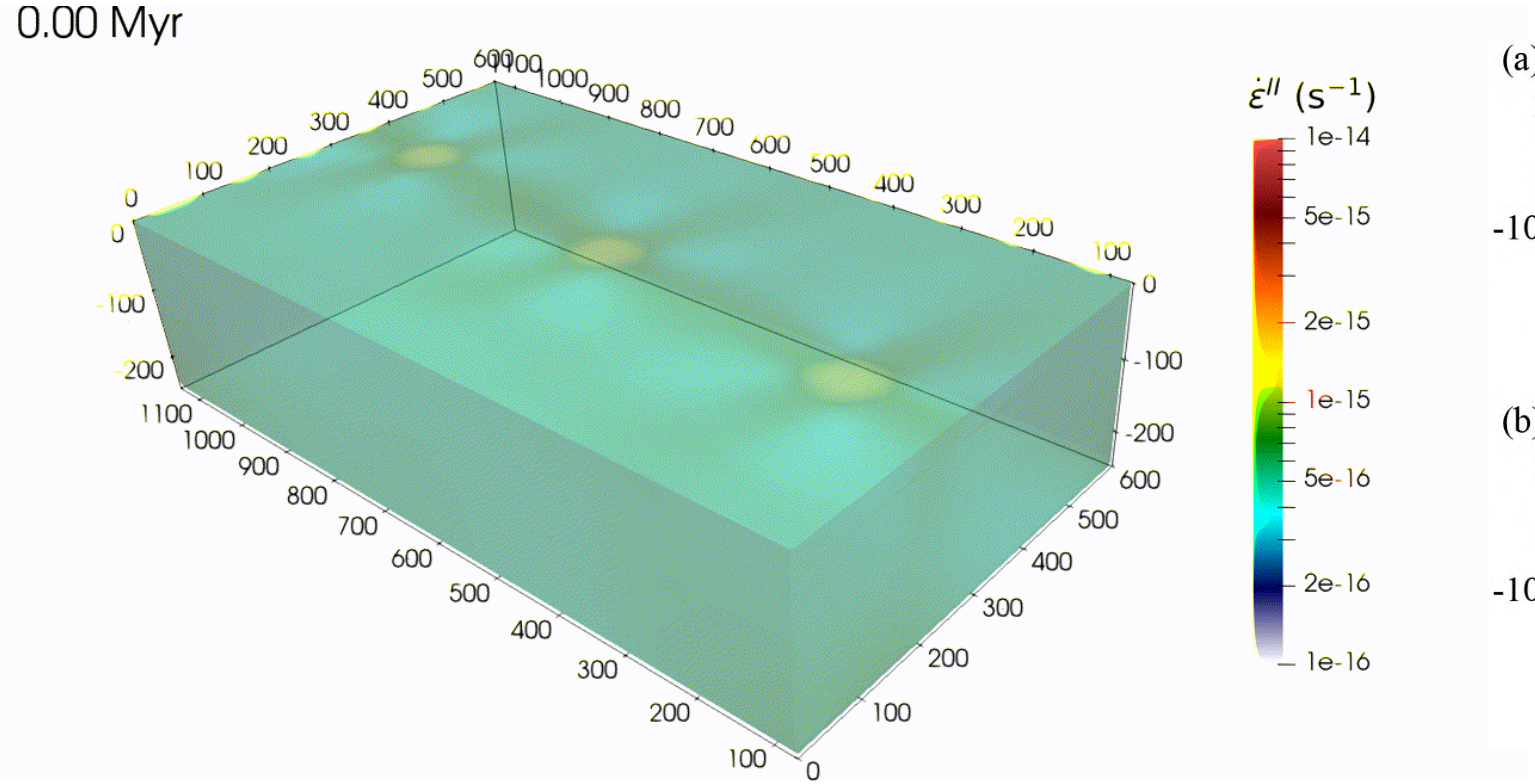
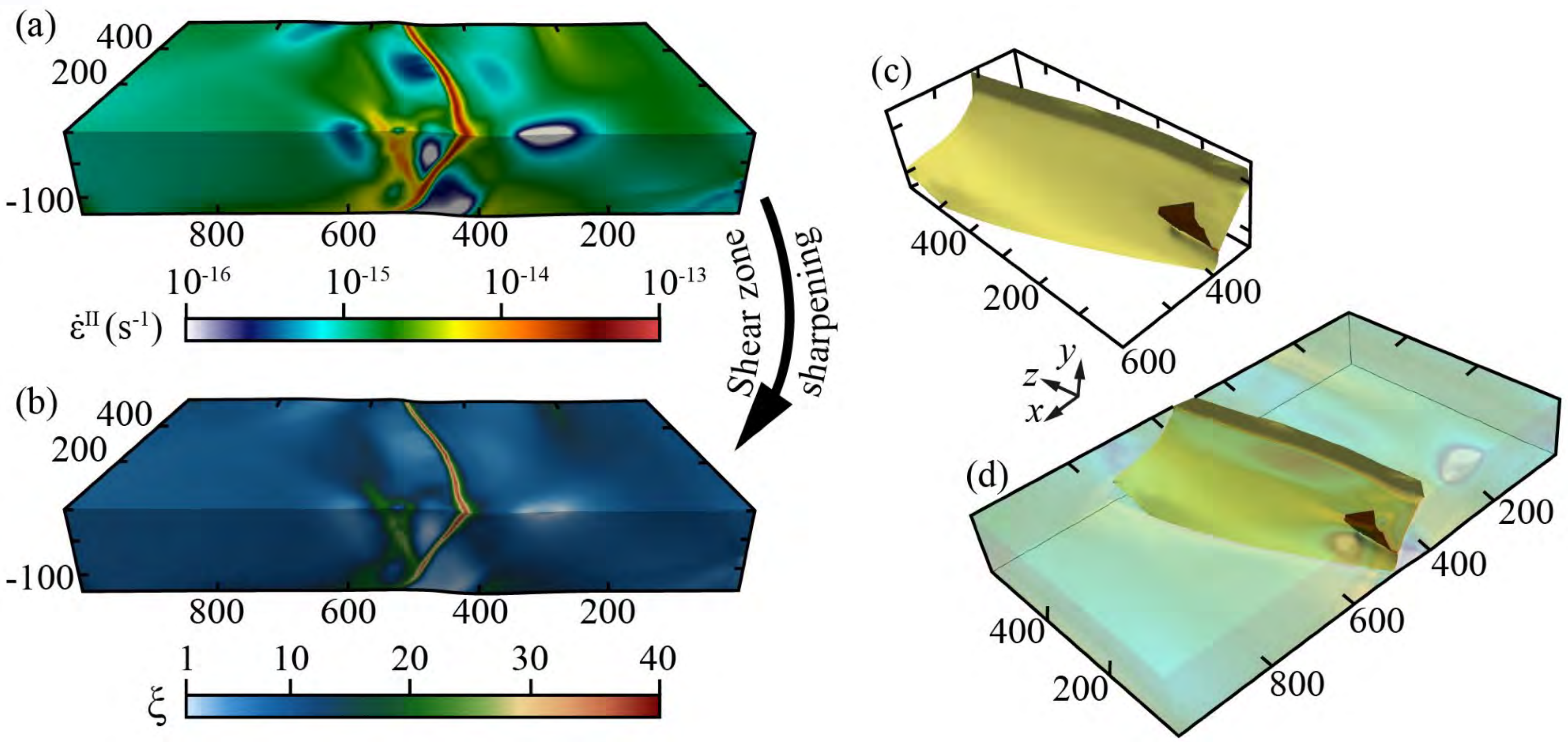
Earthquake faults, stress and rheology from novel 3D strike-slip geodynamic models

Anthony Jourdon, J. Nicolas Hayek,
Dave A. May, **Alice-Agnes Gabriel**





Using novel 3D strike-slip geodynamic models to derive crucial information about earthquake faults, their stress states, and the rheological properties of the Earth's crust.

