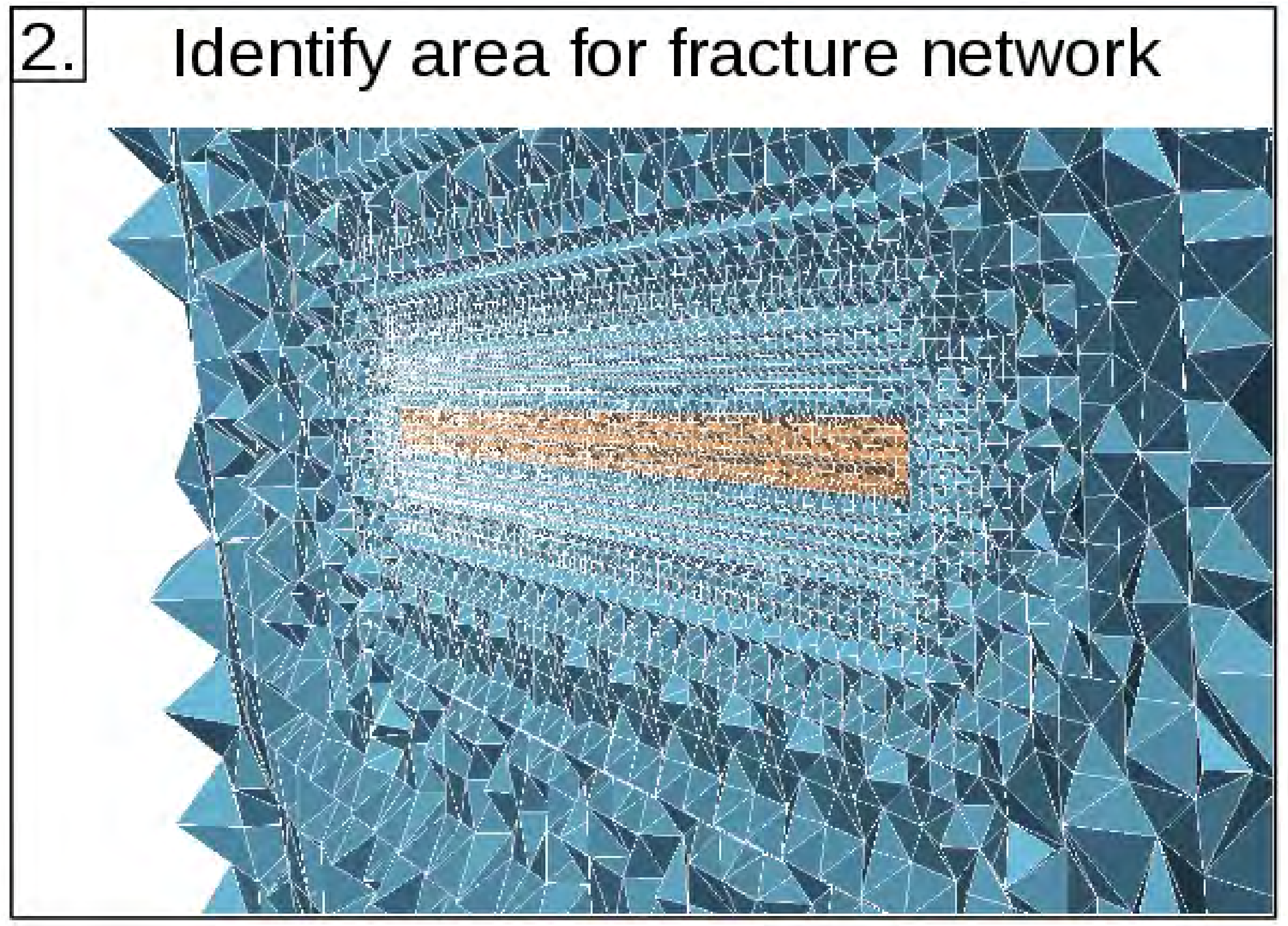
"Given the occurrence of a seismic event, what are the driving forces for its strength?"

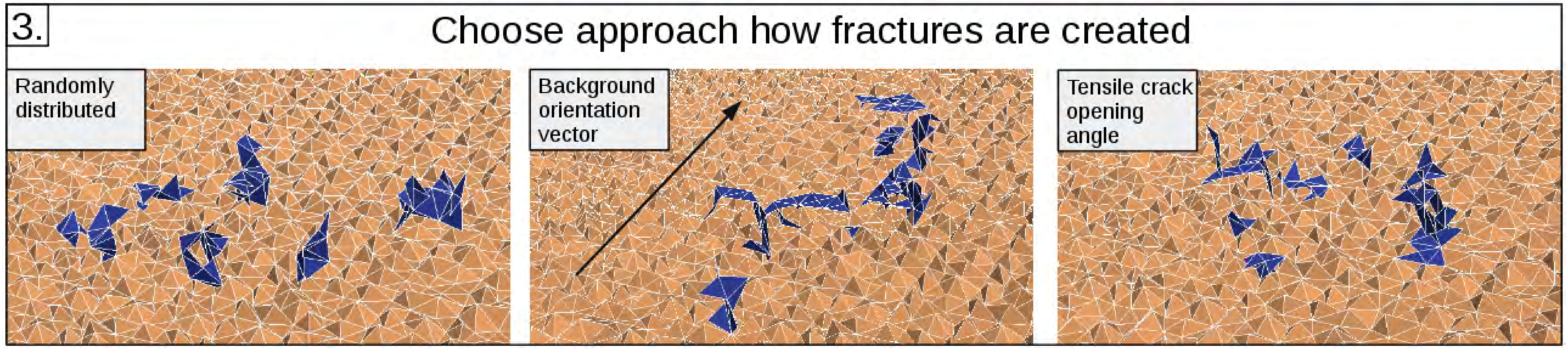
"How are fault- or operation-specific parameters associated with the maximal magnitudes of seismic events?"

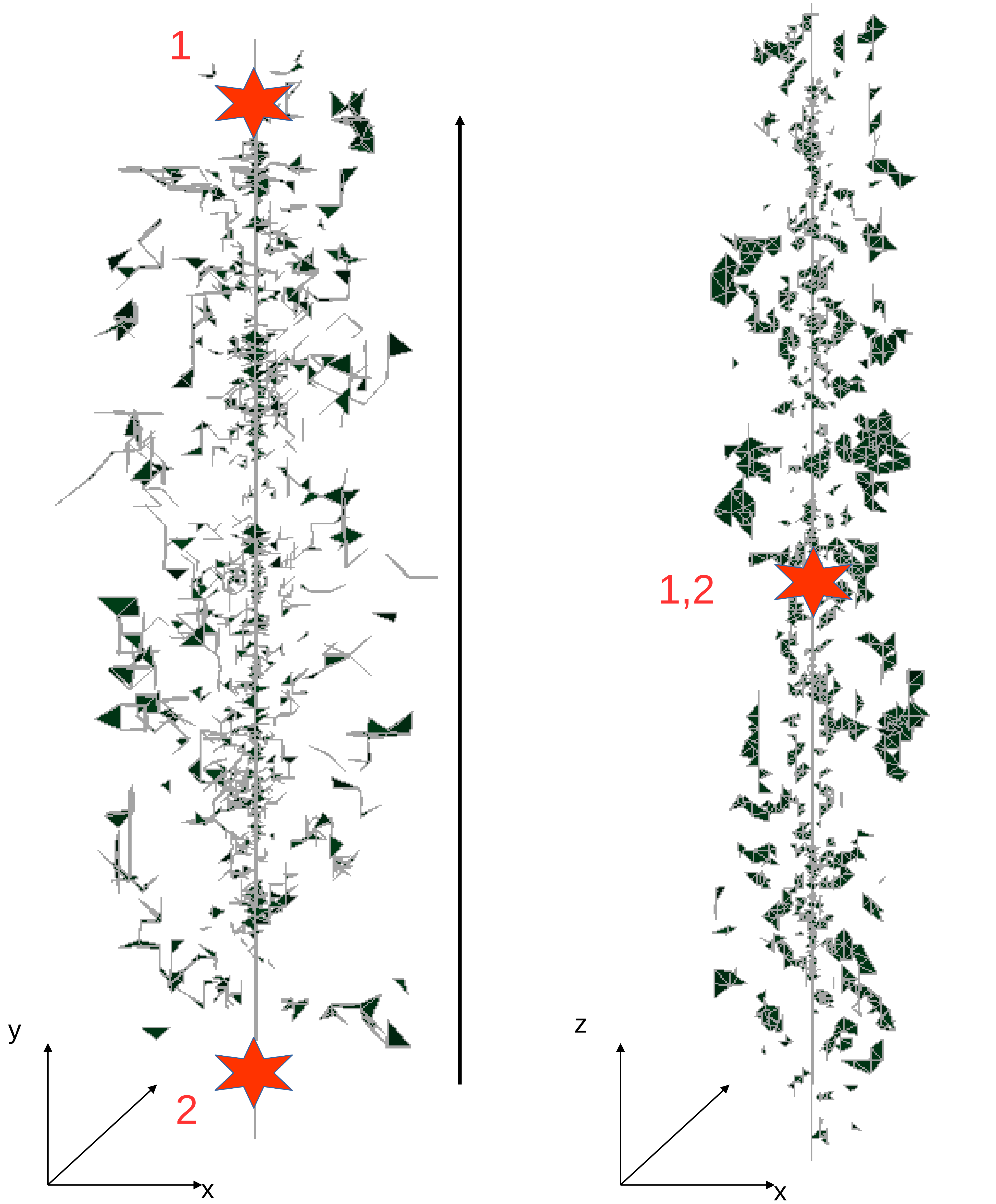
Fracture activation in geo-reservoirs

- We study the physics of (induced) earthquakes in complex fault networks which are at geo-reservoir scales inherently **geometrically complex**







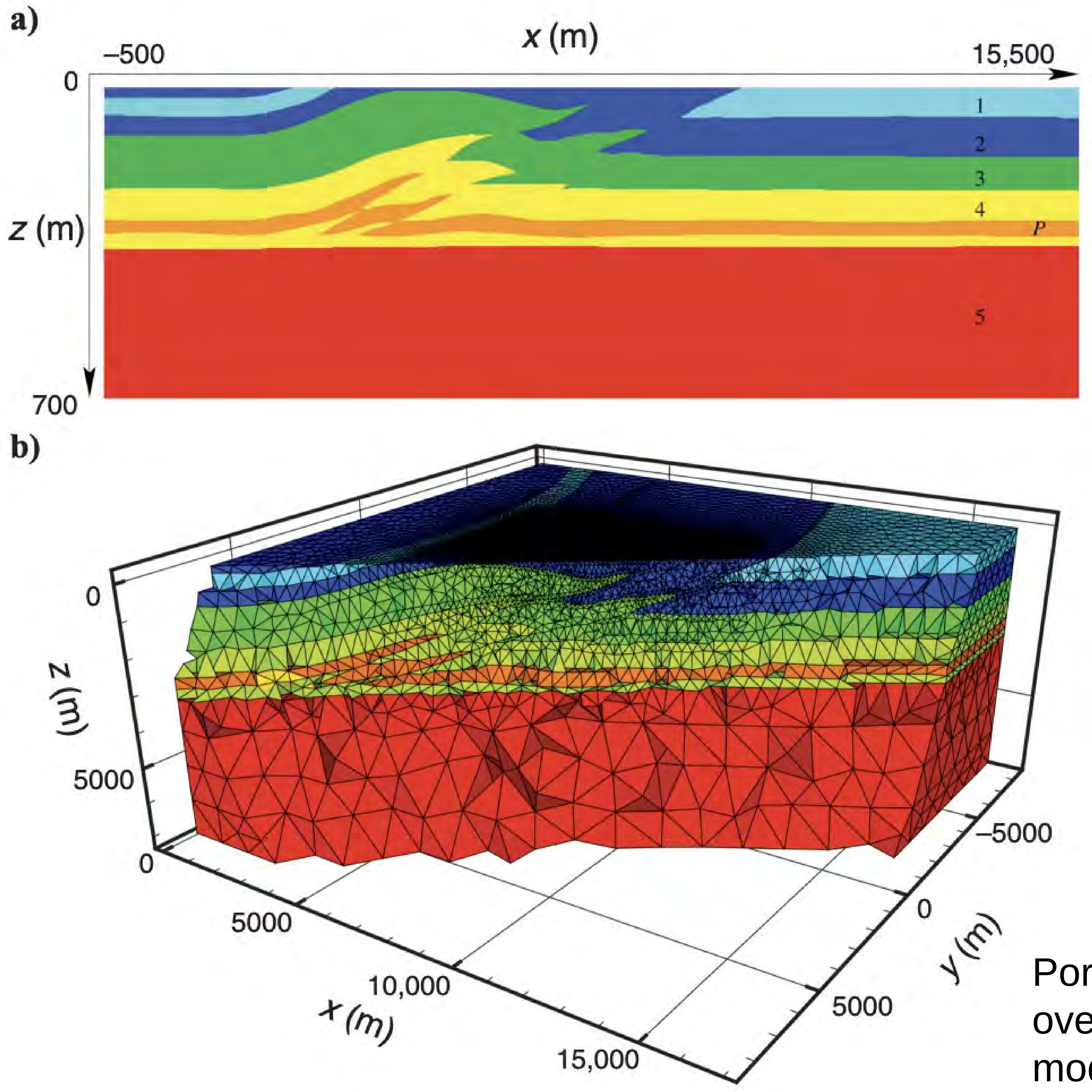


Statistical fracture network for dynamic rupture simulations from physics-based Markov Chain Monte Carlo approach (Sebastian Anger, POSTER P2-10 3320)

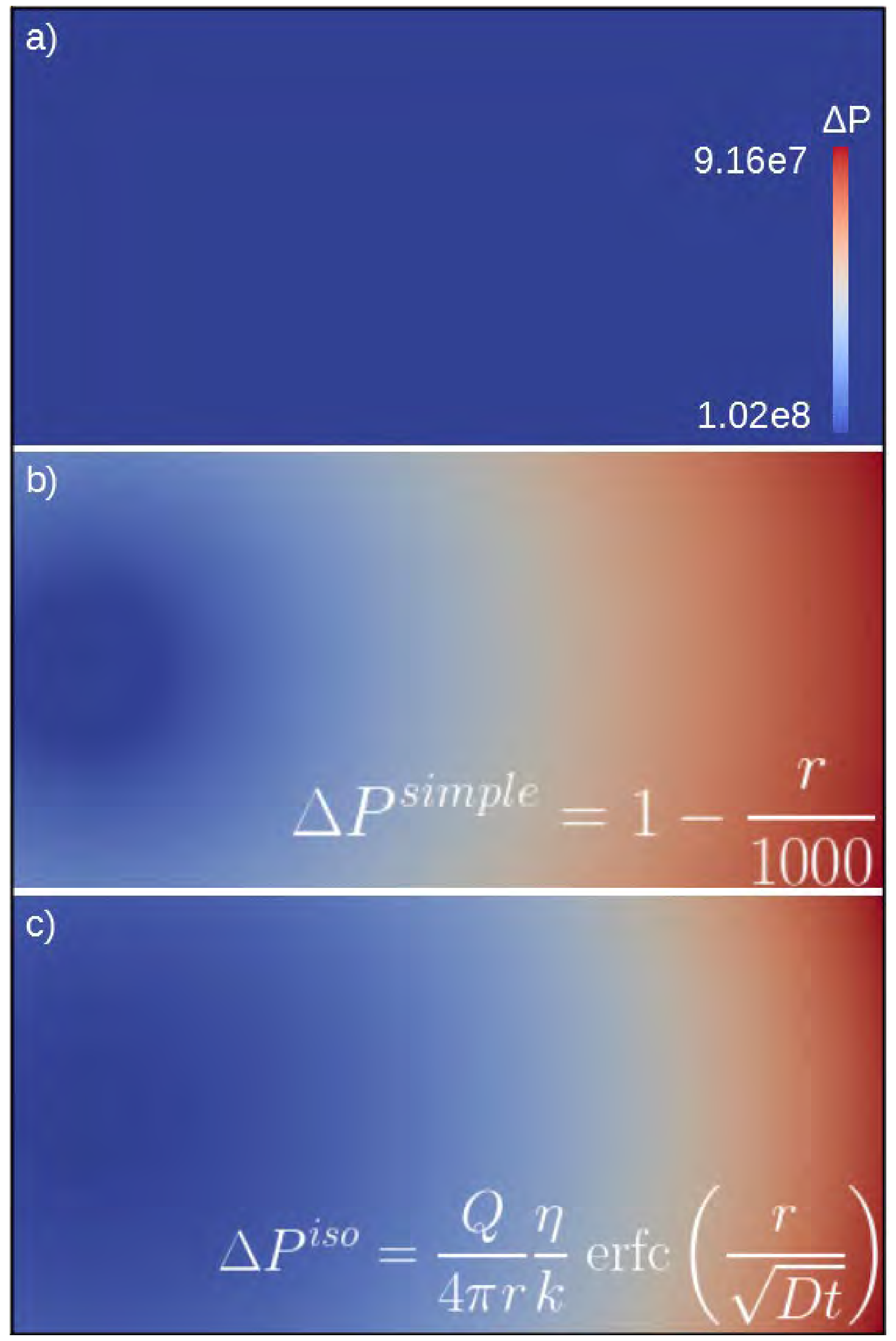
Rice & Cleary (1976): Some basic stress diffusion solutions for fluid-saturated elastic porous media with compressible constituents. Rev. Geophys. Space Phys

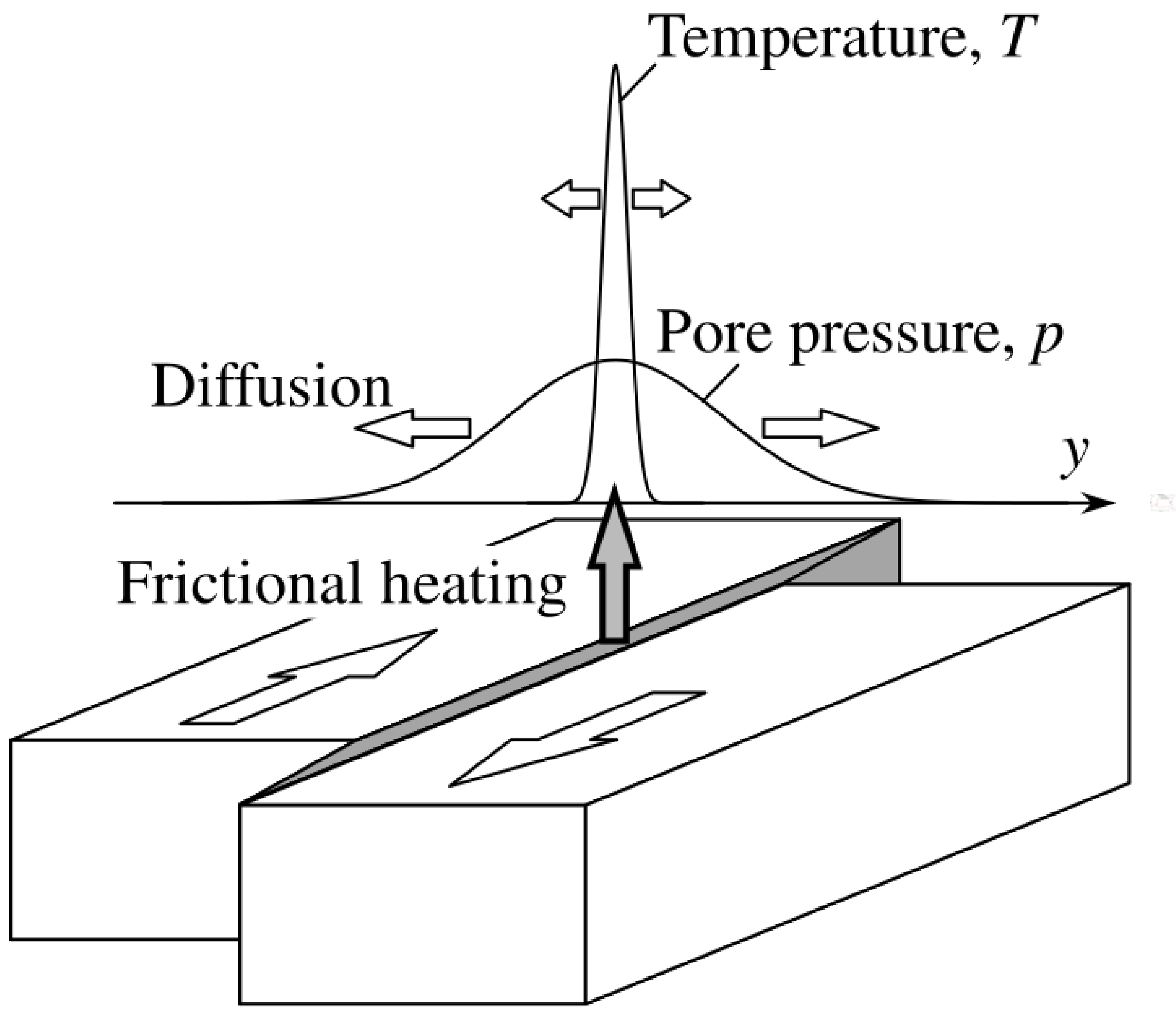
Fracture activation in geo-reservoirs

- We develop methods to study **fault-fluid interaction on-fault and off-fault: thermal pressurisation** frictional weakening, **pressure gradients** combined with **poro-elastic wave propagation**



Poroelastic 3D wave propagation in SEG overthrust model of Aminzadeh et al., 1997 modeled with SeisSol (de la Puente et al., 2008, now work with Martin Galis)