Jourdon, Hayek, May & Gabriel, 2024, ArXiv: doi:10.48550/arXiv.2407.20609

What is the impact of long-term deformation and rheology of the continental crust on earthquake dynamic rupture?

- Over **millions of years**, Earth's interior can be treated as non-linear highly viscous fluids
- Long-term mechanical behavior of the lithosphere heavily depends on rock rheology, influenced by chemical composition, temperature & deformation history
- Lower continental crust deforming exclusively viscously (i.e., a **weak crust**) promotes **diffuse deformation**, low reliefs, and relatively low stress states, while continental crust with alternating layers of brittle/plastic and viscous/ductile behavior favors **strain localization**, supports high reliefs, and generates higher stresses
- However, how **long-term rheology of the continental crust impacts earthquake mechanics remains unresolved**

Adapted from van Dinther et al., 2013

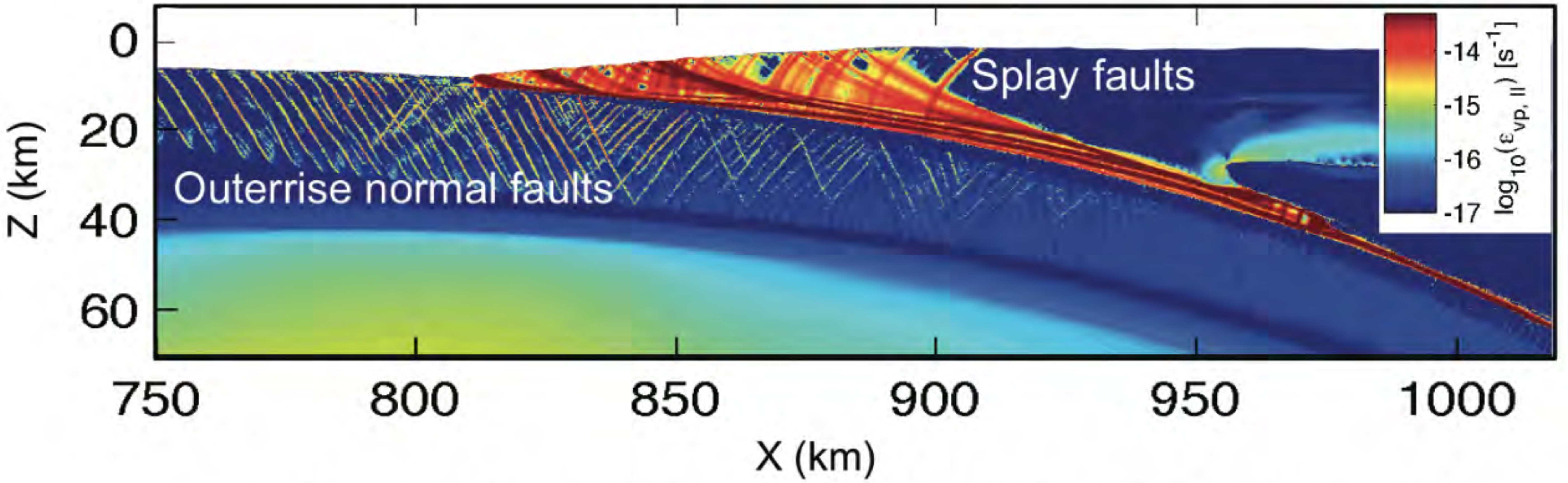


Fig. 1) Spontaneously developed plastic localizations shown in second invariant of the visco-plastic strain rate for a long-term model with dt = 1000 yr.

Solve conservation of momentum for a non-linear incompressible fluid:

$$\nabla\cdot\underbrace{\underline{\underline{\tau}}(\mathbf{u},p,T)}_{\text{Deviatoric stress}} - \overbrace{\nabla p}^{\text{Pressure}} + \overbrace{\rho\mathbf{g}}^{\text{Volume forces}} = \mathbf{0}$$

$$\underbrace{\nabla\cdot\mathbf{u} = 0}_{\text{Mass conservation}}$$

Coupled with thermal advection-diffusion:

$$\rho C_p\left(\frac{\partial T}{\partial t} + \underbrace{\mathbf{u}\cdot\nabla T}\right) = \underbrace{\nabla\cdot(k\nabla T)} + \underbrace{H}_{\text{Heat sources}}$$

(radiogenic + shear heating)

Rheological model:

$$\underline{\underline{\tau}}(\mathbf{u},p,T) = 2\underbrace{\eta(\mathbf{u},p,T)}_{\text{Non-linear viscosity}}\underbrace{\underline{\dot{\varepsilon}}(\mathbf{u})}_{\text{Strain-rate}}$$

Viscous flow → **Dislocation creep:**

$$\eta_v(\mathbf{u},p,T) := A^{-\frac{1}{n}}\left(\underbrace{\dot{\varepsilon}^{II}(\mathbf{u})}_{\text{Strain-rate tensor norm}}\right)^{\frac{1}{n}-1}\exp\left(\frac{E+\overbrace{pV}^{\text{Pressure}}}{nR\underbrace{T}_{\text{Temperature}}}\right)$$

Frictional/plastic behaviour → **Drucker-Prager:**

$$\tau_{yield}(p) = \underbrace{C}_{\text{Cohesion}}\cos(\phi) + p\sin(\underbrace{\phi}_{\text{Friction}})$$

$$\eta_p(\mathbf{u},p) := \frac{\tau_{yield}(p)}{2\dot{\varepsilon}^{II}(\mathbf{u})}$$

Effective viscosity:

$$\eta(\mathbf{u},p,T) = \min(\eta_v,\eta_p)$$

Dynamic rupture simulations must rely on initial conditions

- For example, the **2021 Mw 7.4 Maduo, Tibet,** earthquake: Complex fault **geometry**, **prestress** heterogeneity, and **fracture energy variability** drive **non-typical** unilateral, double-onset **supershear** transition, cascading rupture dynamically triggering two adjacent fault branches and signals in off-fault damage patterns

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Non-Typical Supershear Rupture: Fault Heterogeneity and Segmentation Govern Unilateral Supershear and Cascading Multi-Fault Rupture in the 2021 M_w7.4 Maduo Earthquake