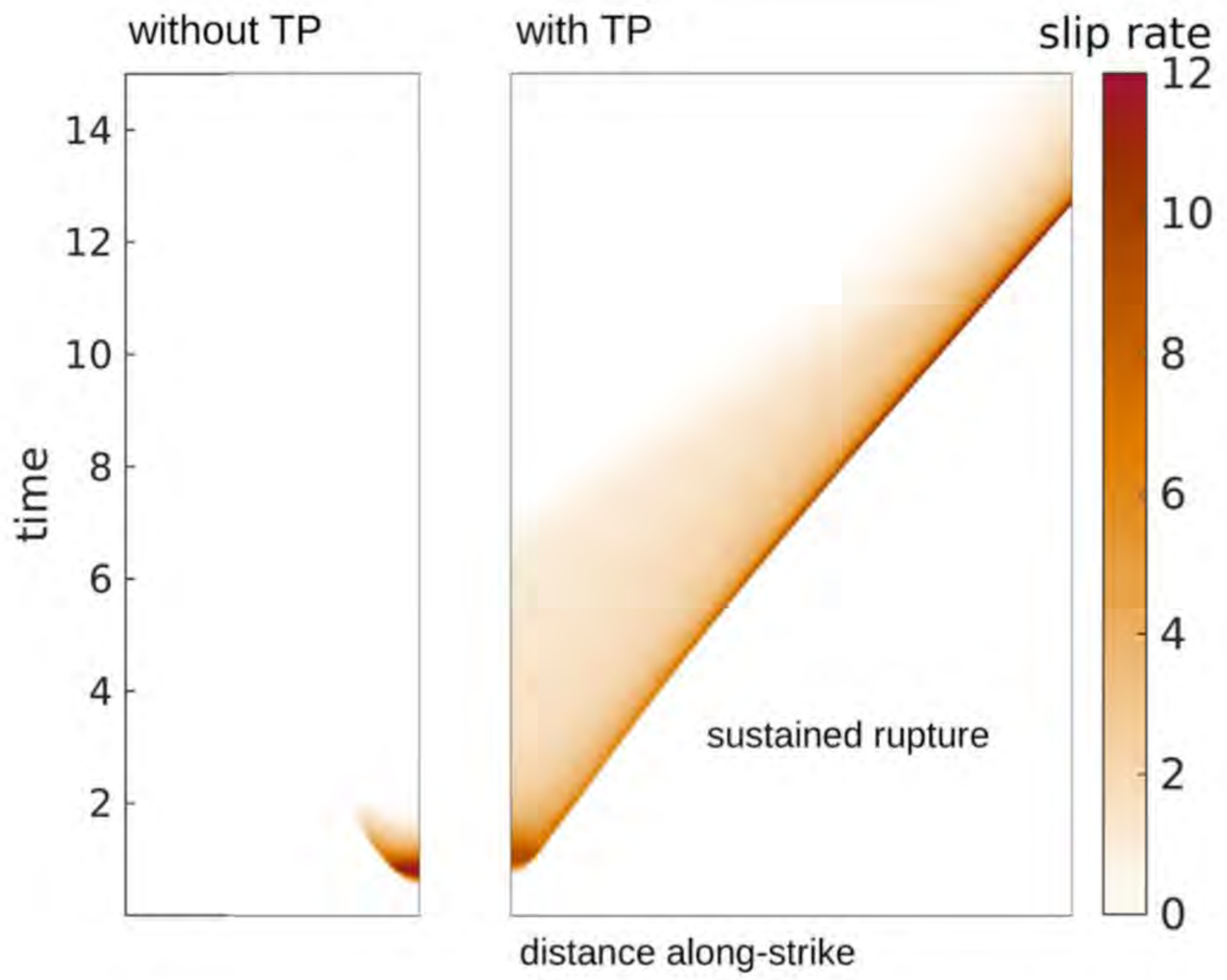


Fig 3.: Slip rate over time and along-strike for a 2D strike-slip scenario using the software SeisSol. Rupture quickly dies out without thermal pressurization (TP, left) but can be sustained for the same initial conditions when we include TP (right), taken from Wollherr et al. (2018a).

Fracture activation in geo-reservoirs

- Case-study: **The 2017 Pohang ML5.4 earthquake**
- Dynamic rupture models based on multiple faults of Kim et al., 2018; Grigoli et al., 2018
- Source complexity and strong non-DC component may be related to changes in timing/azimuth/rupture directivity of complex faults (cf. Grigoli et al., 2018)

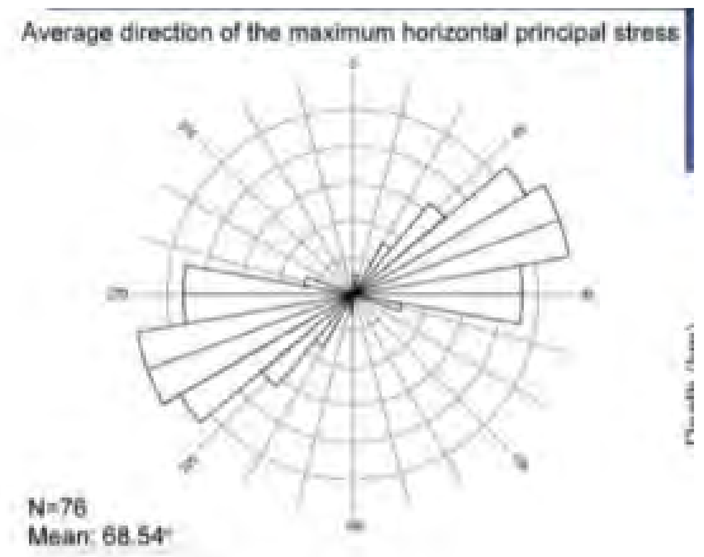
strong non-DC component

Moment Tensor

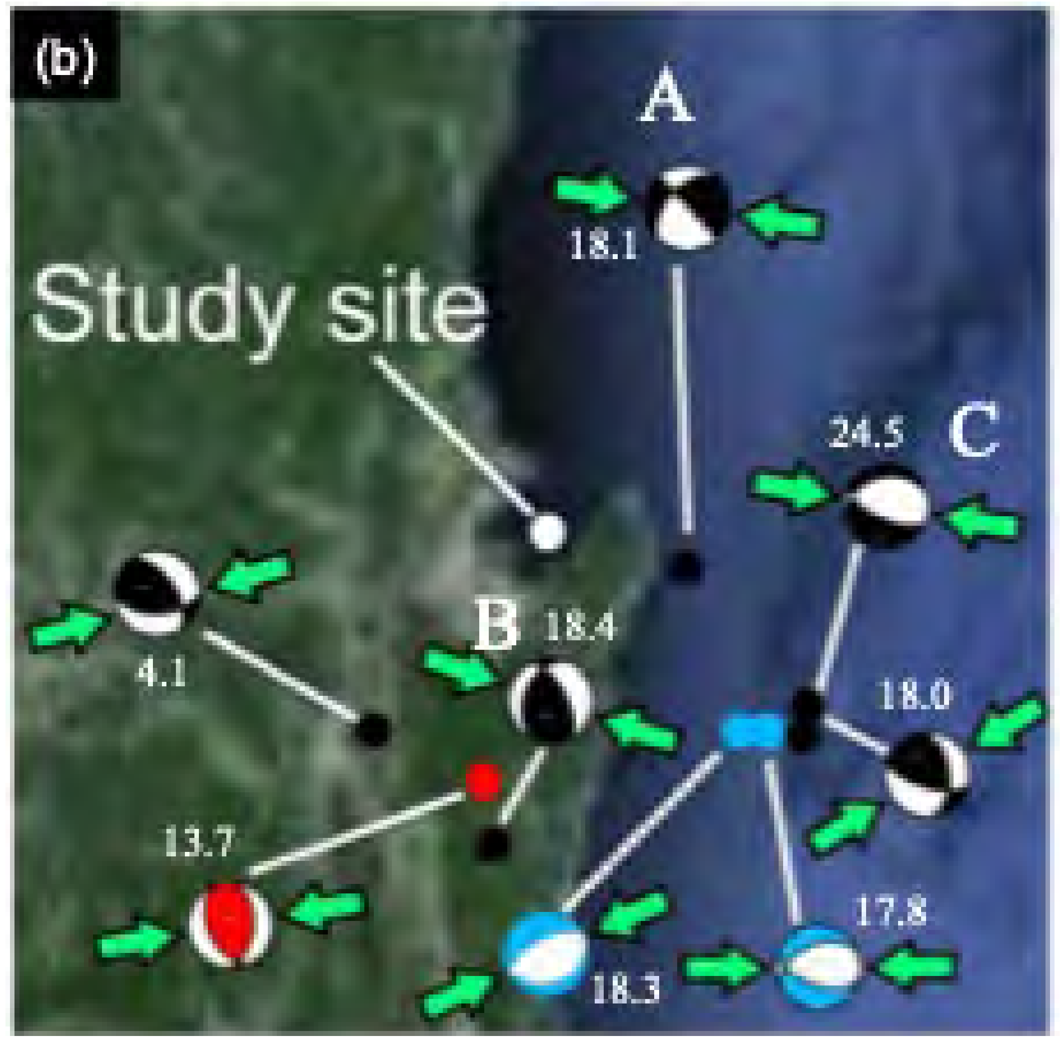
Fault Plane Solution

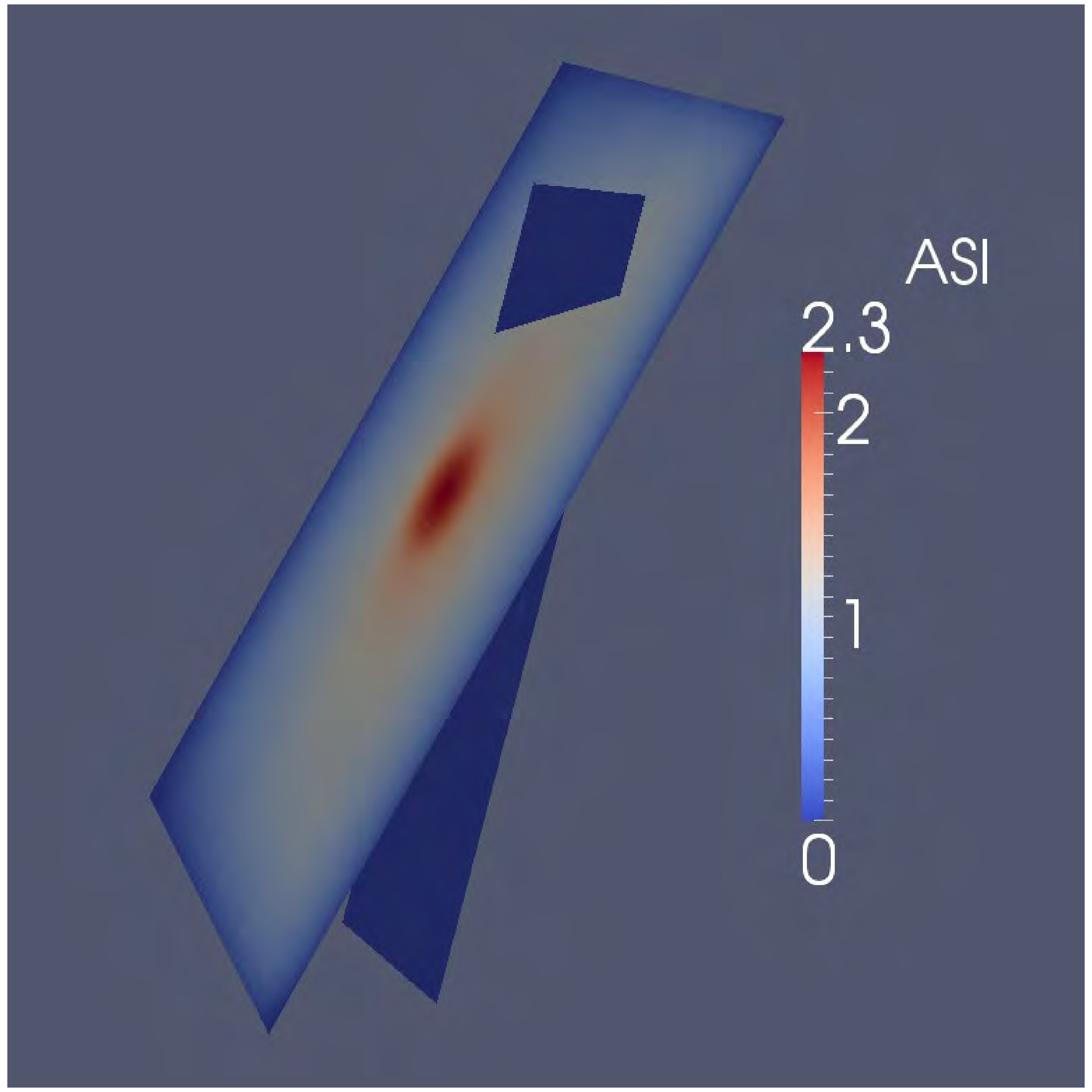
Grigoli et al, 2018

SHmax~70

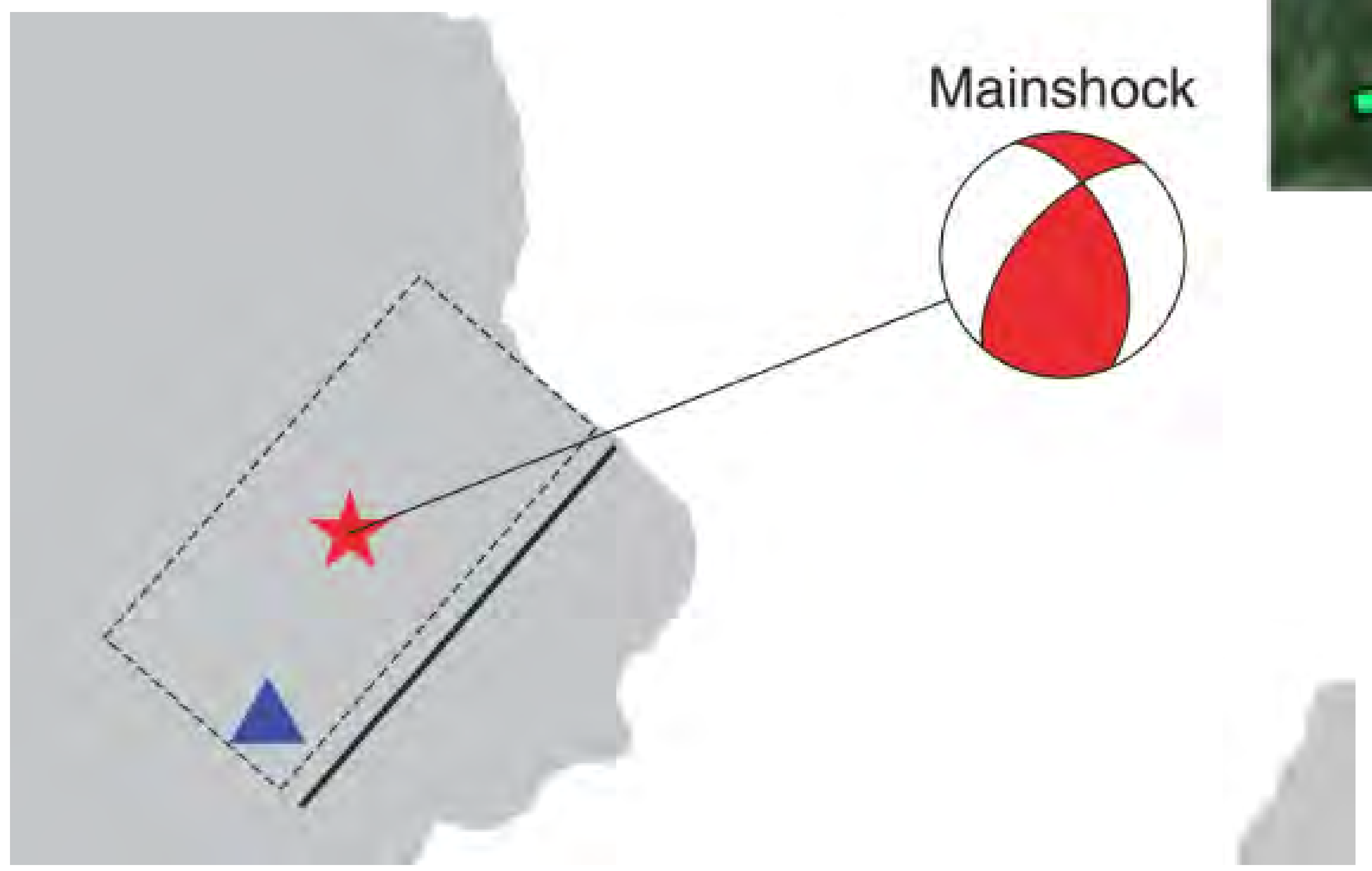


Lee et al., 2017





SW-NE faults dipping NW
Moment tensor suggest strike-slip/thrusting (Song and Lee, 2019)



Fracture activation in geo-reservoirs

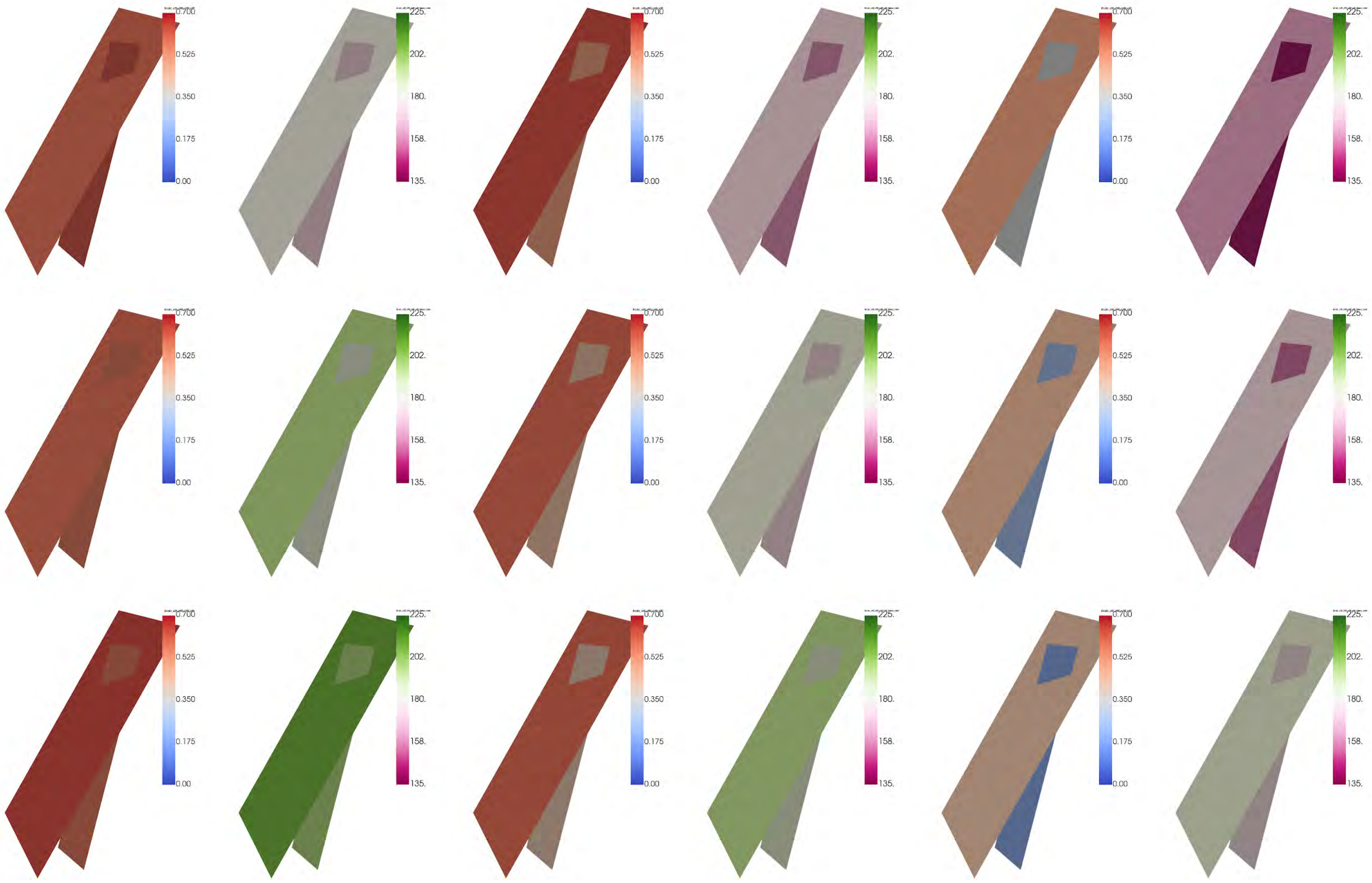
- Assuming an Andersonian stress regime, high fluid pressure

SHmax=55° SHmax=70° SHmax=85°

transpression

pure-shear

transtension



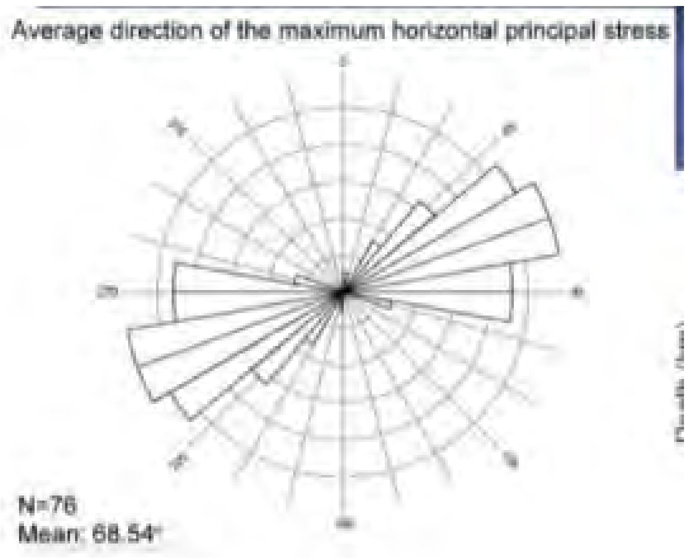
Rake of shear tractions
Thrust-faulting component
Normal-faulting component

Red means favourable for spontaneous rupture propagation

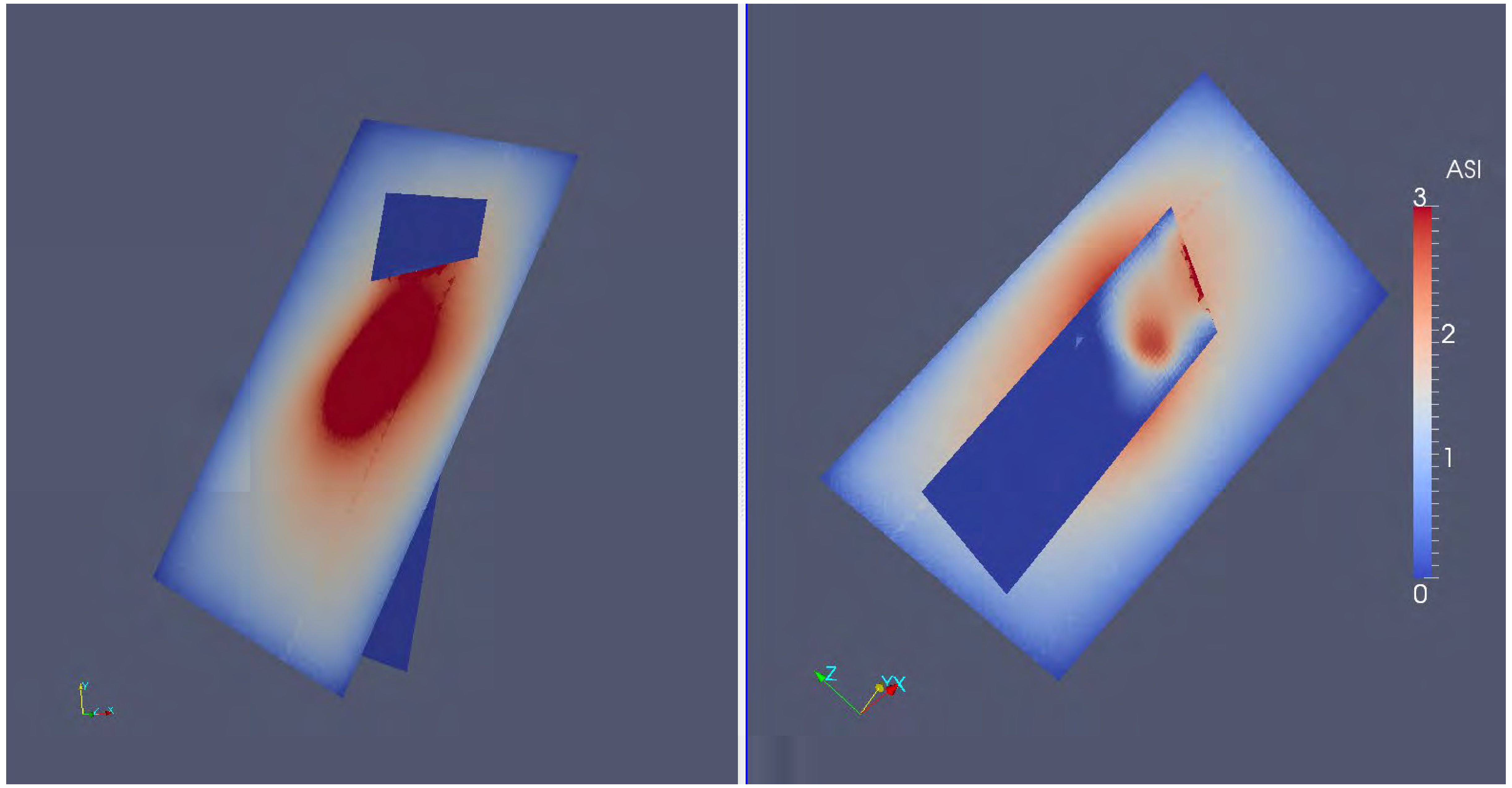
Fracture activation in geo-reservoirs

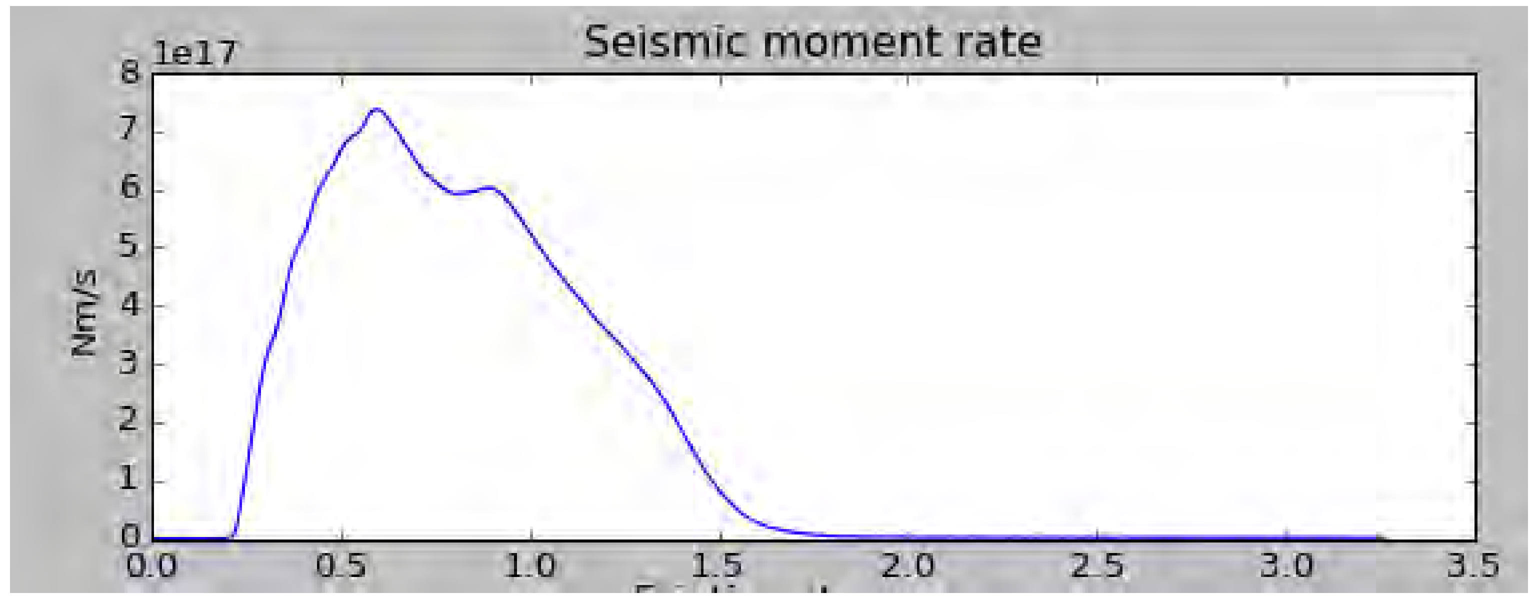
- Case-study: **The 2017 Pohang ML5.4 earthquake**
- **A fault geometry based on Kim et al., 2018 and regional SHmax estimates seems incompatible for dynamic rupture thrust faulting**
- **Uniform increase in pore pressure would not change this picture (only acting on normal stresses)**

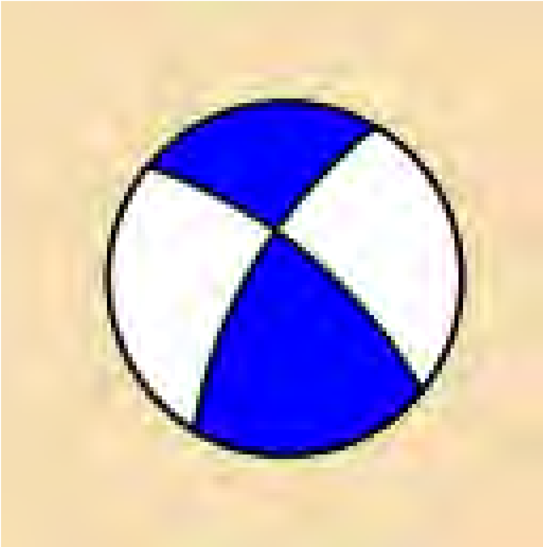
SHmax~70



Lee et al., 2017



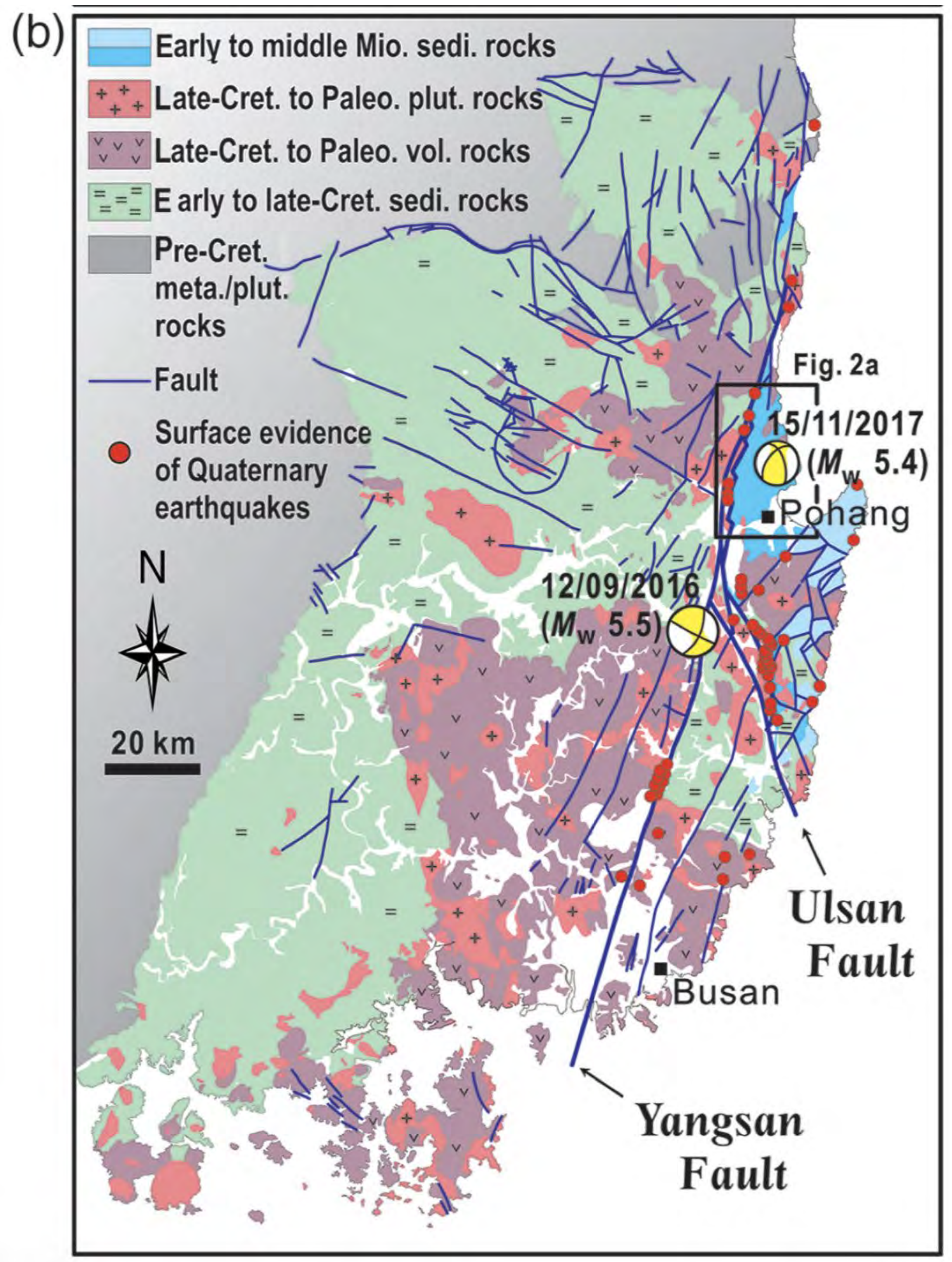




- **Different fault geometry, local stress variations or stress concentrations (e.g. creep induced) will likely change rupture dynamics**

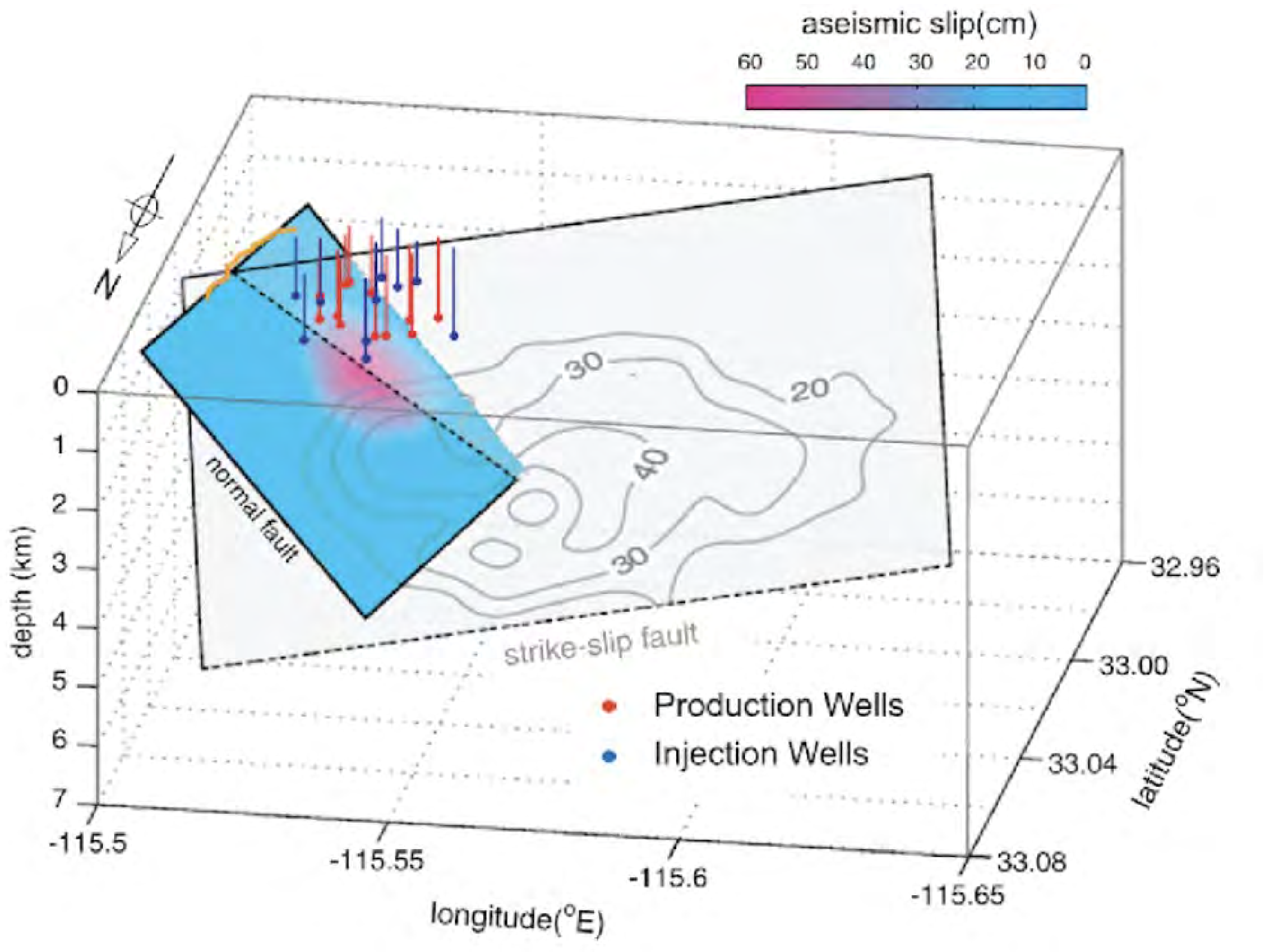
- Preliminary **fault reconstruction** using ACLUD (Wang et al., 2013) produces two fault planes, with the secondary fault at larger strike

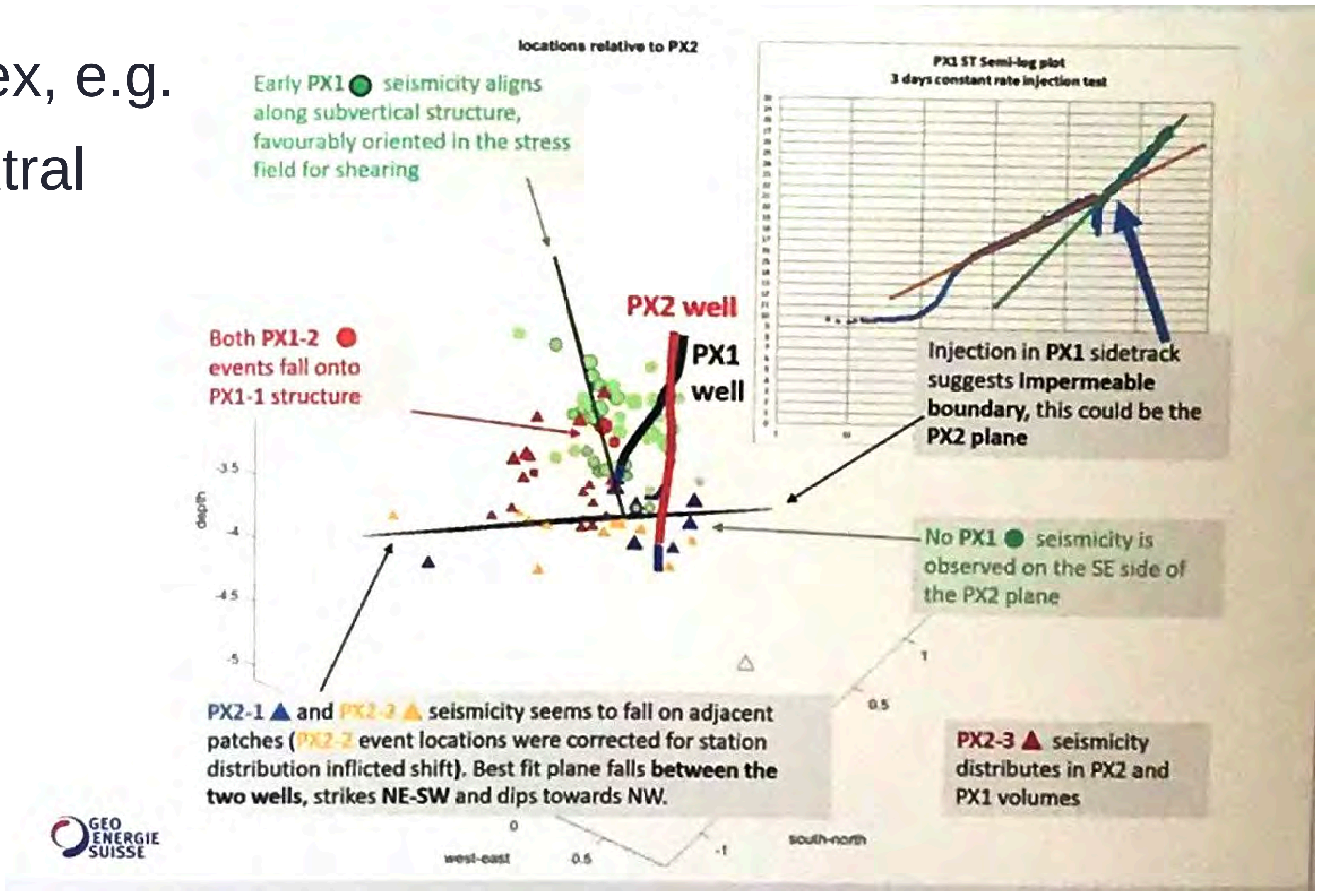
- Local stresses may be complex, e.g. affected by close-by large dextral strike-slip Yangsan Fault