J. N. Hayek, M. Marchandon, D. Li, L. Pousse-Beltran, J. Hollingsworth, T. Li, A.-A. Gabriel

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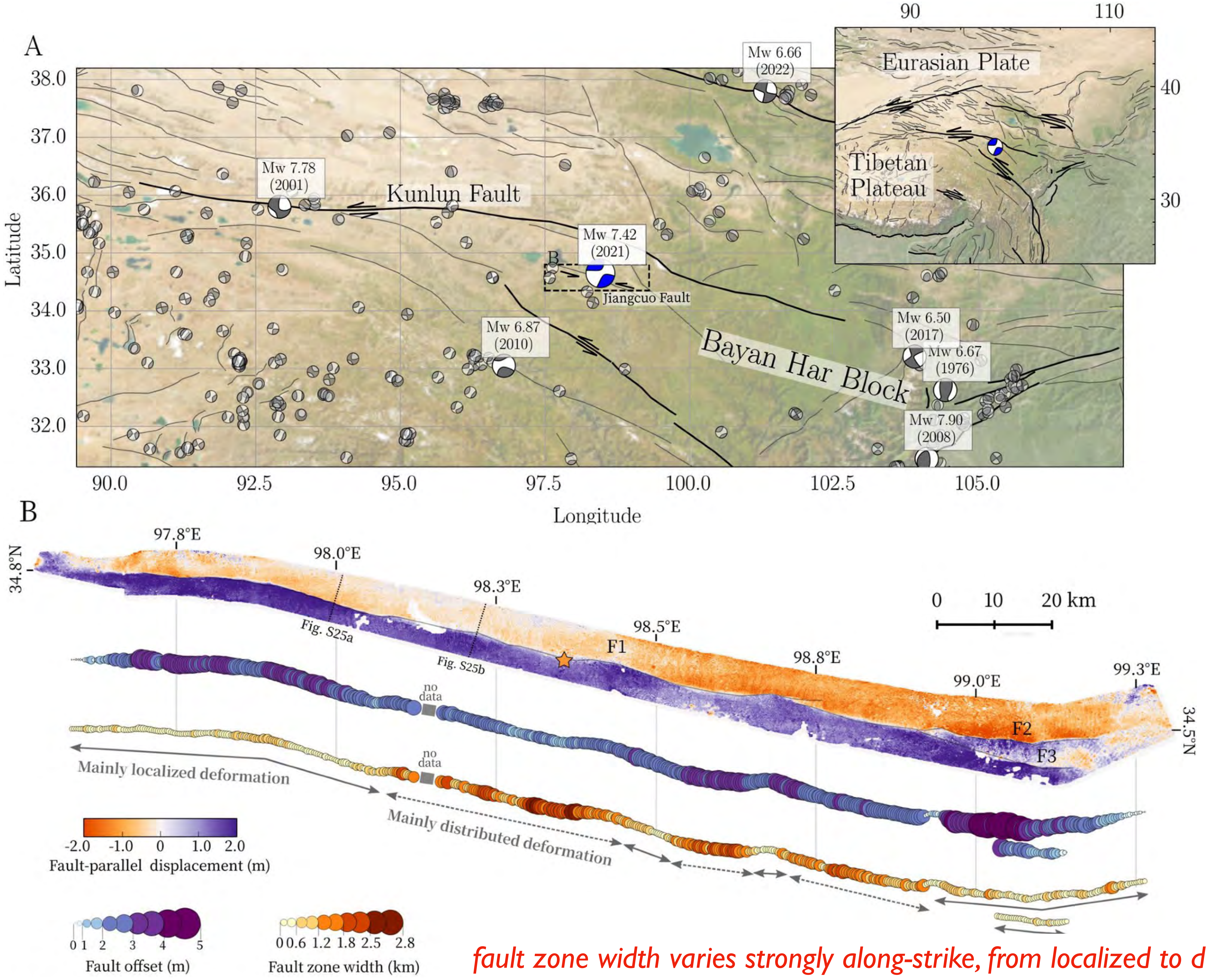
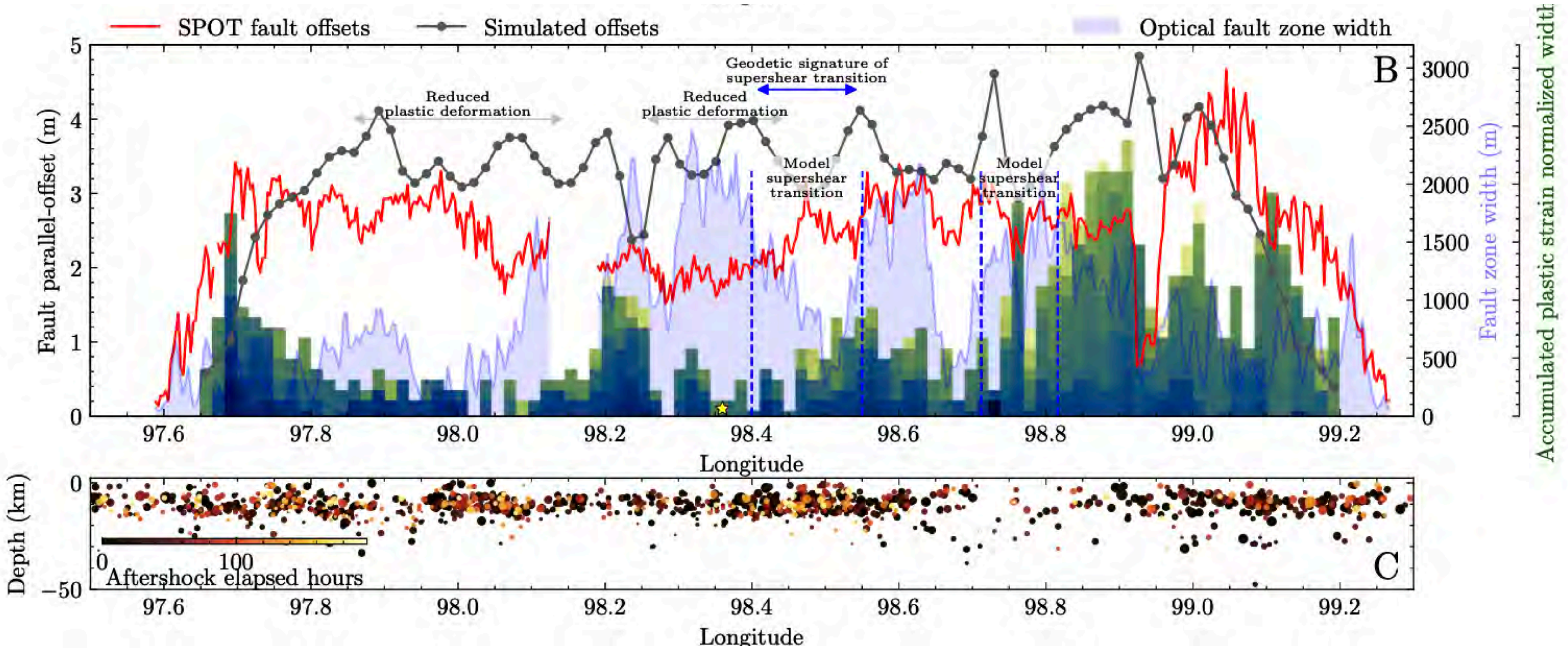


fault zone width varies strongly along-strike, from localized to distritubed (6m resolution SPOT 6/7 satellite imagery)



Signatures of multiple supershear transitions in modeled and measured off-fault deformation (as in Jara et al., 2021)

Dynamic rupture simulations must rely on initial conditions

- **Initial conditions** govern how earthquakes propagate (e.g., crack- vs. pulse-like dynamics and subshear vs. supershear rupture speeds) and arrest (e.g., Kame et al., 2003; Bai & Ampuero, 2017) and the radiation of seismic waves and ground shaking (e.g., Harris et al., 2021; Taufiqurrahman et al., 2023)

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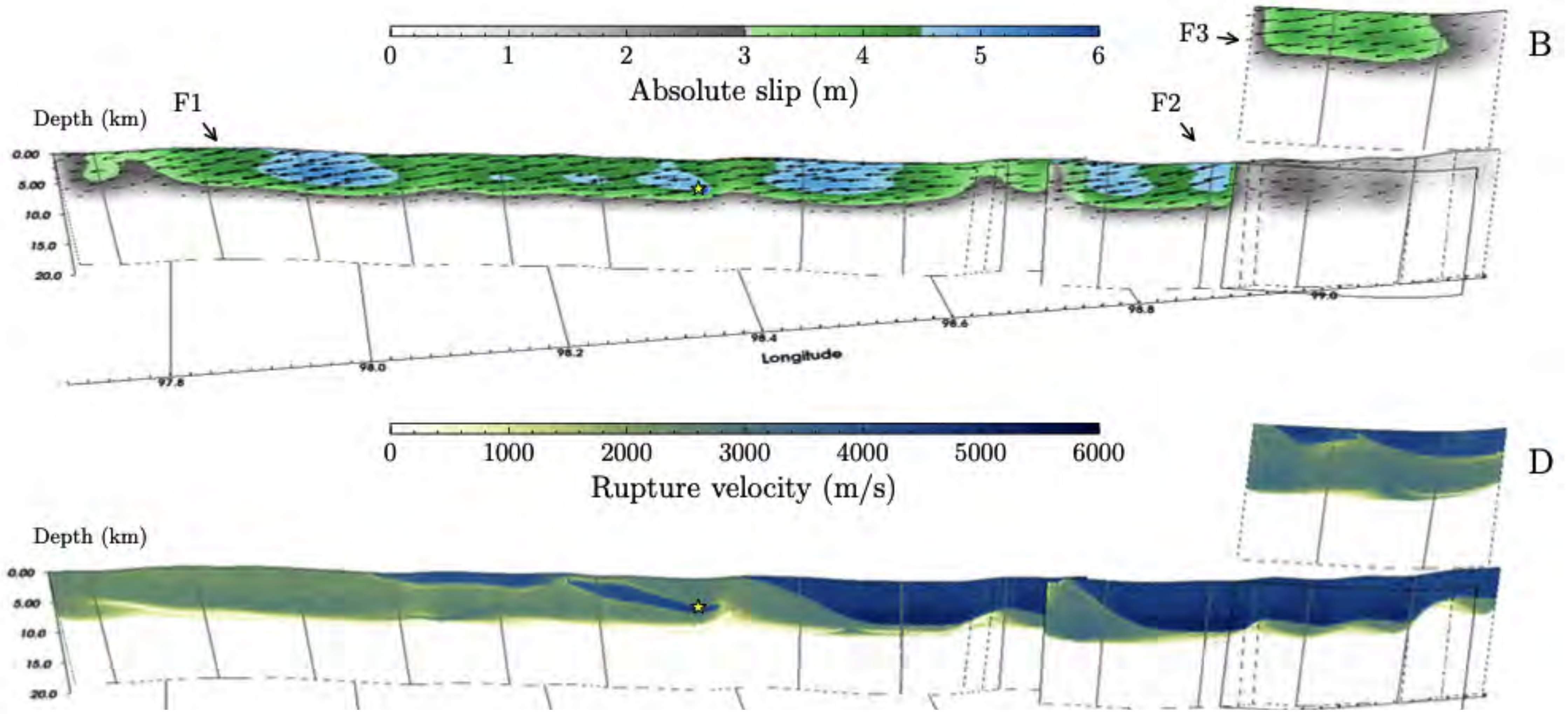
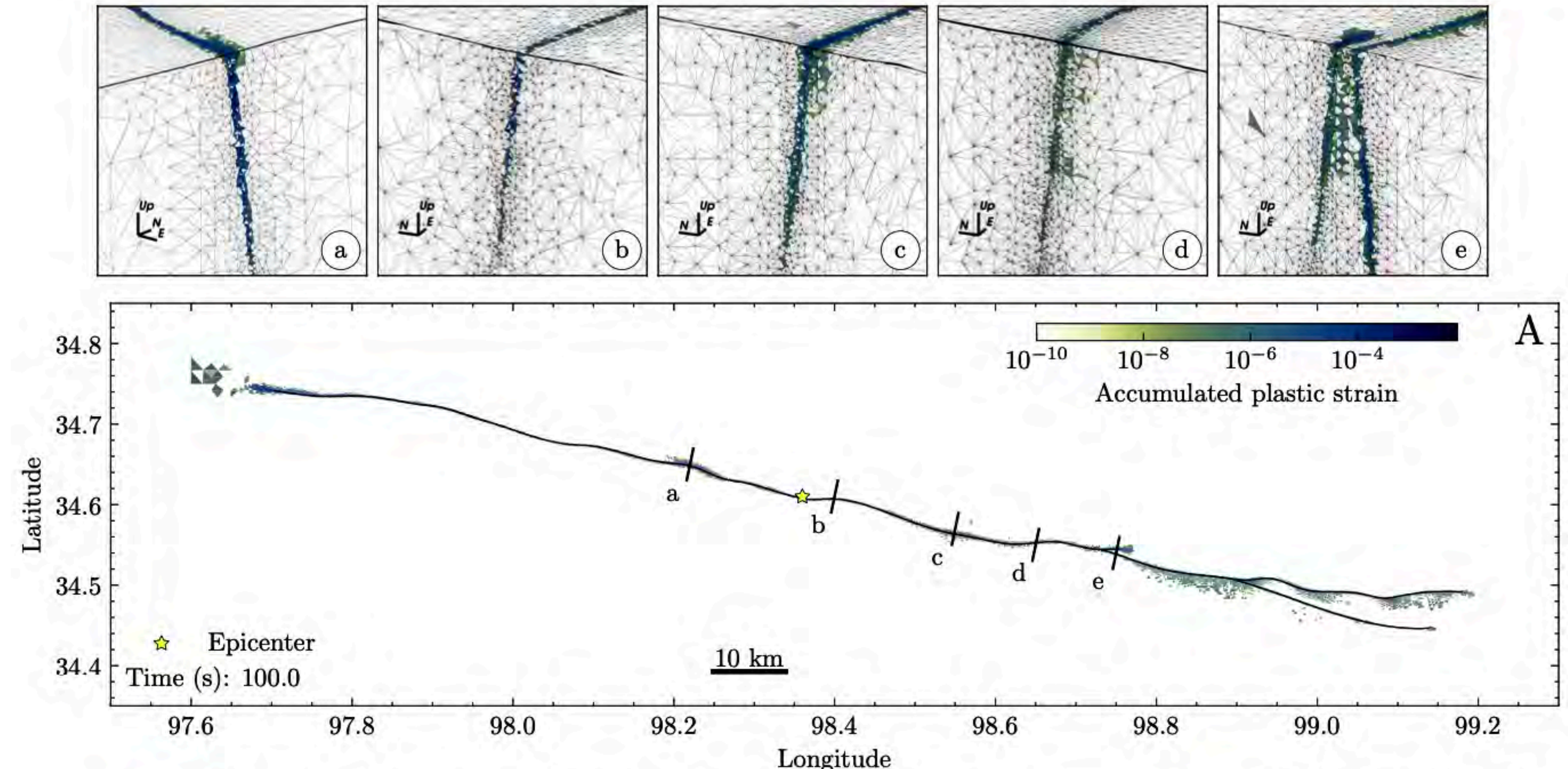
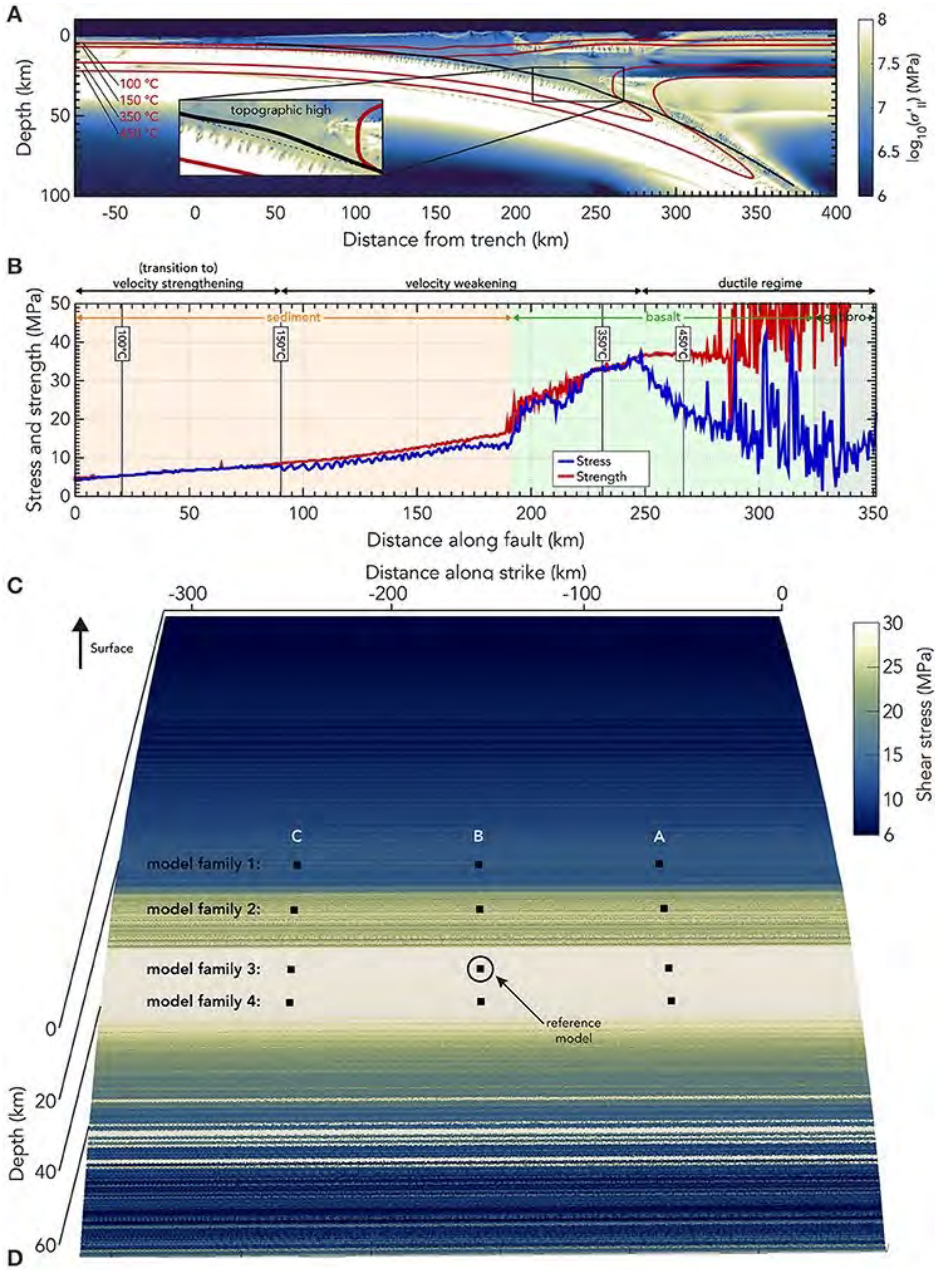