The 2012 Brawley swarm triggered by injection-induced aseismic slip

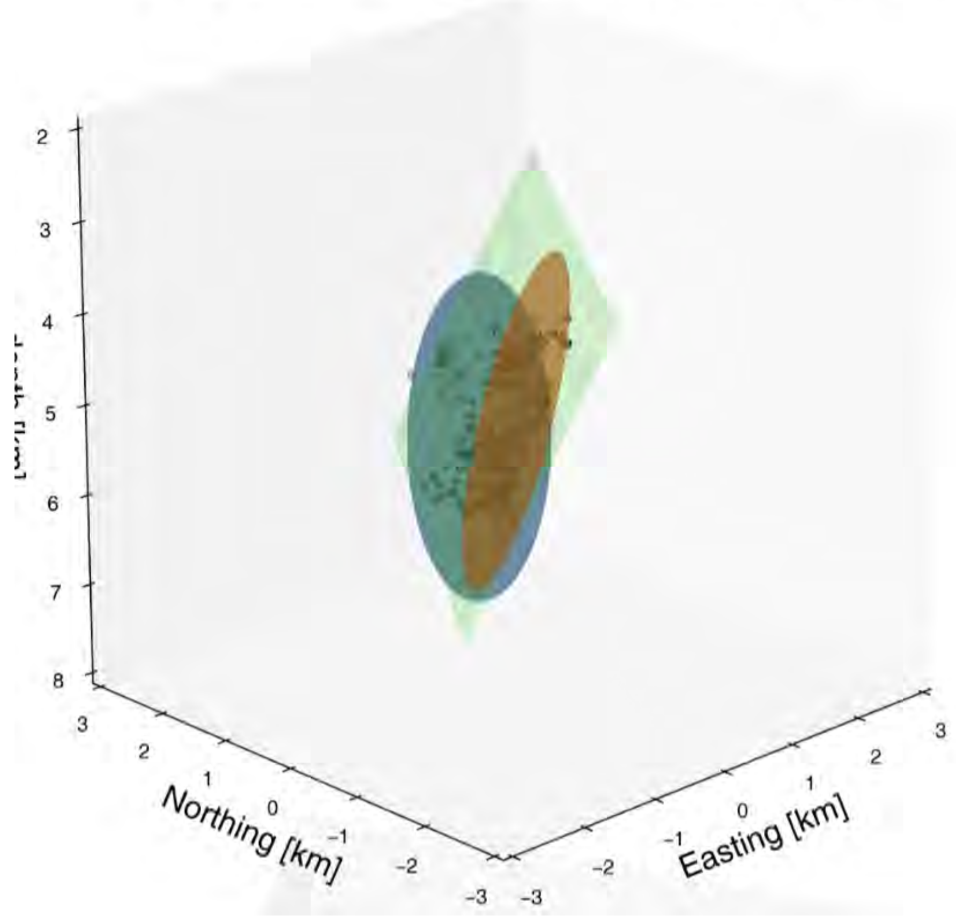
Shengji Wei [a, f], Jean-Philippe Avouac [a], Kenneth W. Hudnut [b], Andrea Donnellan [c], Jay W. Parker [c], Robert W. Graves [b], Don Helmberger [a], Eric Fielding [c], Zhen Liu [c], Frederic Cappa [a, d], Mariana Eneva [e]





Falko Bethmann et al., Poster yesterday

ACLUD algorithm (Wang et al,. 2013)

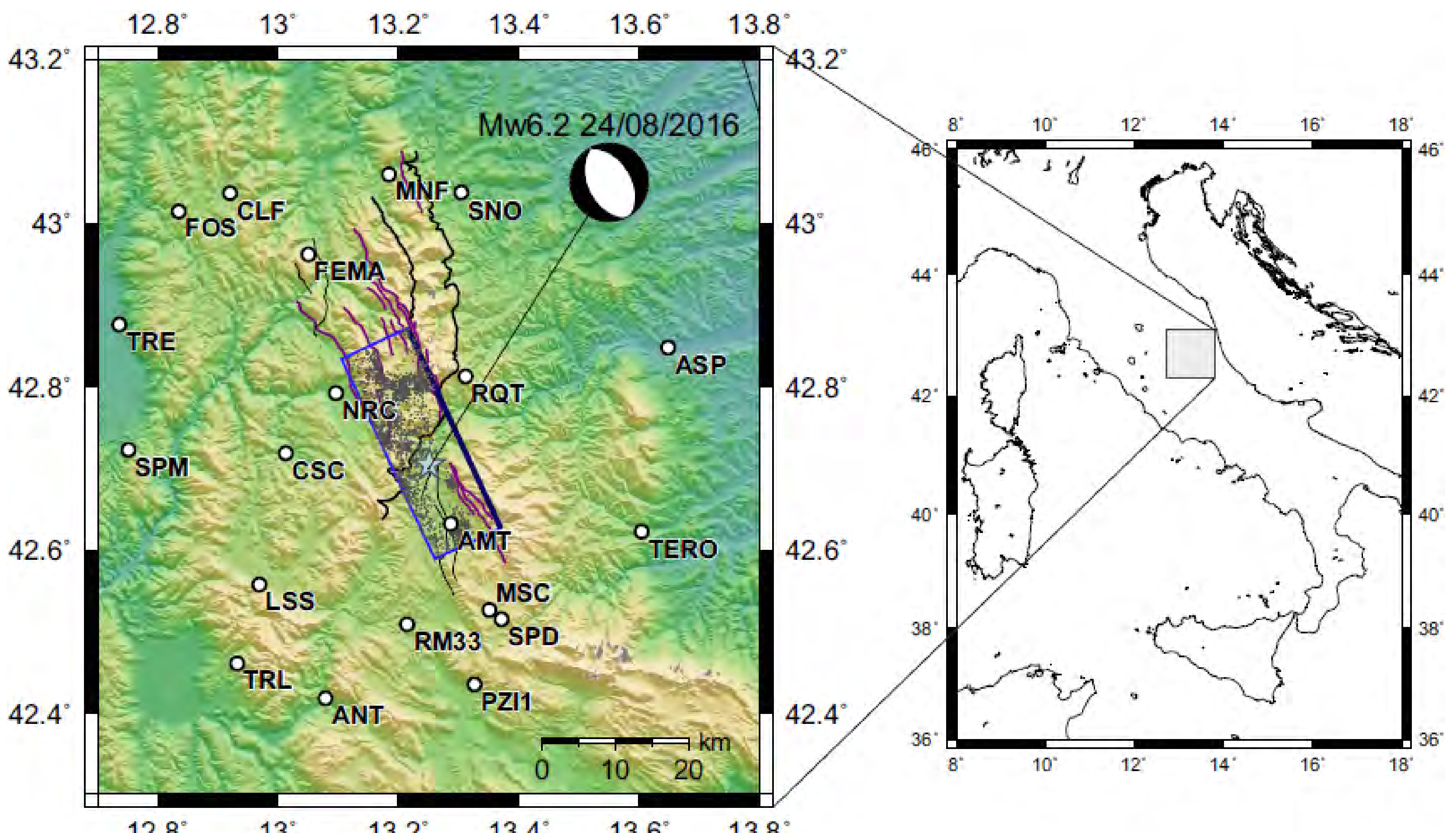


- Green plane: based on focal mechanims
- Red and blue planes are generated from the algorithm

Preliminary fault reconstruction by Kadek Palgunadi

Fracture activation in geo-reservoirs

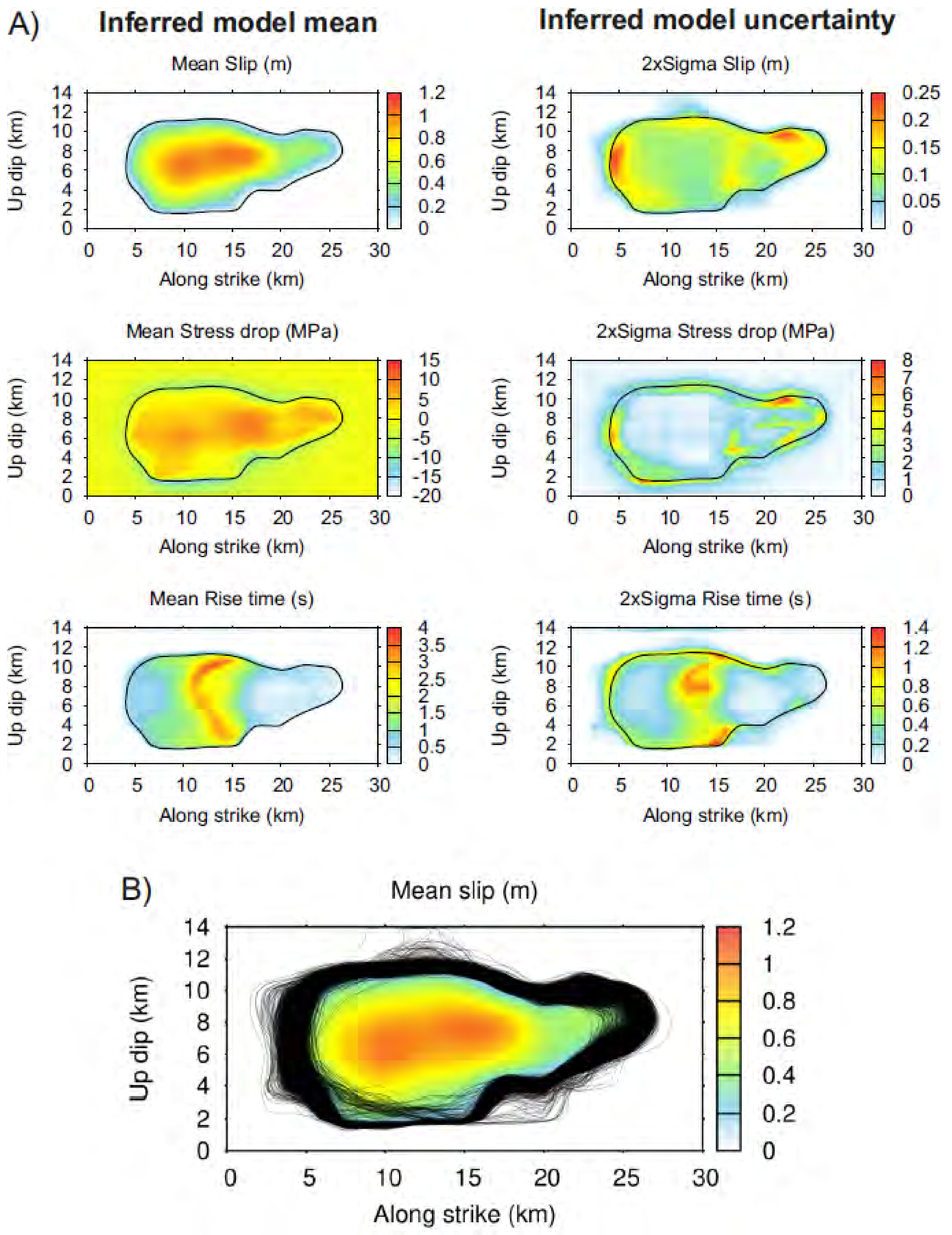
- Future directions: **Beyond scenario-based simulations**
- **Dynamic source inversion** for spatial distribution of initial stress and friction parameters
- **Bayesian framework** using Parallel Tempering Monte Carlo algorithm applied it to the 2016 Mw6.2 Amatrice, Italy event - visiting **millions** of dynamic rupture models
- Uncertainty quantification and constraining non-uniqueness in source inversions with: **Adjoint sensitivity analysis. Uncertainty quantification. Optimal design. Ensemble simulations.**



Gallovic et al., 2019a, subm.,

Gallovic et al., 2019b, subm.,

https://eartharxiv.org/tmjv4/



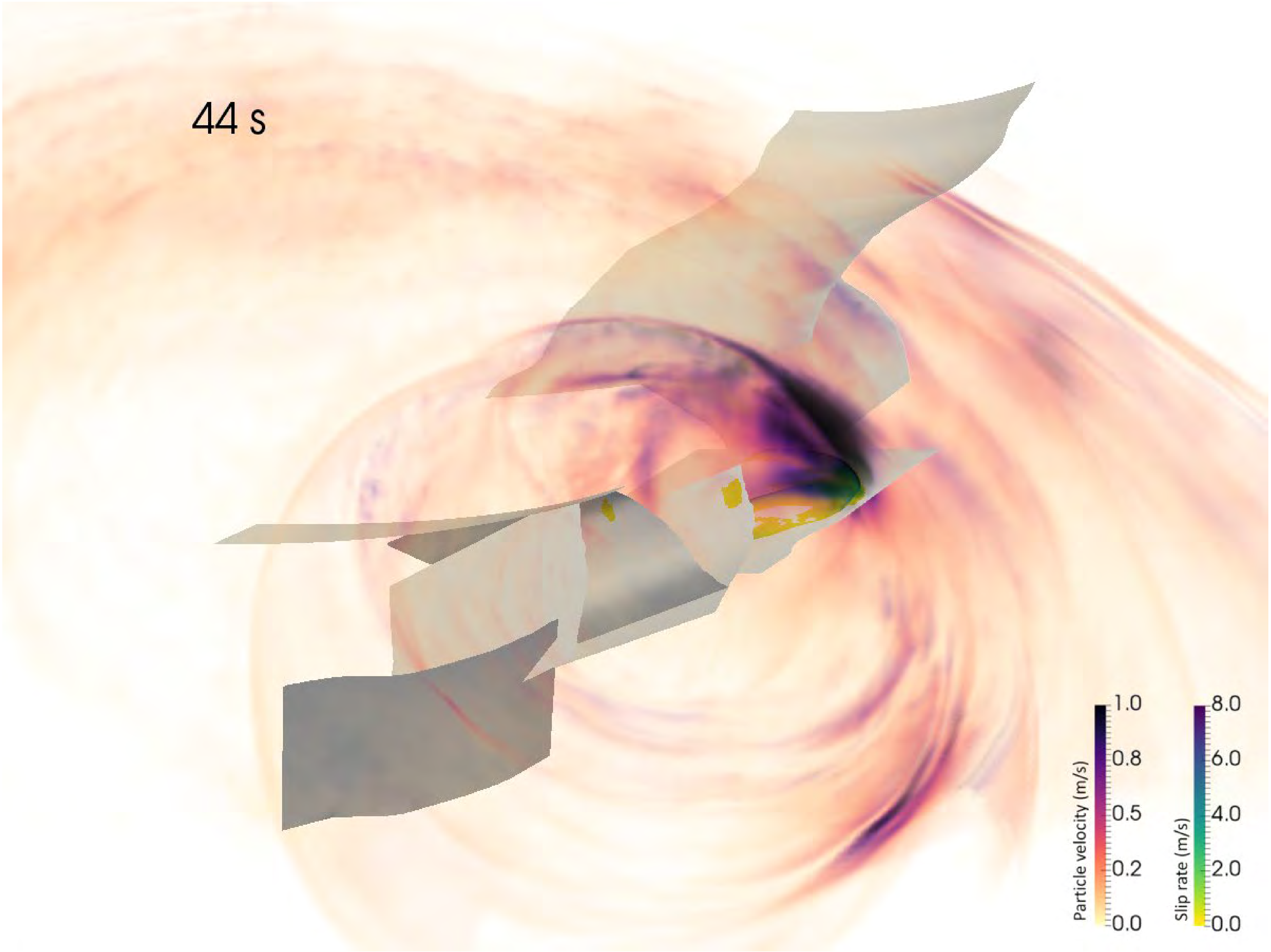
A) Rupture parameters inferred by the Bayesian dynamic inversion averaged over posterior samples (left) and the model parameters' uncertainty in terms of two sigma (right). B) Averaged model of slip (color-coded) with slip contours of all accepted posterior model samples displaying the uncertainty of the inferred spatial rupture extent.

Conclusions

- Physics-based modeling provides mechanically viable insight into the physical conditions that allow rupture on complex fault systems and helps constraining competing views on earthquake sources

- Observational constraints can be routinely included; Observational methods can themselves be constrained

- Advances in high-performance computing and dense observations allow us to go beyond scenario-based analysis, aiming for urgent response quickly after an event occurs, ensemble simulations, dynamic inversion and uncertainty quantification



A true epilogue is removed
from the story in time or space.

- Extra Slides -

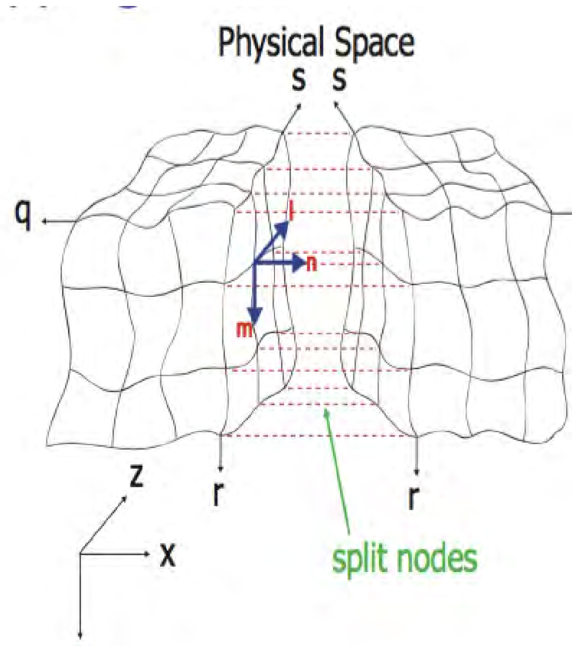
Acknowledgements

LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN

My research team at LMU Munich:

Bo Li

Duo Li



Kenneth Duru

Betsy Madden

Stephanie Wollherr

Thomas Ulrich

Sebastian Anger

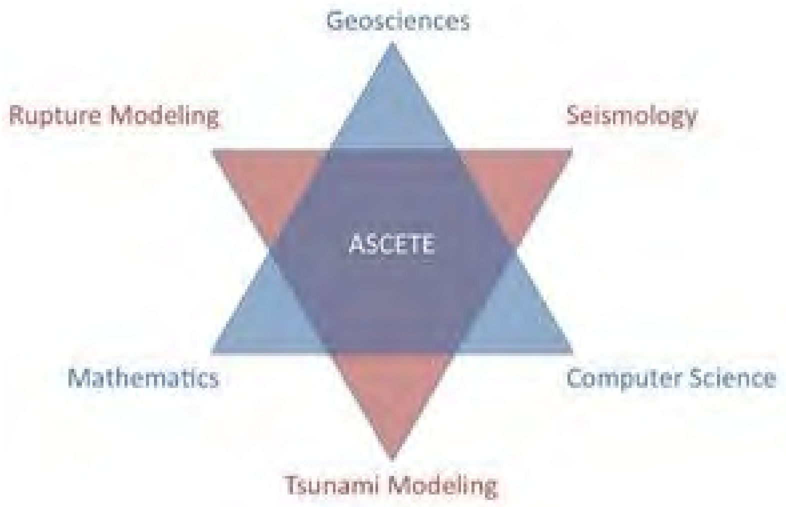
Taufiqurrahman

Aniko Wirp

Current projects:

ExaHyPE

ChEESE
www.cheese-coe.eu



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King Abdullah University of Science and Technology

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Collaborators:

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lrz Leibniz-Rechenzentrum der Bayerischen Akademie der Wissenschaften

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Rensselaer

KAUST

Seismological Laboratory California Institute of Technology

ETH

IBM

Durham University

CHARLES UNIVERSITY

www.seissol.org github.com/SeisSol

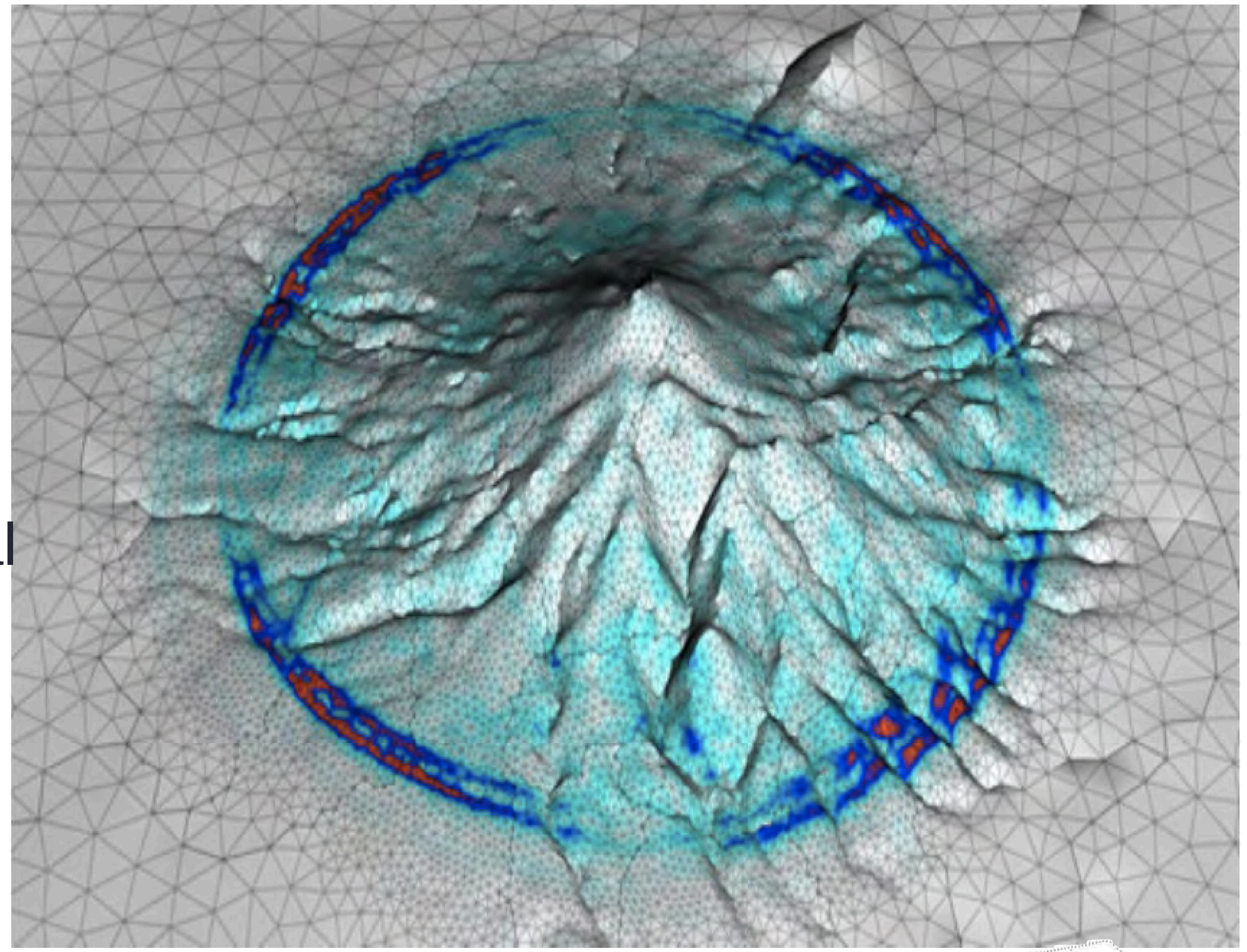
SeisSol - ADER-DG
A unique modelling framework

We develop and host an open-source Arbitrary high-order DERivative Discontinuous Galerkin (**ADER-DG**) software package. SeisSol solves the seismic wave equations in elastic, viscoelastic, and viscoplastic media on unstructured tetrahedral meshes.