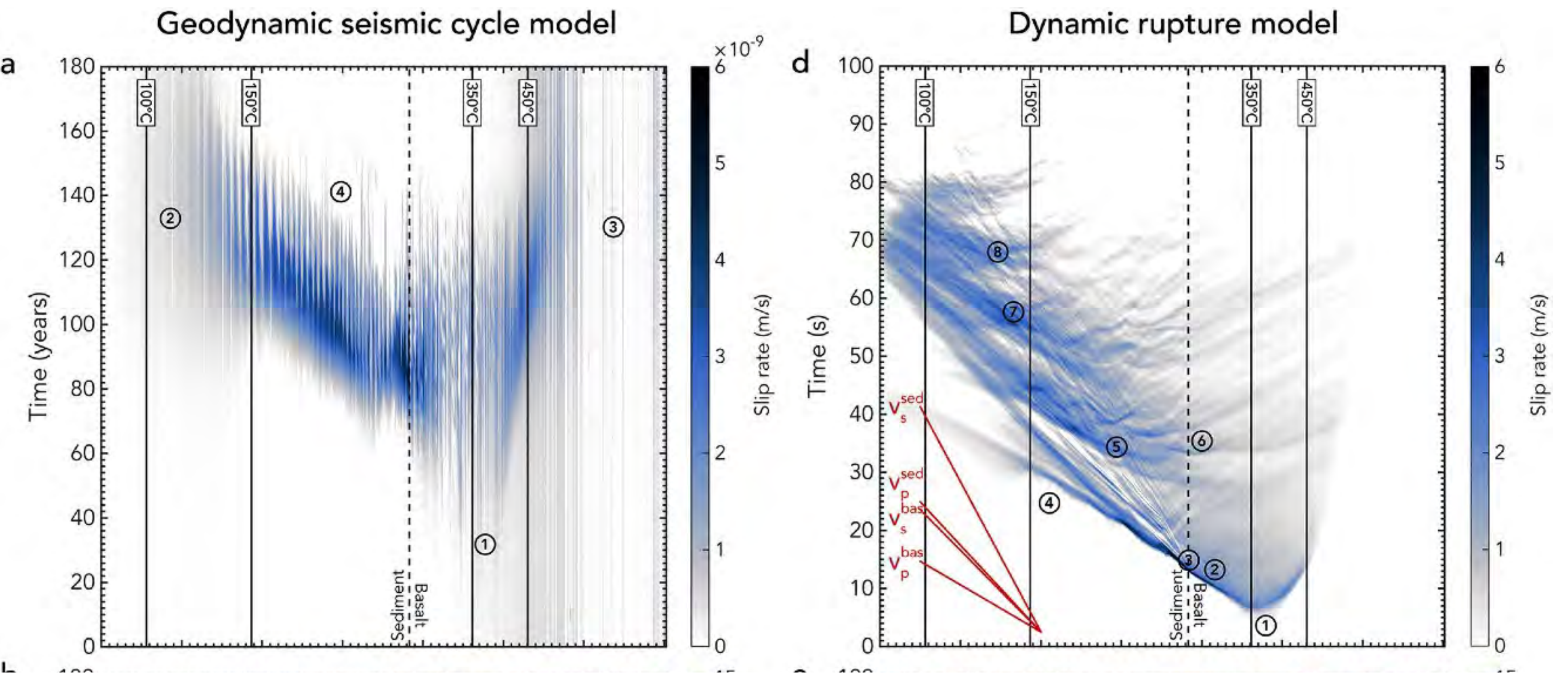
multiple, sustained supershear episodes to the East: fault maturity, homogeneous stress-strength conditions and geometric simplicity not required for supershear rupture

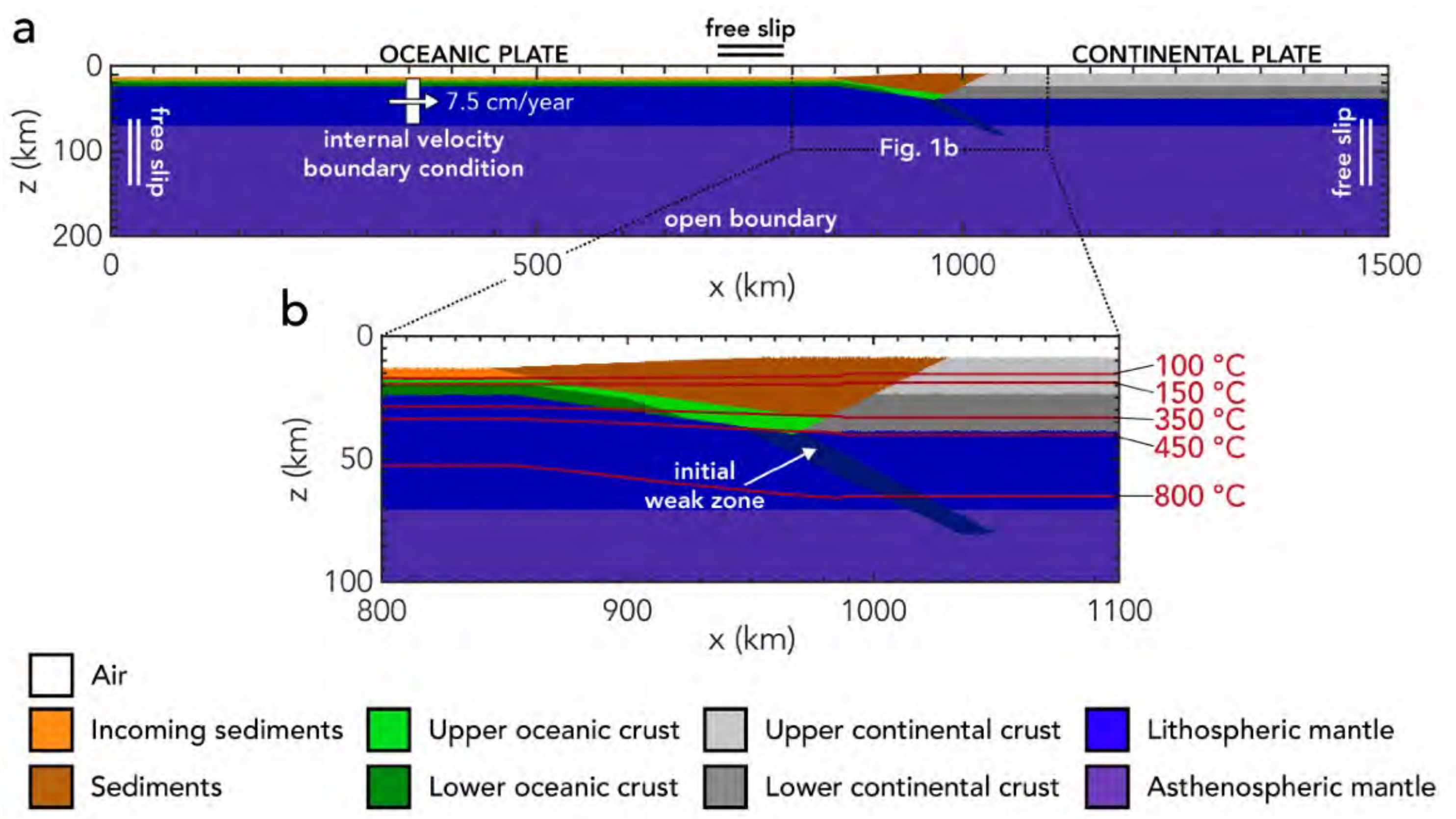


Previous work linking 2D subduction geodynamic models and rupture dynamics

- **2D subduction** geodynamic models have been linked to megathrust and splay fault rupture dynamic earthquake and tsunami models
- **Linked rupture dynamics** models revealed a strong dependency on lithological variations resolved by the long-term model, which are capable of slowing, stopping, or accelerating rupture when passed and thus significantly altering co-seismic deformation
- Typically requires **constructing** infinitesimally thin **2D fault surfaces** from geodynamic volumetric shear zones
- 2D megathrust shear stress and fault strength from a geodynamic model were **extruded** to the third dimension for 3D dynamic rupture models *(Wirp et al., 2021; Madden et al., 2021)*