Our method, by design, permits:

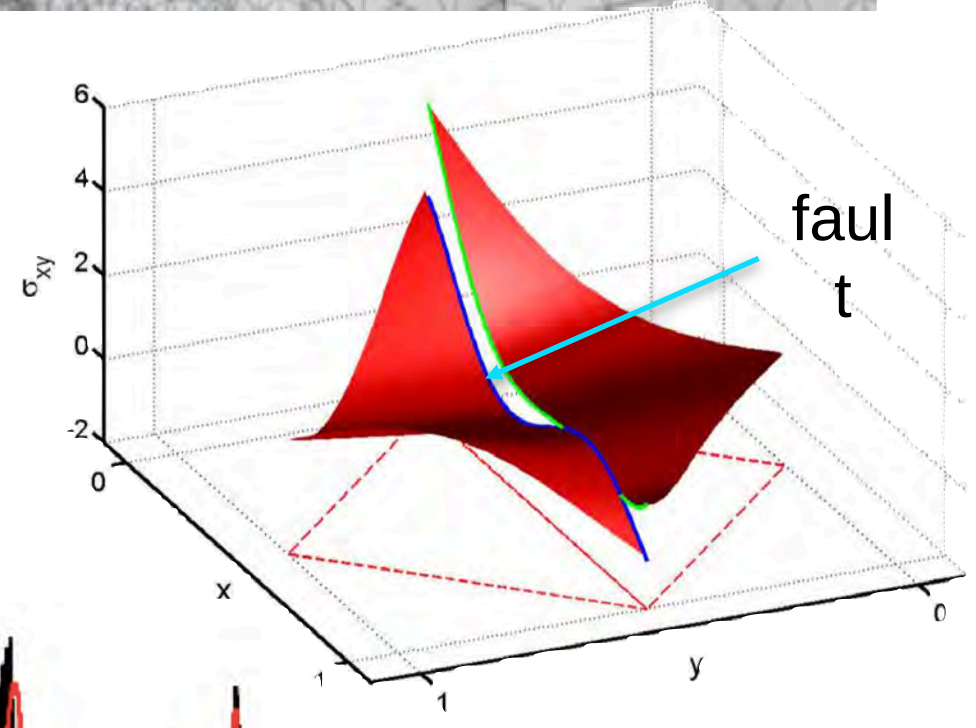
- representing **complex geometries** - by discretising the volume via a tetrahedral mesh
- modelling **heterogenous media** - elastic, viscoelastic, viscoplastic, anisotropic
- **multi-physics coupling** - flux based formulation is natural for representing physics defined on interfaces
- **high accuracy** - modal flux based formulation allows us to suppress spurious (unresolved) high frequencies
- **high resolution** - suitable for parallel computing environments

Käser and Dumbser, 2006; de la Puente et al., 2008; Pelties et al., 2014

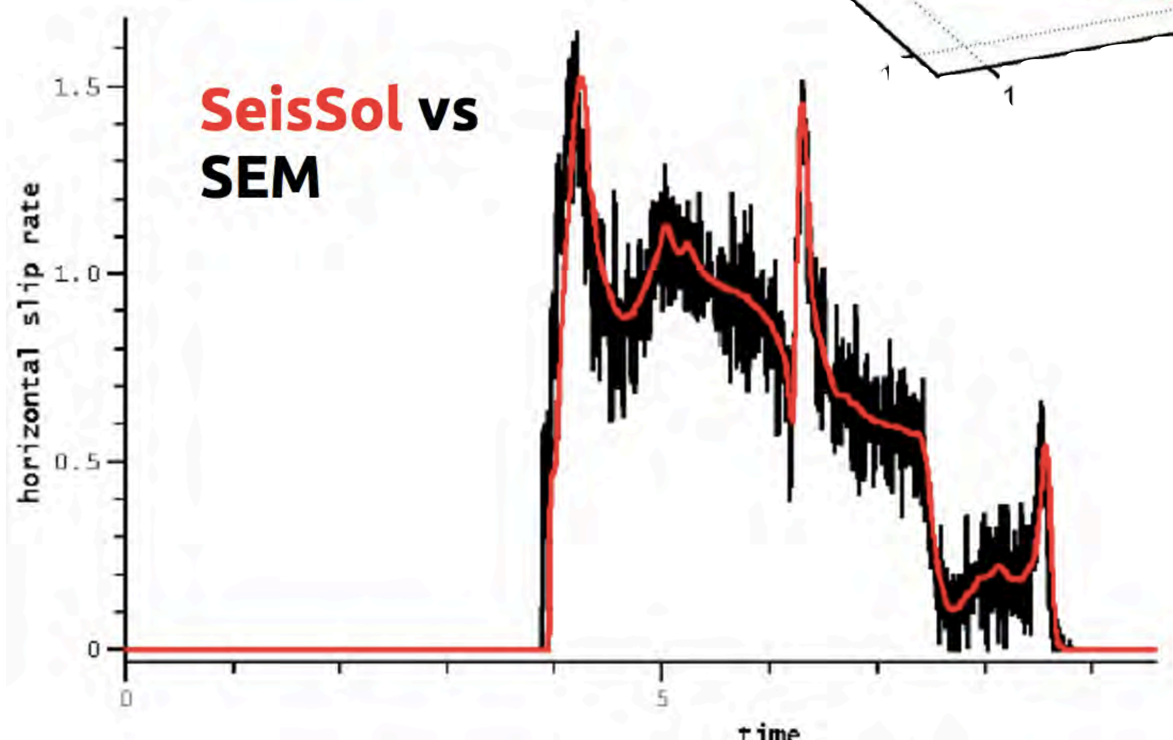


Wave field of a point source interacting with the topography of Mount Merapi Volcano.

PRACE ISC Award for producing the first simulations that obtained the “magical" performance milestone of 1 Peta-flop/s (10^{15} floating point operations per second) at the Munich Supercomputing Centre.



Representation of the shear stress discontinuity across the fault interface. Spontaneous rupture = internal boundary condition of flux term.



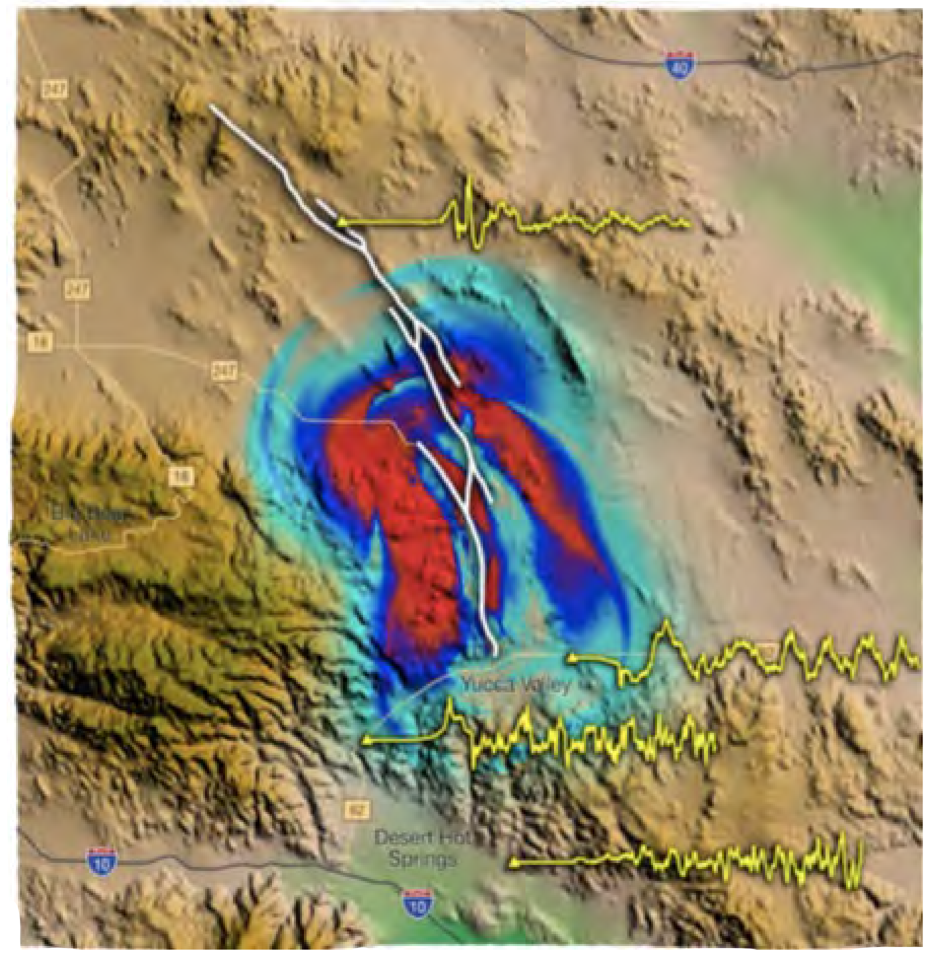
Due to the properties of the exact Riemann solver, solutions on the fault remain free of spurious oscillations

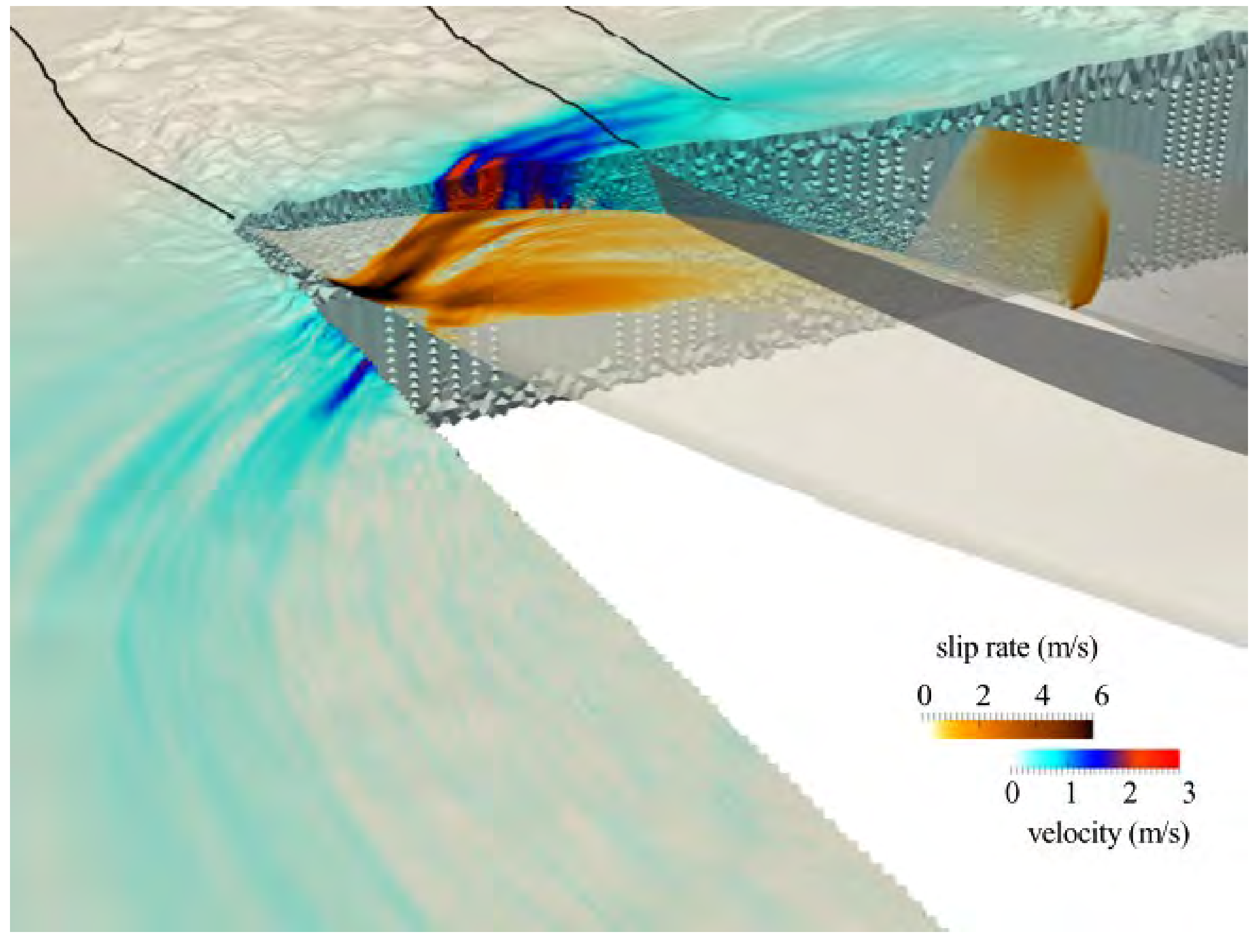
SeisSol - ADER-DG

A unique modelling framework

Breuer et al.,ISC14, Heinecke et al.,SC14
Breuer et al.,IEEE16, Heinecke et al.,SC16
Rettenberger et al., EASC16
Upphoff & Bader, HPCS'16
Uphoff et al., SC17

Gordon Bell Prize Finalist, SC14





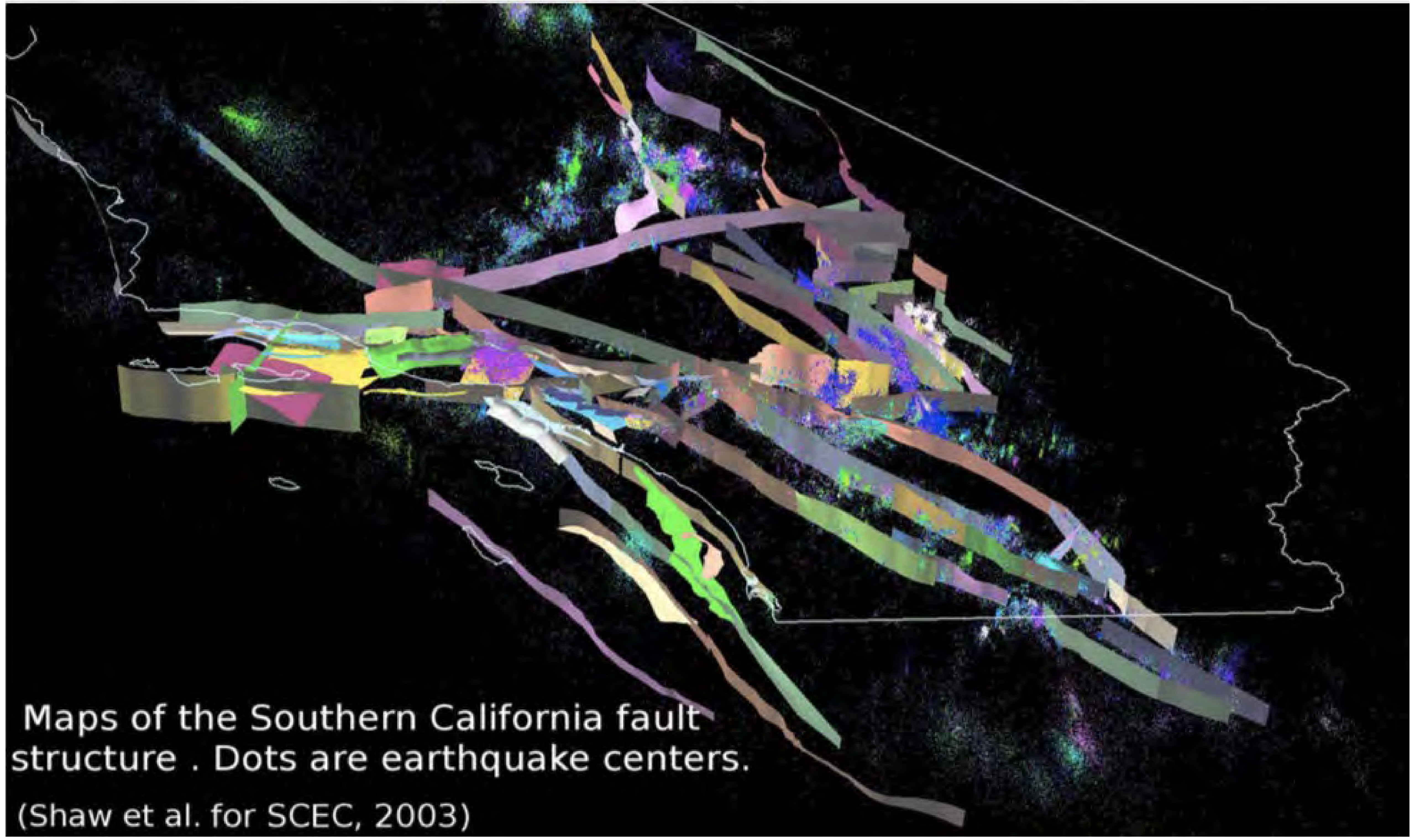
Best Paper Award, SC17

"Geophysics" Version	• Fortran 90 • MPI parallelised • Ascii based, serial I/O	
Landers scenario (96 billion DoF, 200,000 time steps)	• Hybrid MPI+OpenMP parallelisation • Parallel I/O (HDF5, inc. mesh init.) • Assembler-level DG kernels • multi-physics off-load scheme for many-core architectures	• > 1 PFlop/s performance • 90% parallel efficiency • 45% of peak performance • 5x-10x faster time-to-solution • 10x-100x bigger problems
Sumatra scenario (111 billion DoF, 3,300,000 time steps)	• Cluster-based local time stepping • Code generator also for advanced PDE's as viscoelastic attunation • Asagi (XDMF)-geoinformation server • Asynchronous input/output • Overlaping computation and communication	• Optimized for Intel KNL • Speed up of 14x • 14 hours compared to almost 8 days for Sumatra scenario on SuperMuc2

The only software that allows for rapid setup of models with realistic non- planar fault systems while exploiting the accuracy of a high-order numerical method.

Dynamic rupture
earthquake simulations

→ Few methods support all modelling requirements



Multitude of spatio-temporal scales: fault geometry spans hundreds of km; frictional process zone size is m (or even cm) scale, tectonic loading (seismic cycle) 10-10000 years; rise time on second scale

the real world

- Non-planar, intersecting faults
- Non-linear friction
- Heterogeneities in stress and strength
- Dynamic damage around the fault
- Fault roughness and segmentation on all scales
- Bi-material effects
- Low velocity zones surrounding faults
- Thermal pressurization of fault zone fluids
- Thermal decomposition
- Dilatancy of the fault gouge
- Flash heating, melting, lubrication
- Feedback mechanisms across time scales

… this list grows continuously

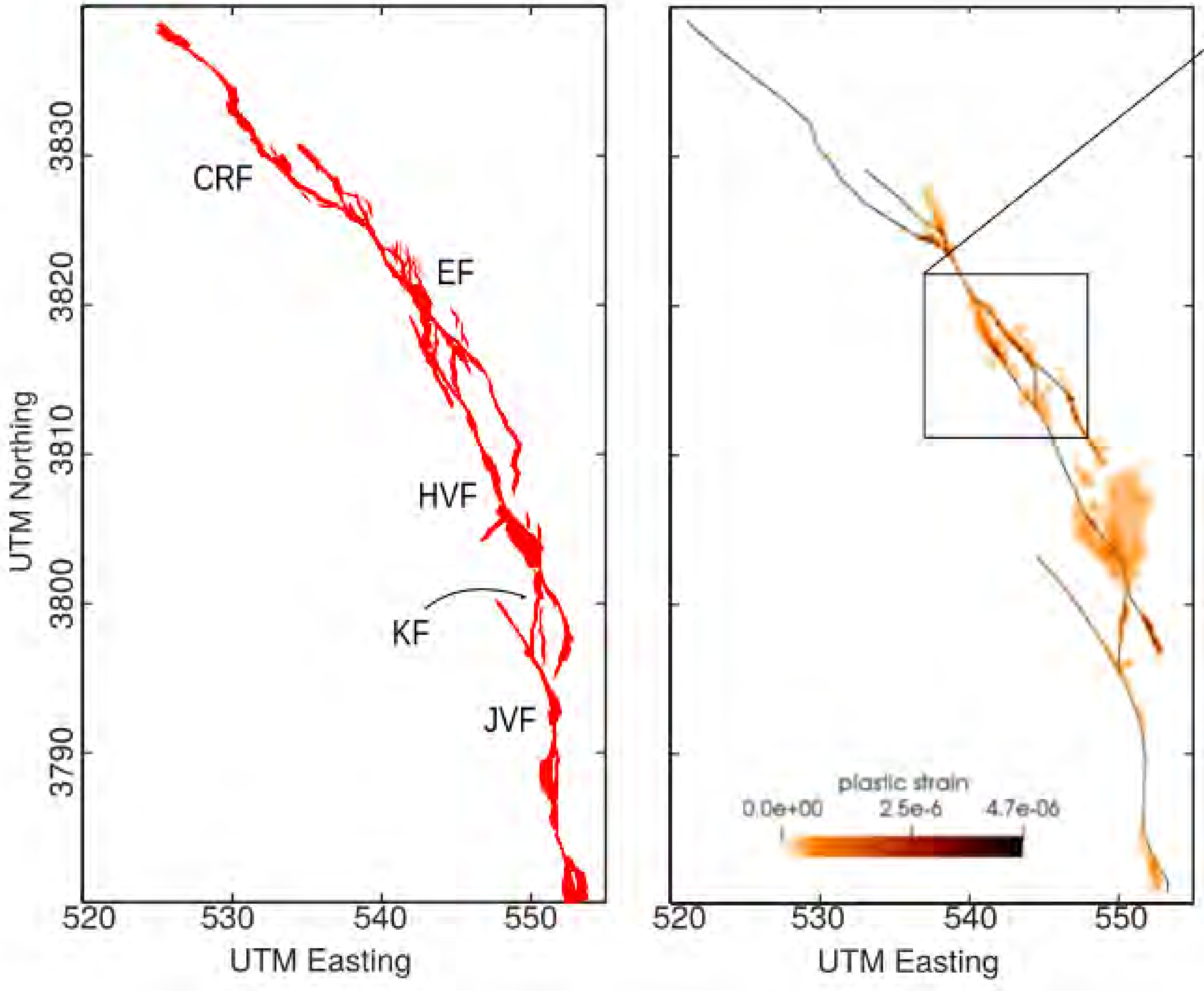
The 1992 Mw 7.3 Landers earthquake "reloaded" (Wollherr et al., preprint doi:10.31223/osf.io/kh6j9)

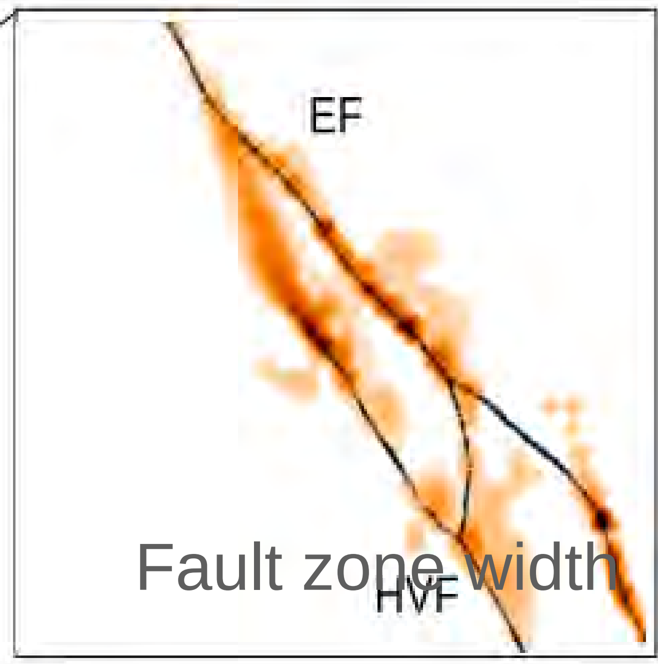
➡ Multi-physics, such as off-fault plasticity, matters!