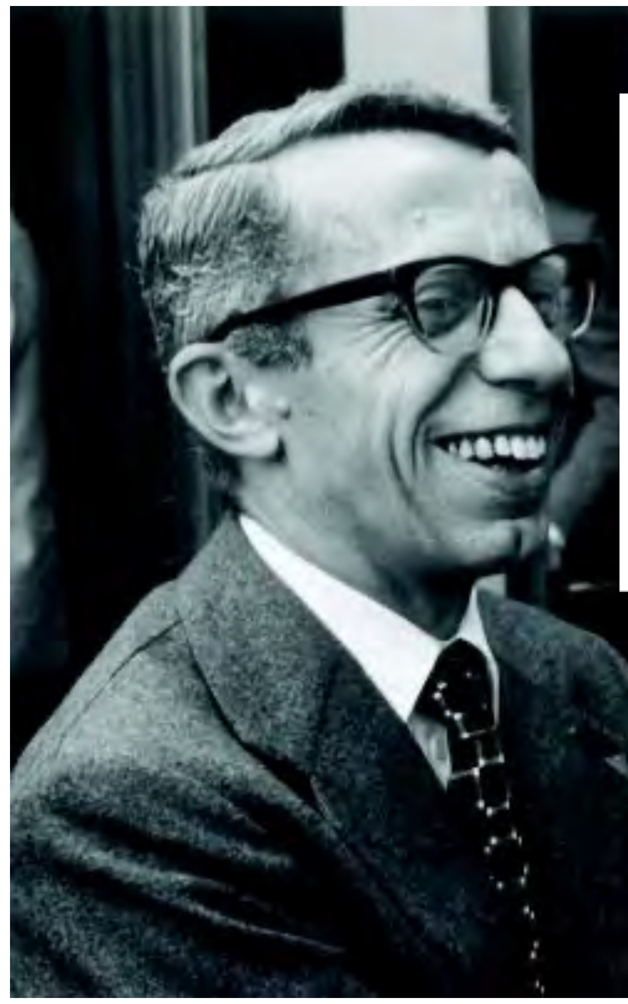


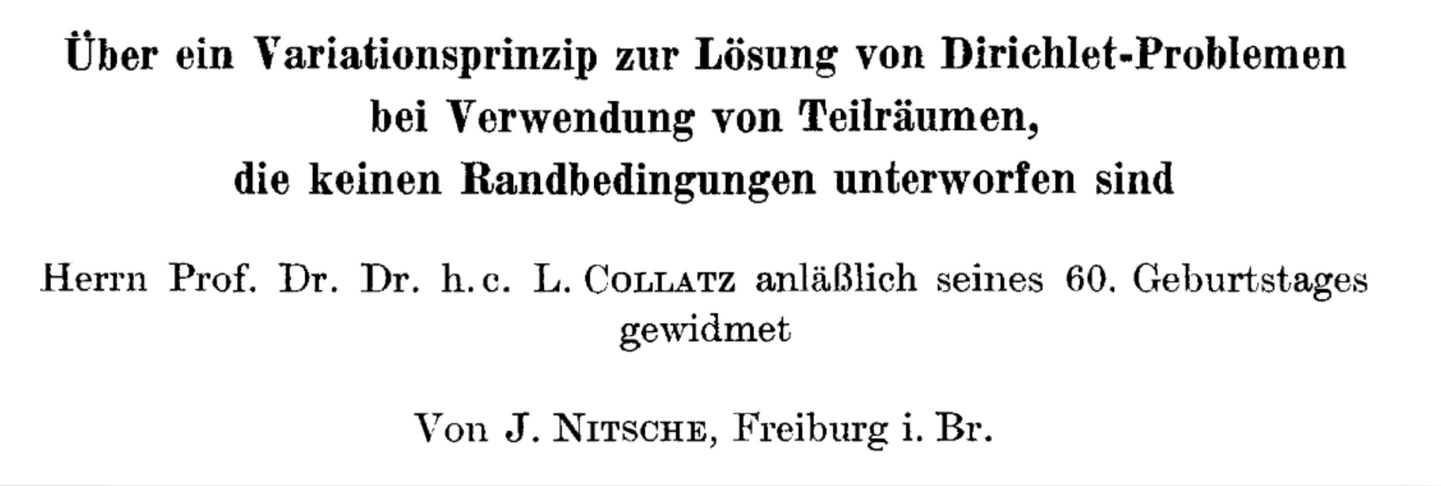


Sobolev & Muldashev, 2017, "Modeling seismic cycles of great megathrust earthquakes across the scales with focus at postseismic phase"
Van Zelst et al., 2019, "Modeling Megathrust Earthquakes Across Scales: One-way Coupling From Geodynamics and Seismic Cycles to Dynamic Rupture"
Madden et al., 2021, "Linked 3D modeling of megathrust earthquake-tsunami events: from subduction to tsunami run-up"
Wirp et al., 2021, "3D linked subduction, dynamic rupture, tsunami and inundation modeling: dynamic effects of supershear and tsunami earthquakes, hypocenter location and shallow fault slip"
Van Zelst et al., 2022, "Earthquake rupture on multiple splay faults and its effect on tsunamis"

Novel 3D strike-slip geodynamic models

- Using open-source FE software **pTatin3D** (PETSc-based, *May et al., 2015*) solving Stokes equations
- **Novel generalized Navier-slip geodynamic boundary conditions** (*Jourdon, May, Gabriel (2024), ArXiv*) using the Nitsche method that allow for **self-consistent formation of strongly oblique systems of strike-slip shear zones minimizing boundary effects**
- Prescribing 3 Gaussian weak zones, which help to obtain a **simple but non-planar shear zone**



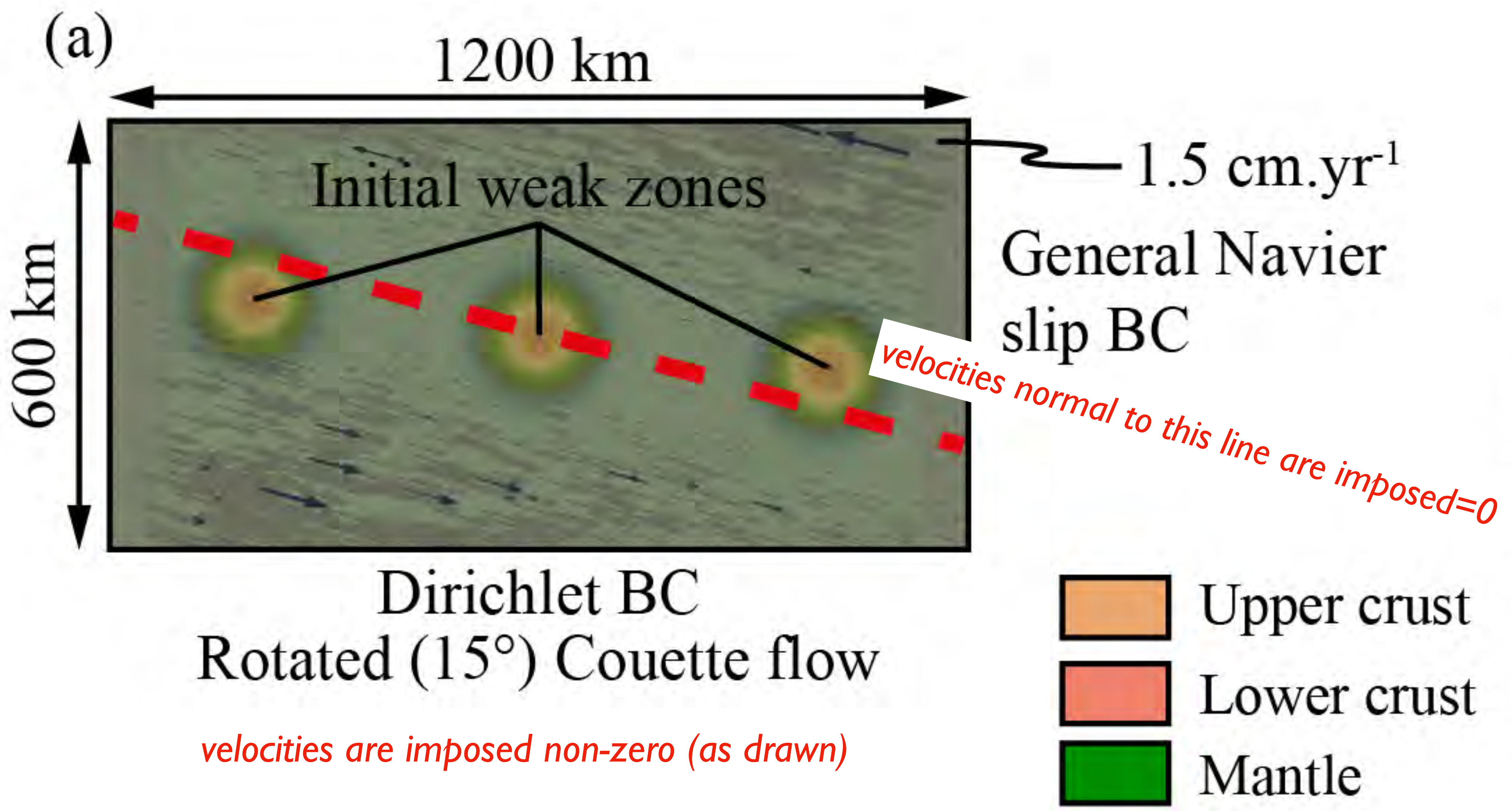


Über ein Variationsprinzip zur Lösung von Dirichlet-Problemen
bei Verwendung von Teilräumen,
die keinen Randbedingungen unterworfen sind

Herrn Prof. Dr. Dr. h.c. L. Collatz anläßlich seines 60. Geburtstages gewidmet

Von J. Nitsche, Freiburg i. Br.