- **Drastic increase** of **off-fault deformation** in **geometrically complex fault regions** enhancing geometric barriers, hindering rupture transfers and matching newly available mapping

- **Strain localisation** forming non-prescribed 'faults'

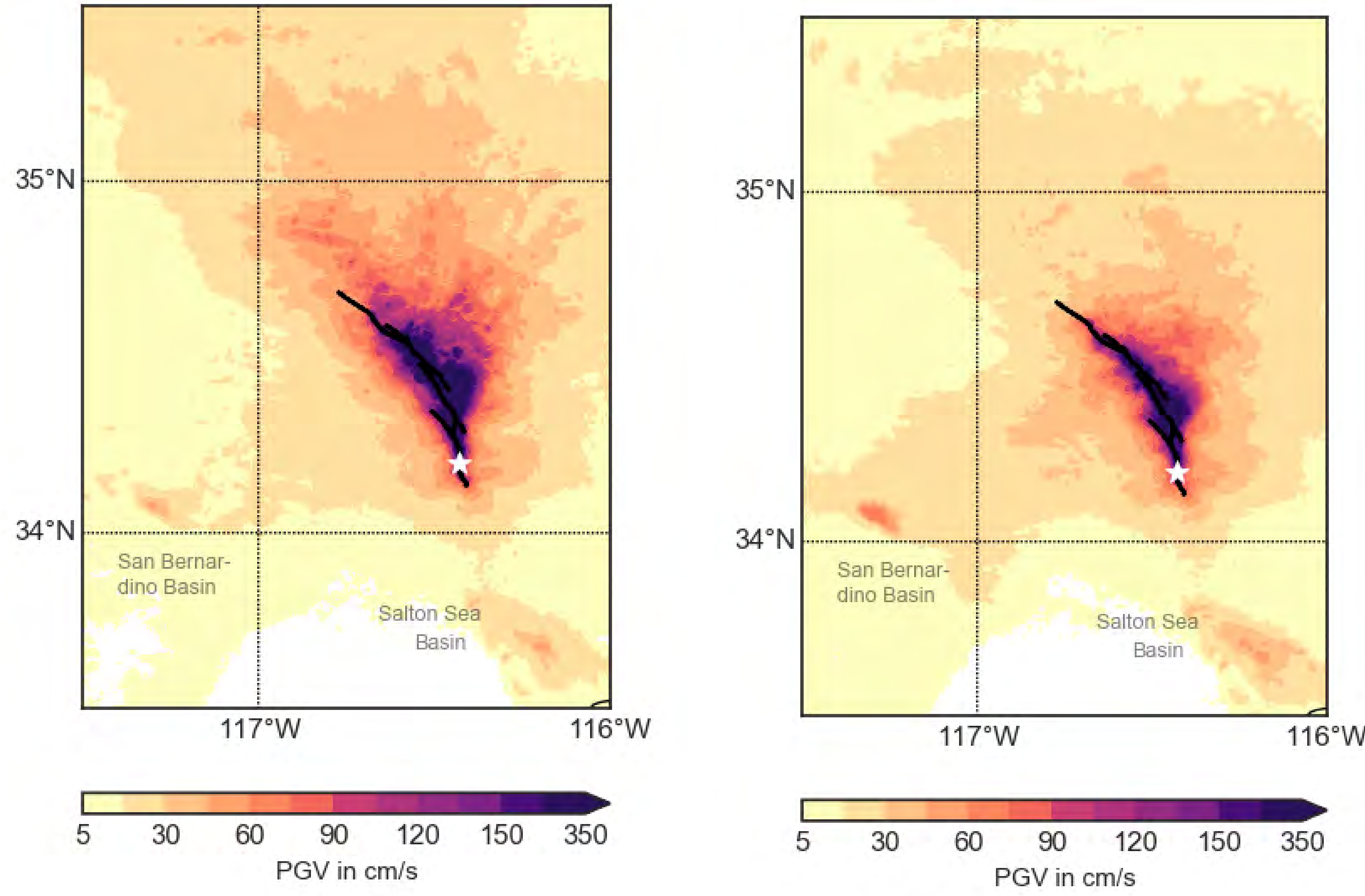
- Off-fault plasticity **reduces peak ground velocities (by 35%)** as well as ground motion **variability and directivity**



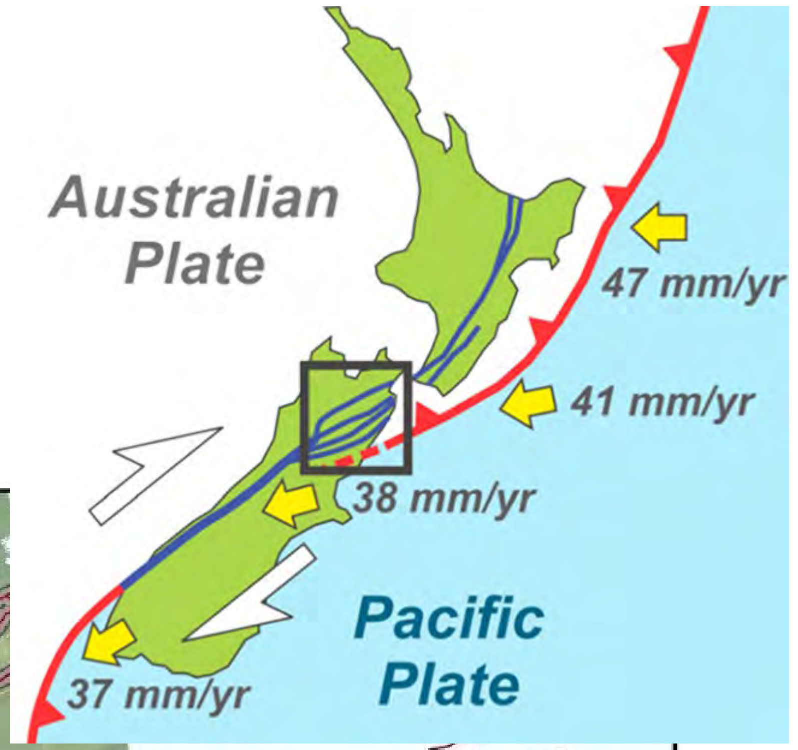


Fault zone width (FZW) compiled by Milliner et al. [2015] from aerial photograph correlations (left) in comparison to the synthetic plastic

Simulated GMRotD50 PGVs for a purely elastic simulation cf. the visco-elasto-plastic simulation



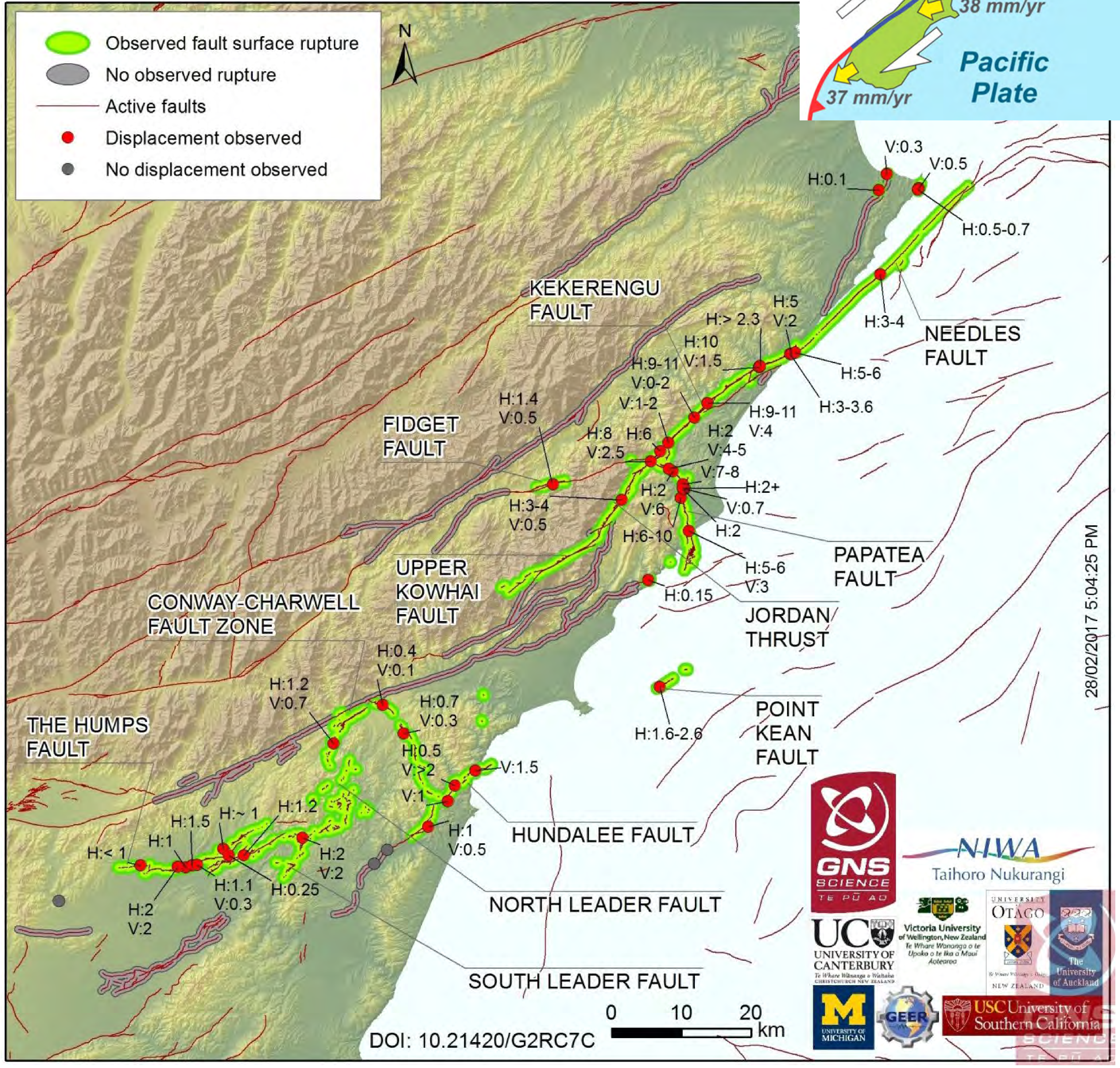
The 2016, Mw7.8 Kaikōura earthquake
- a rupture cascade on weak crustal faults



- Rupture propagation across highly segmented fault system with **diverse orientations and faulting mechanisms (strike-slip, thrusting)**

- Duration of ~100s, 200km of rupture, triggered landslides, local tsunami

- 2 deaths, 57 injured, damaged infrastructure, e.g. bridges, road subsidence



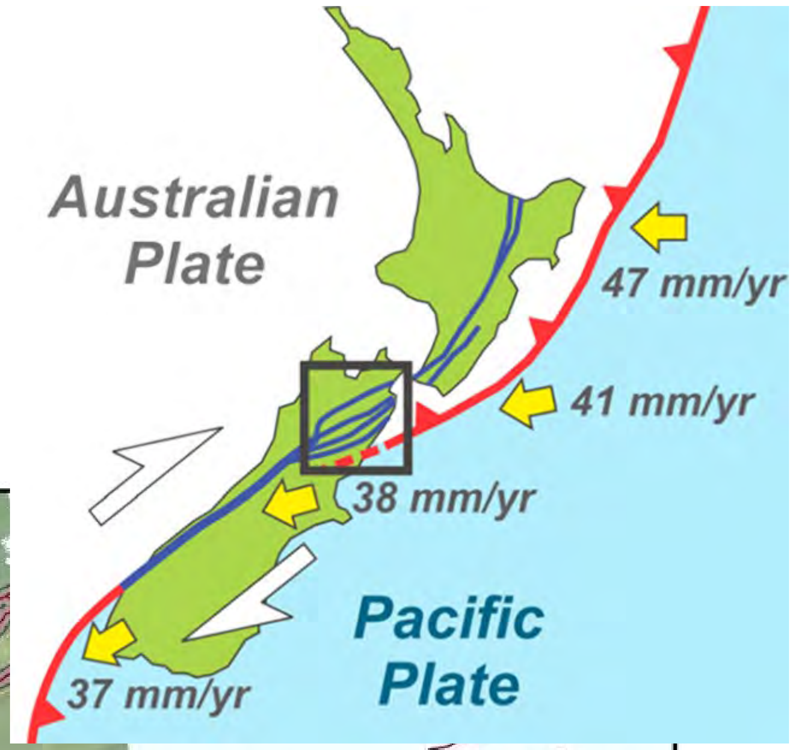
Kekerengu Fault rupture displacement by ~10 meters

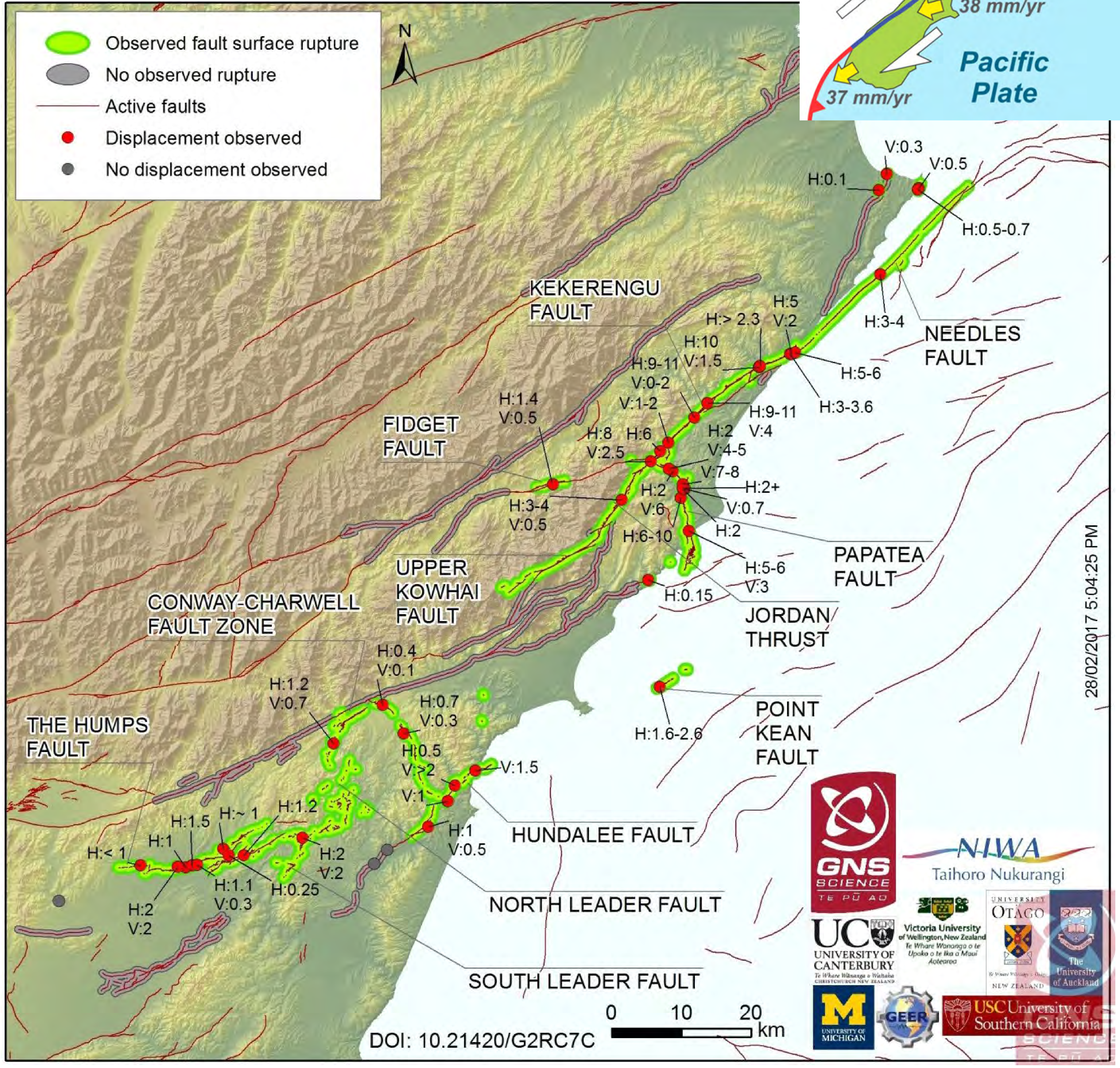
The 2016, Mw7.8 Kaikōura earthquake
- a rupture cascade on weak crustal faults

Open questions:

- Did the rupture of multiple crustal faults **connect via slip on a subduction interface?**
- A 15 km large gap separating the surface ruptures of the Hundalee and Upper Kowhai faults - **Can earthquake ruptures jump across wider fault gaps than previously thought?**
- Why was this earthquake **anomalously slow?**
- Why did the **Hope Fault not rupture?**
- How can such a complex cascade occur on faults that have **low apparent friction?**

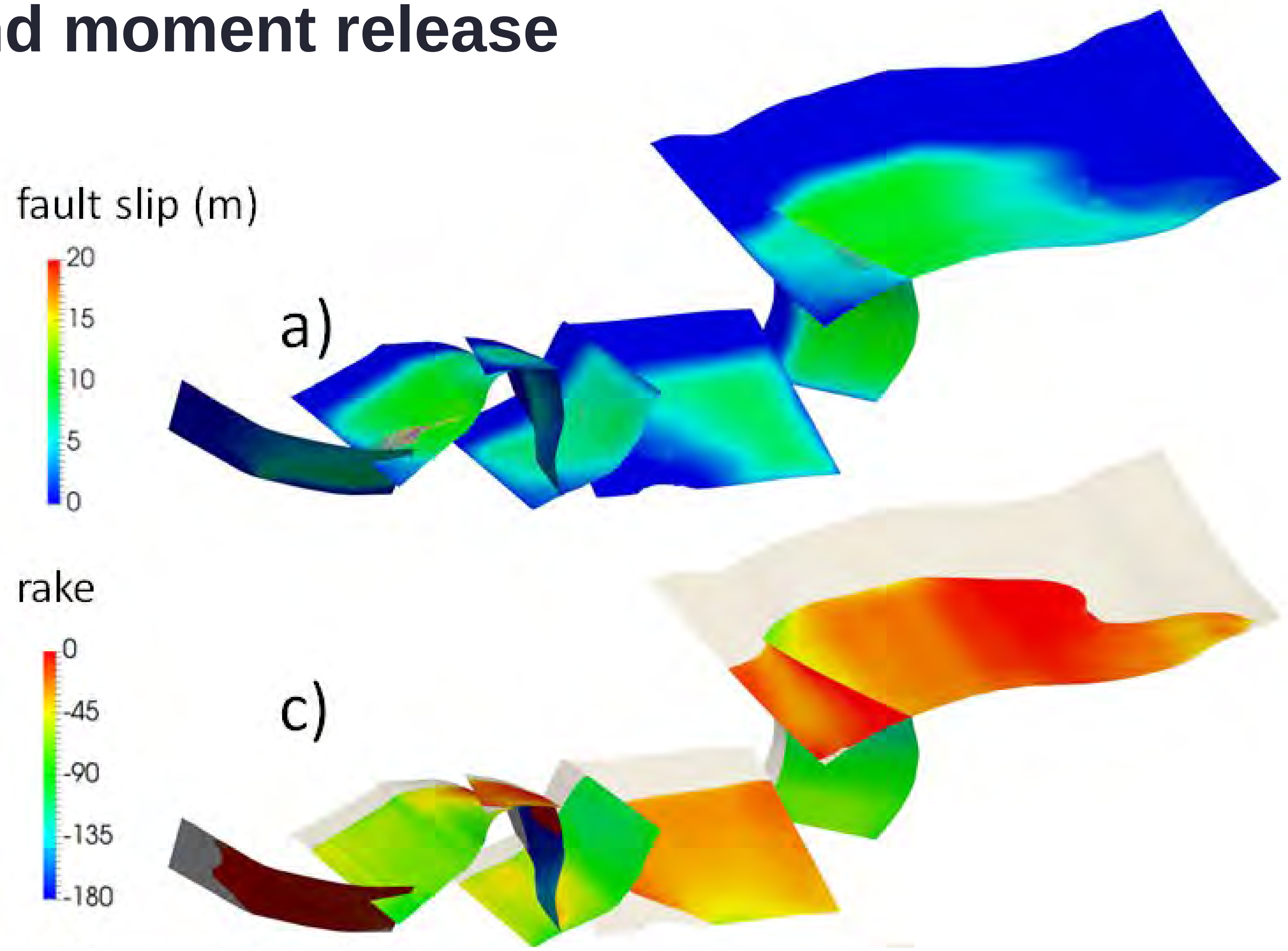
Physics-based dynamic rupture simulations can help constraining those competing views and provide a self-consistent earthquake source description



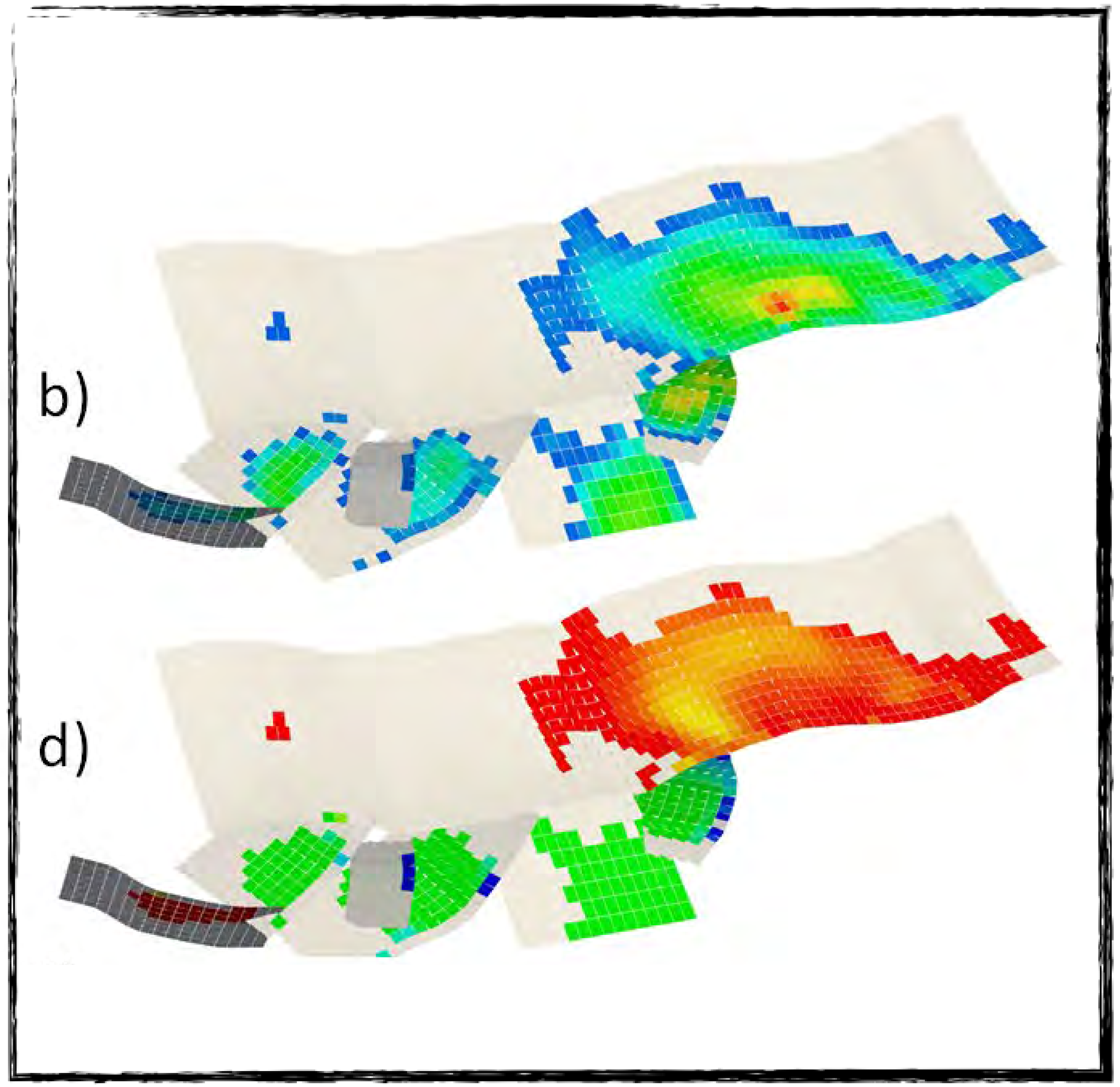


The 2016, Mw7.8 Kaikōura earthquake
- constrained by observation

- **Slip distribution and moment release**

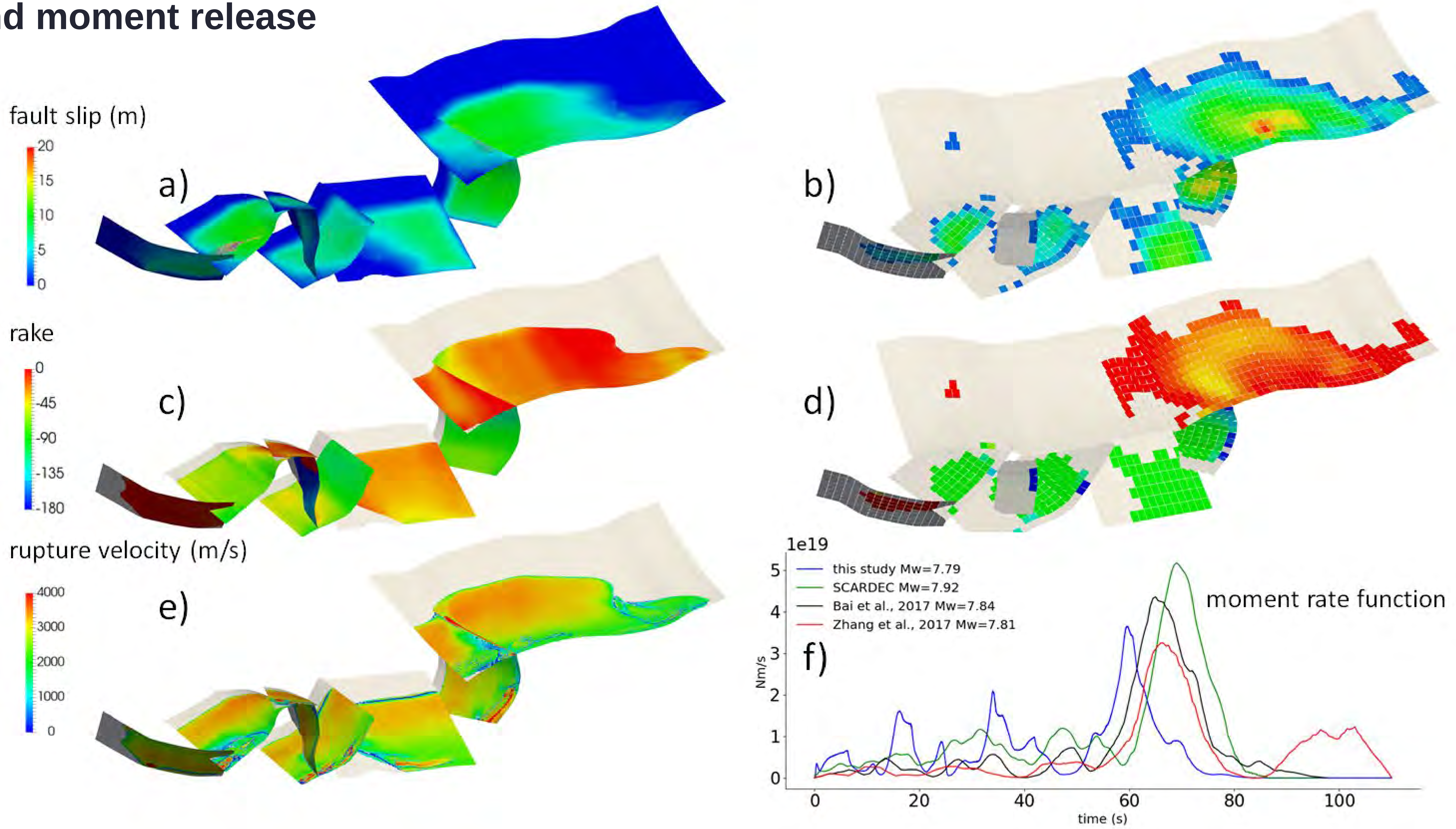


Kinematic source inversion (Xu et al., 2018)



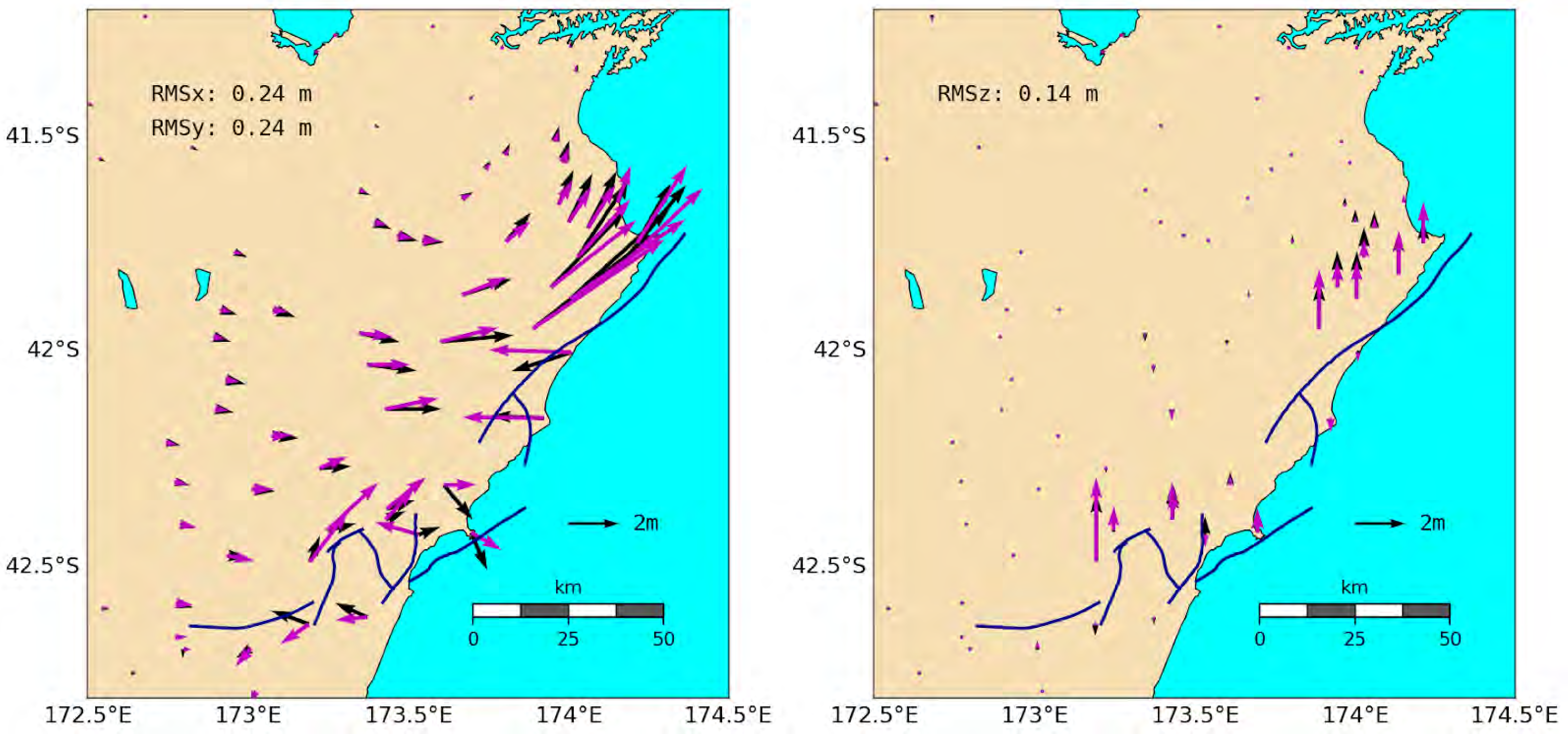
The 2016, Mw7.8 Kaikōura earthquake
- constrained by observation

- **Slip distribution and moment release**



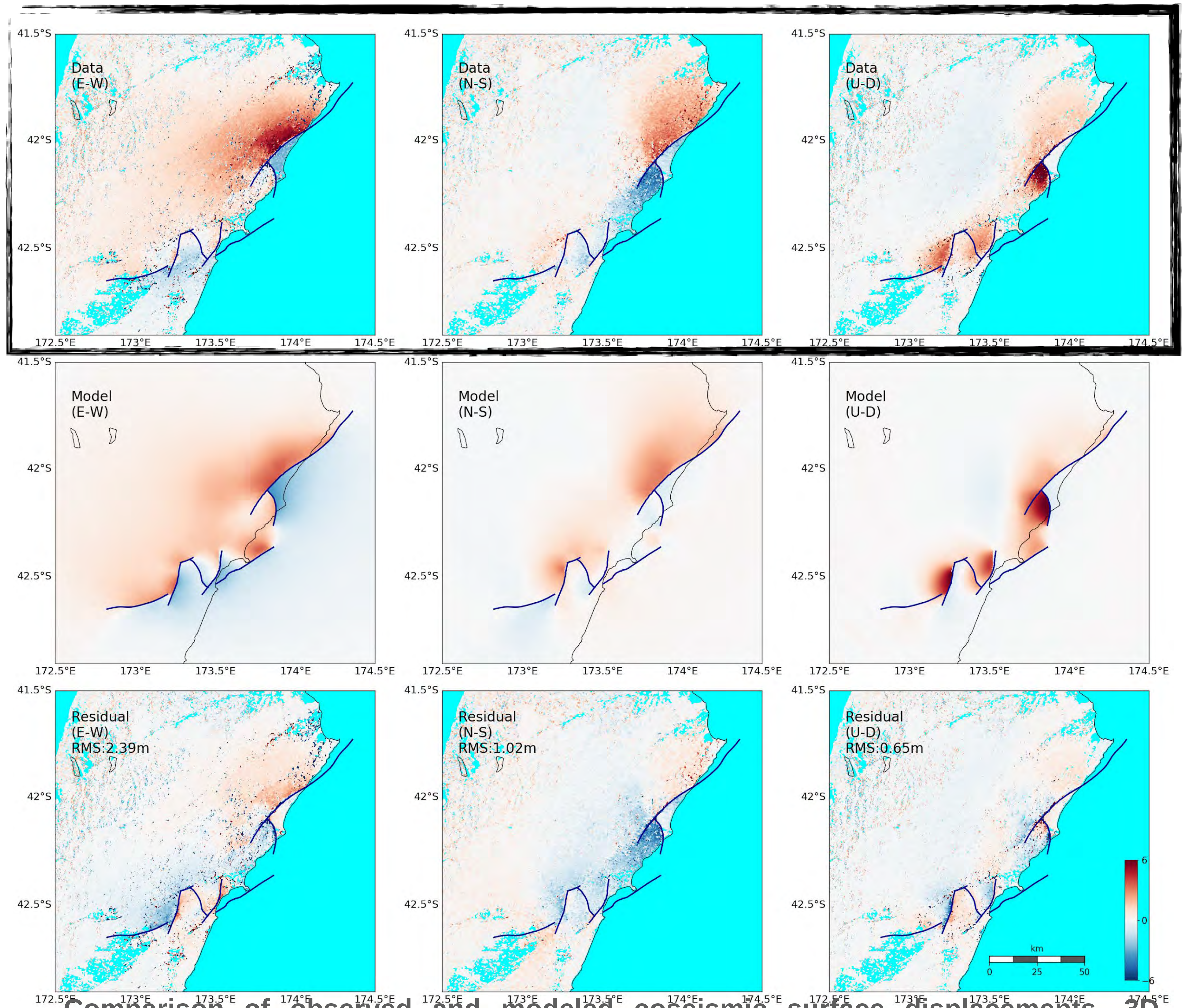
The 2016, Mw7.8 Kaikōura earthquake
- constrained by observation

- **Ground deformation**



Comparison of observed (black, Hamling et al. 2017) and modeled (magenta) horizontal (left) and vertical (right) ground displacement at GPS stations. Root-mean-square (RMS) misfits are provided for each component.

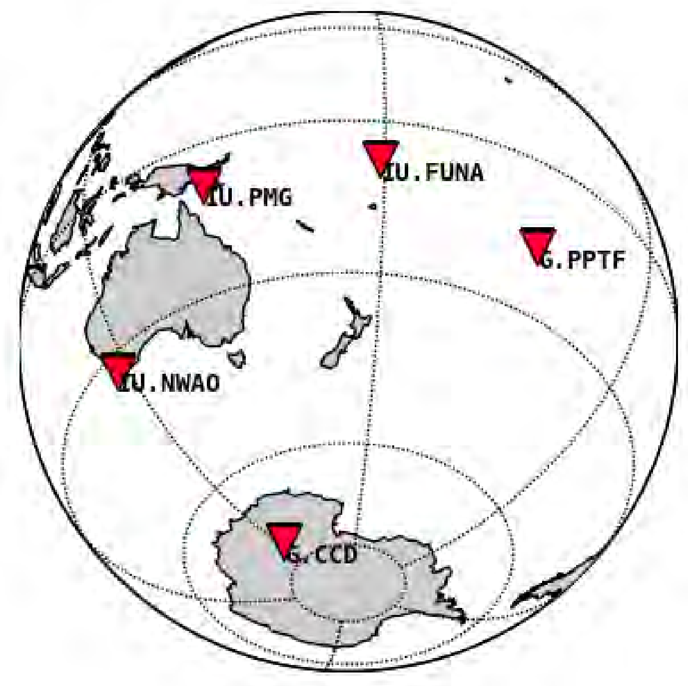
Geodetic data (Xu et al., 2018)

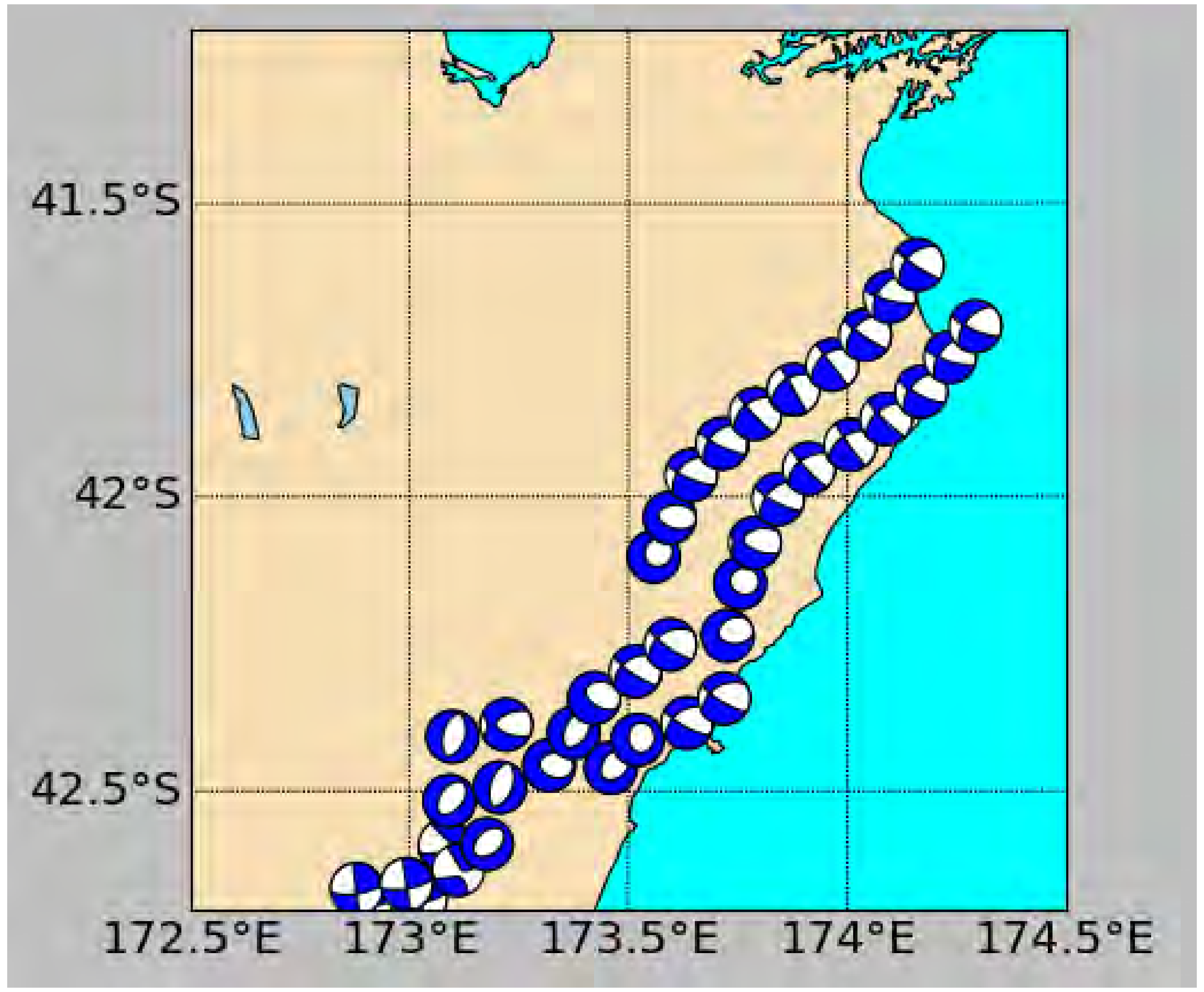


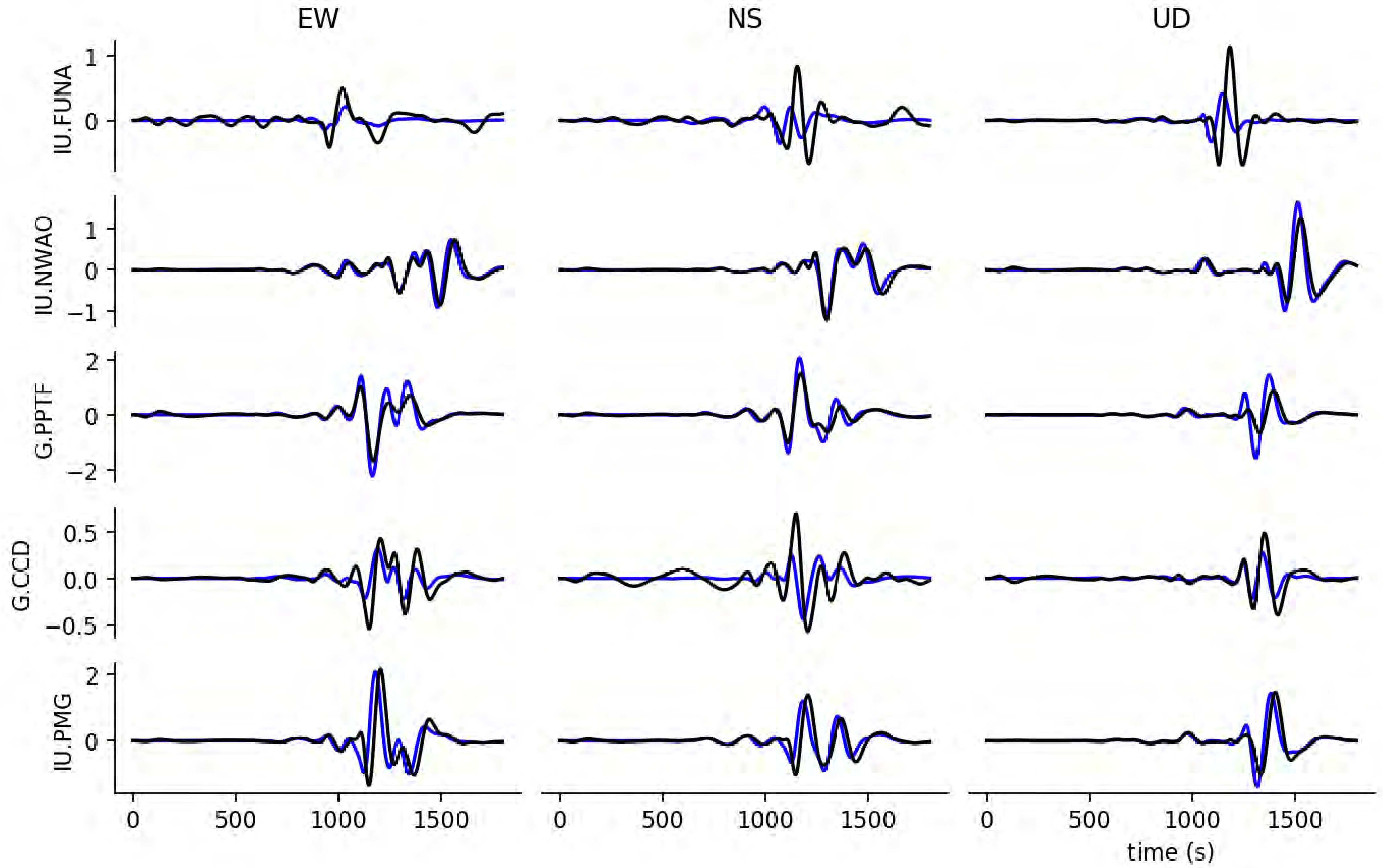
Comparison of observed and modeled coseismic surface displacements. 3D ground displacement (first row) inferred by space geodetic data (Xu et al. 2018), (second row) generated by the dynamic rupture model and (third row) their difference, all in meters. Columns from left to right are EW, NS and UD components. Root-mean-square (RMS) misfits are provided in the third row for each component.

The 2016, Mw7.8 Kaikōura earthquake
- **constrained by observation**

- **Teleseismic waveforms and tsunami data**
  (by off-line coupling)







The 2016, Mw7.8 Kaikōura earthquake
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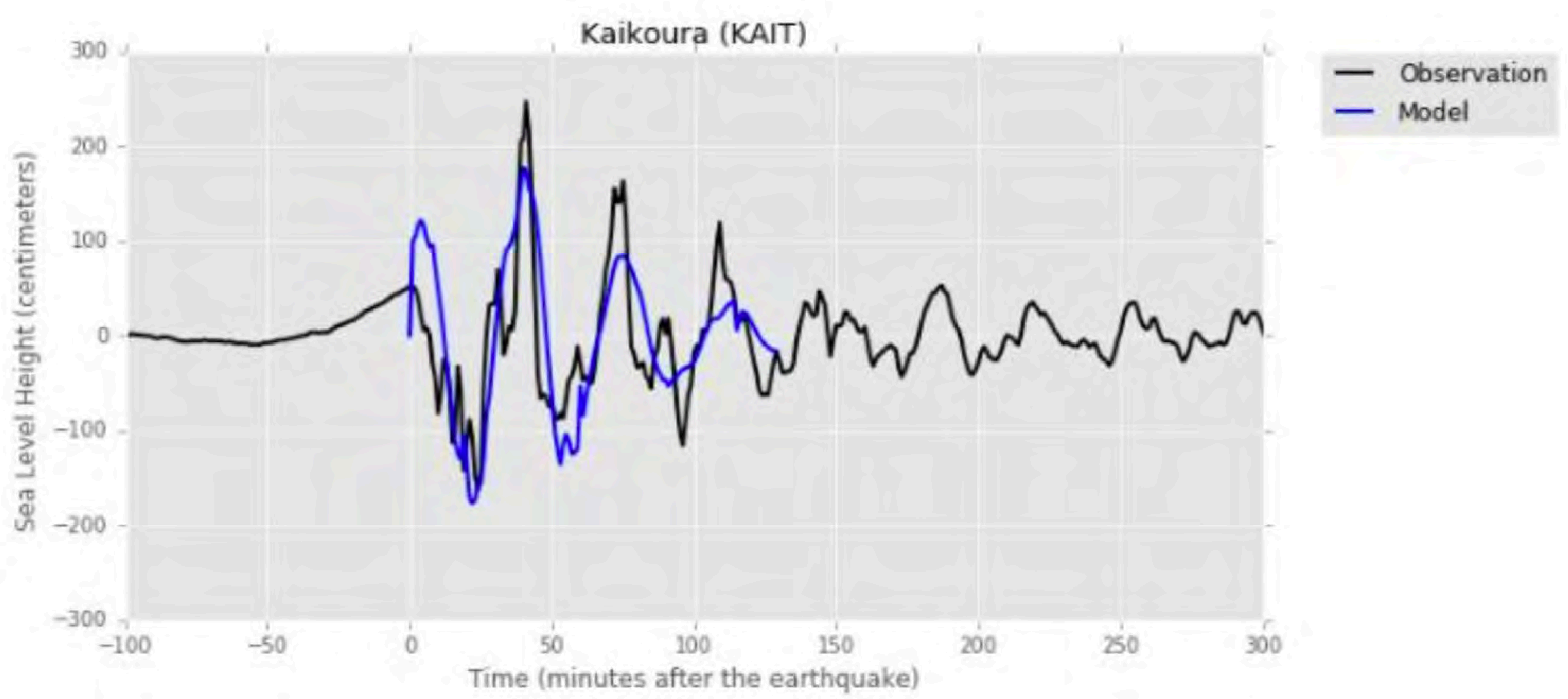
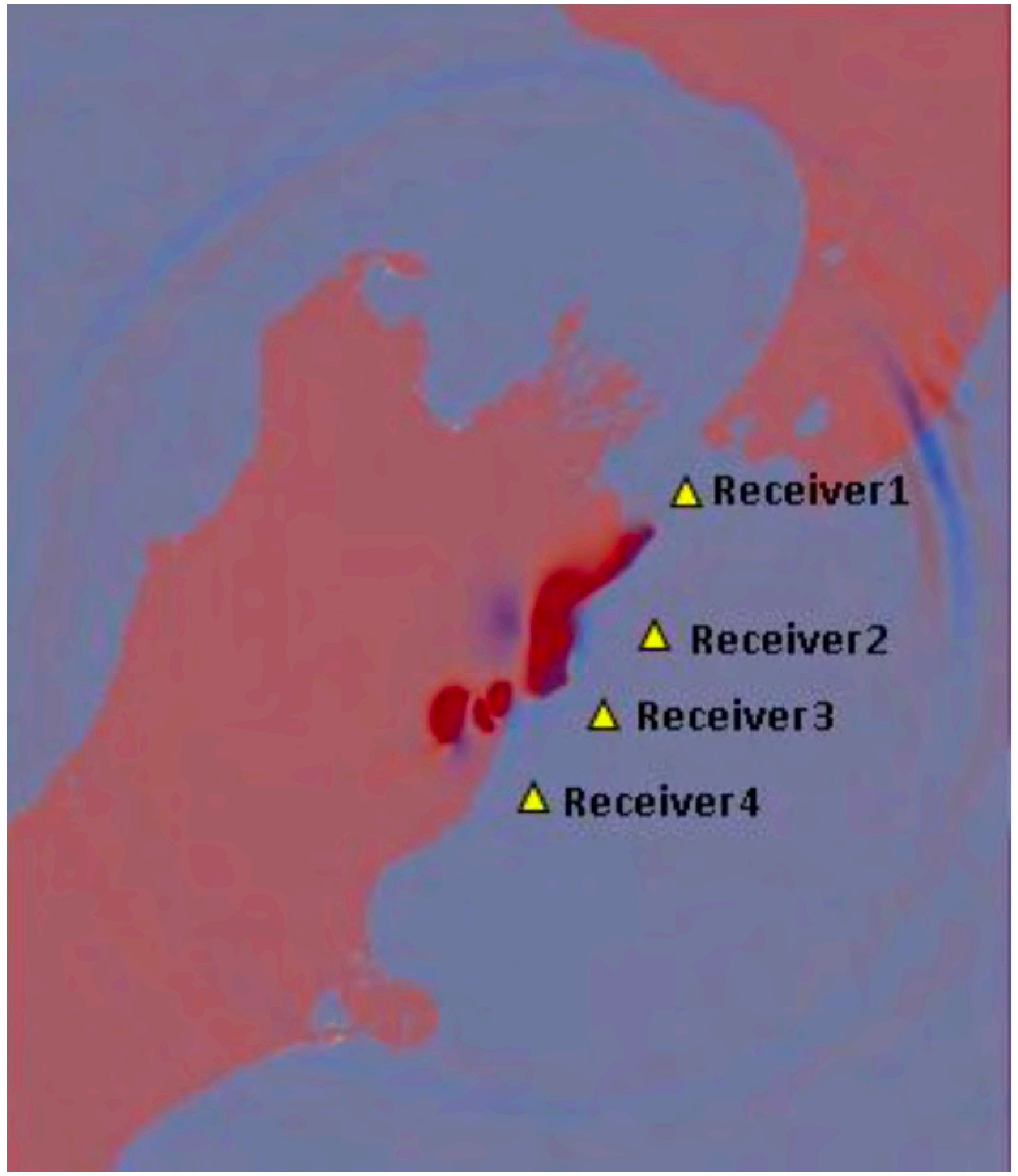
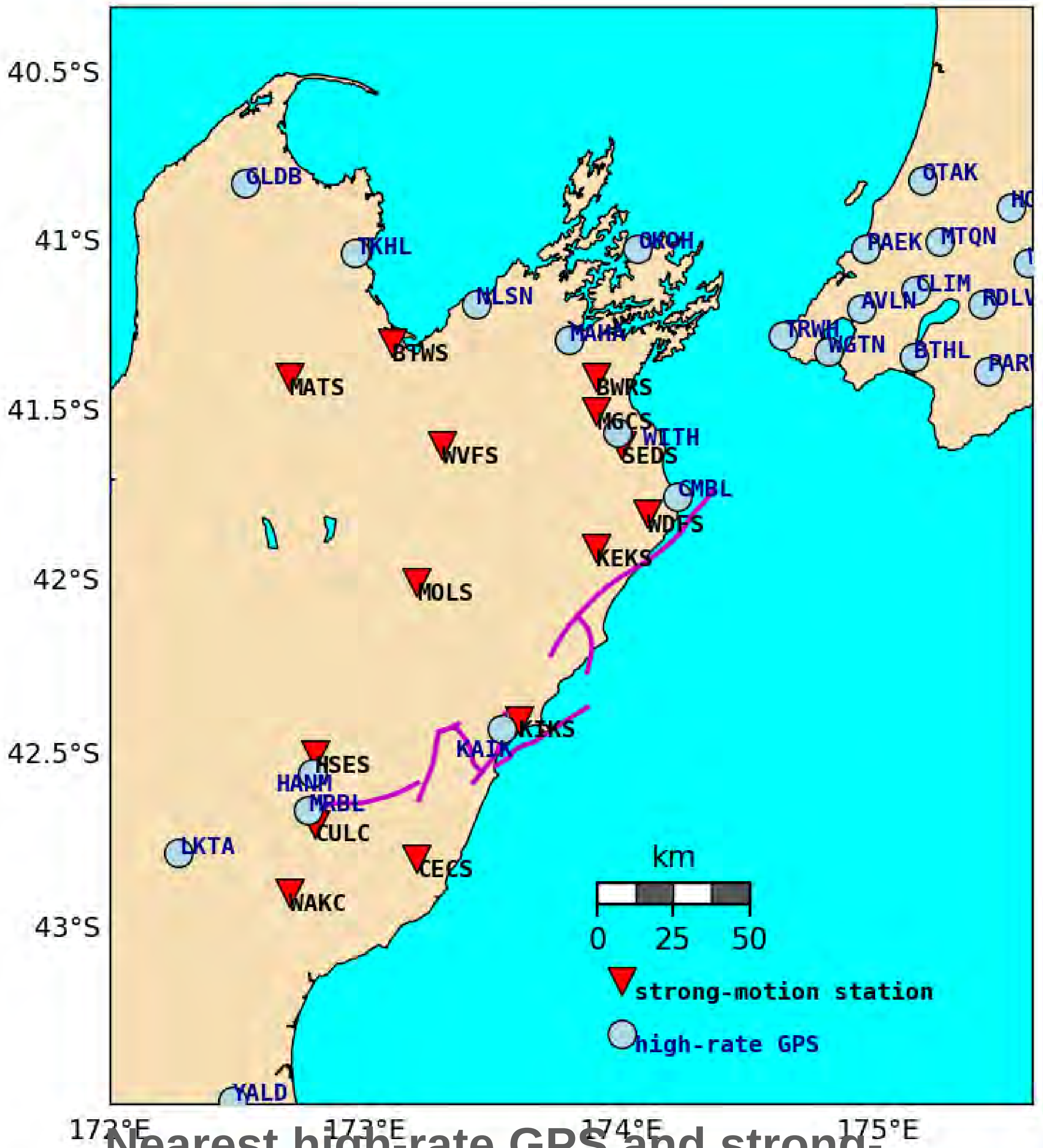


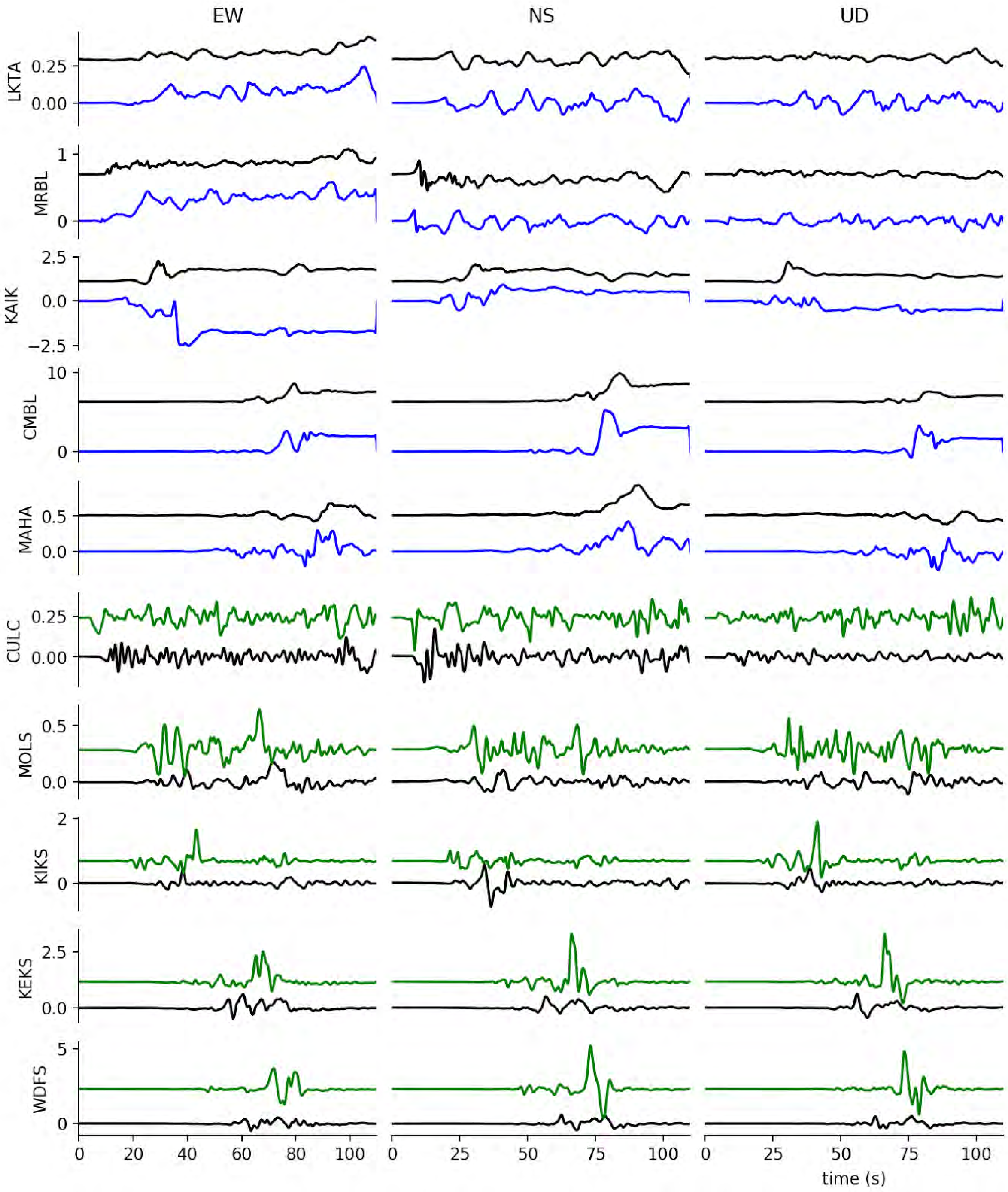


The 2016, Mw7.8 Kaikōura earthquake - (reproducing) observations



Nearest high-rate GPS and strong-motion stations (on South Island) active during the Kaikoura earthquake (left). Teleseismic stations at which synthetic data is compared with observed records (right).

Comparison of modelled and observed ground motions. Five top rows: synthetic (blue) and observed (black) ground displacements at selected GPS stations. A 1 s low-pass filter has been applied to both signals. Five bottom rows: synthetic (green) and observed (black) ground velocities at selected strong-motion stations. A 0.005-1 s band-pass filter has been applied to both signals.



Seismo-tectonic simulations: current capabilities

time-scales

	Dynamic simulation	Kinematic simulation	Dynamic boundary integral	Quasi-dynamic integral	Short-term tectonics, fully numerical	Long-term tectonics, fully numerical
Dimension	3D	3D	2D/3D	2D/3D	2D	2D
Rupture	Spontaneous	Prescribed	Spontaneous	Spontaneous	Spontaneous	Spontaneous
Inertia	Yes	Yes	Yes	Radiation damping	Yes	Limited
Seismic cycle	Single	Single	Multiple	Multiple	Multiple	Simplified
Fault morphology	Complex	Complex	Planar	Fault network	Planar	Complex and emergent
Distributed deformation	Limited	Limited	None	Viscoelastic	Viscoplastic	Viscoplastic
Material heterogeneity	Fine-grain	Fine-grain	None	Simplest cases	Fine-grain	Fine-grain
Fault evolution	None	None	None	None	Allowed	Emergent
Fluid effects	Thermal Press.	None	Poroelastic	Poroelastic	Poroelastic	Poroelastic & metamorphism
Large strain	None	None	None	None	None	Yes

Contribution to Modeling Earthquake Source Physics **White Paper,** in prep. with Nadia Lapusta (Caltech)