Joachim Nitsche (1971)



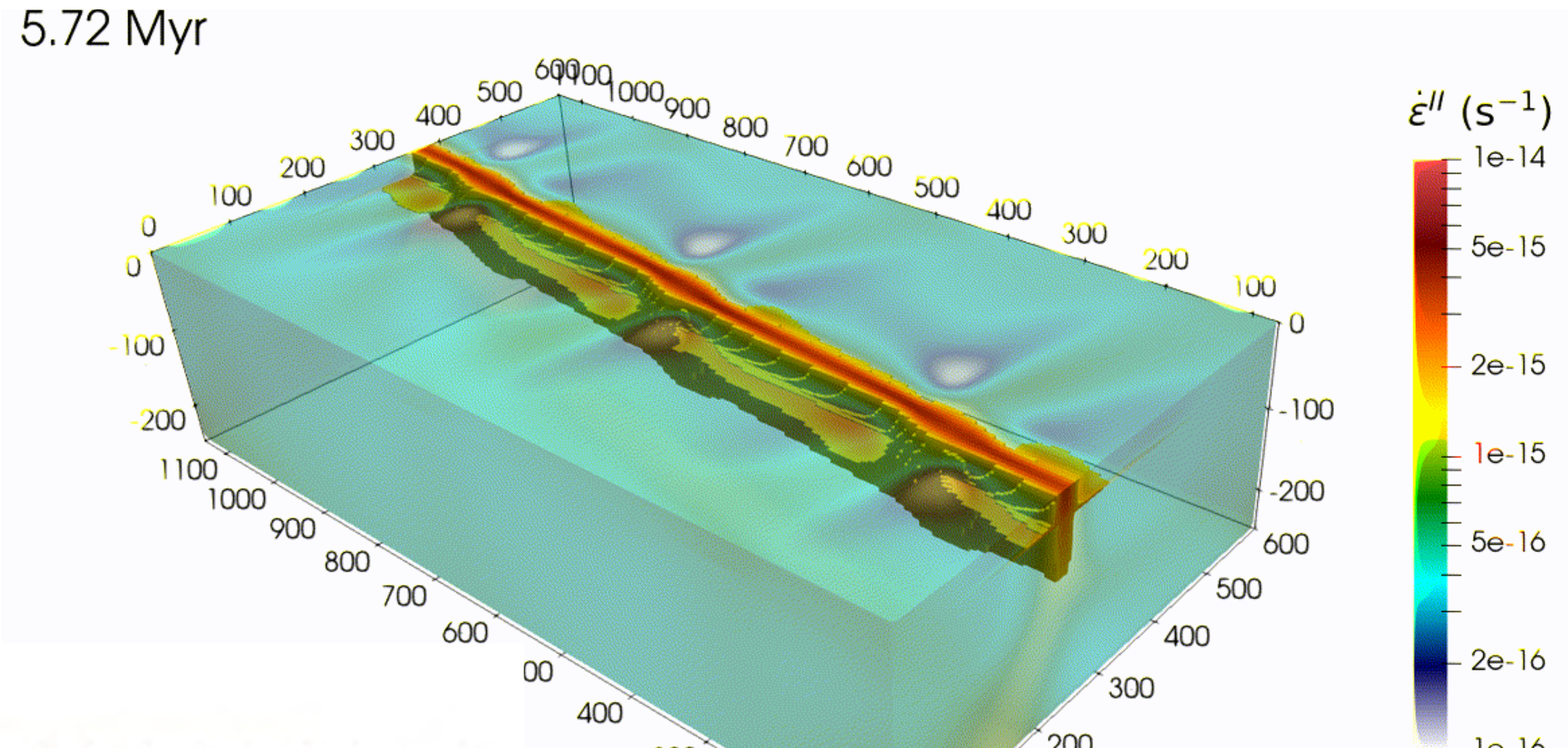
velocities normal to this line are imposed=0

velocities are imposed non-zero (as drawn)

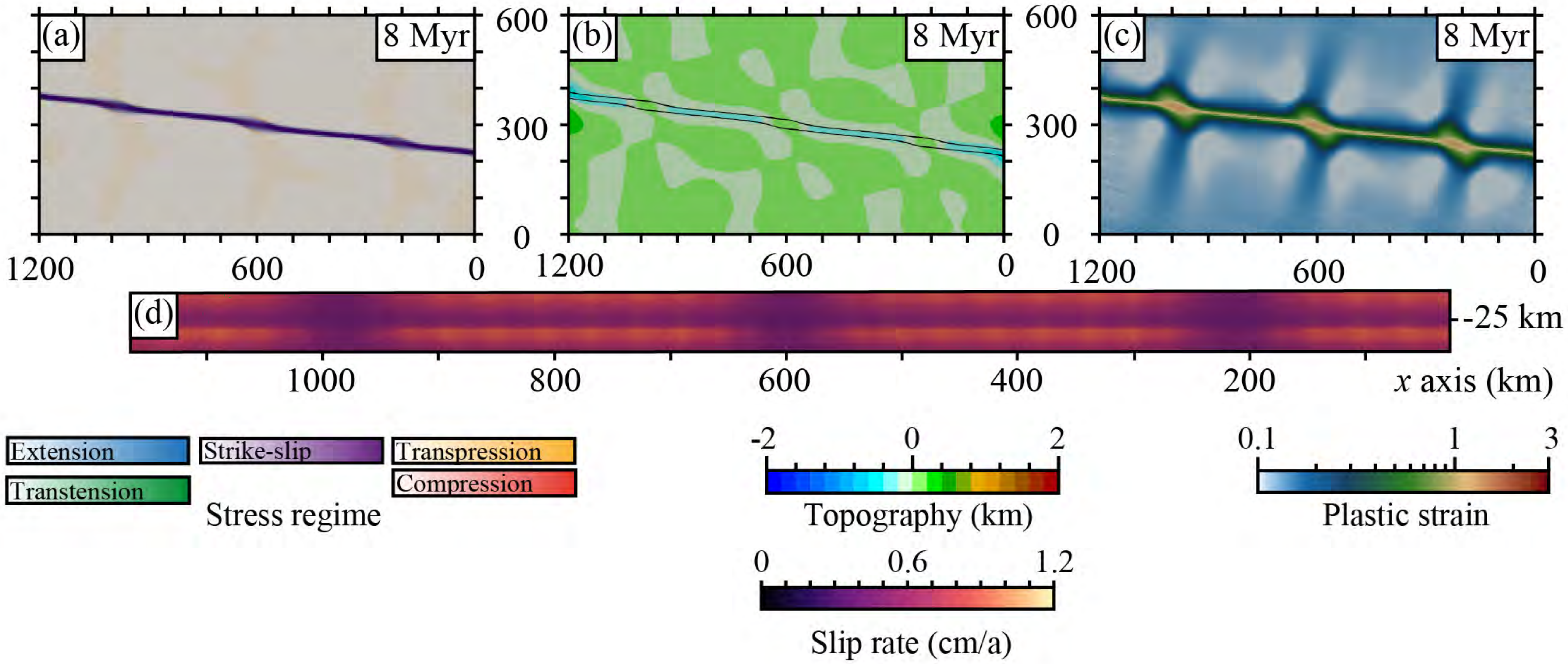
***Jourdon, May, Gabriel (2024).* "Generalisation of the Navier-slip boundary condition to arbitrary directions: Application to 3D oblique geodynamic simulations", https://doi.org/10.48550/arXiv.2407.12361**

Weak crust

- Low **topography**
- **Diffuse deformation** in the lower crust and around the shear zone
- Low long-term slip rate of ~0.6 cm/a (less than half of plate motion)
- Spontaneously evolving **pure strike-slip** stress regime



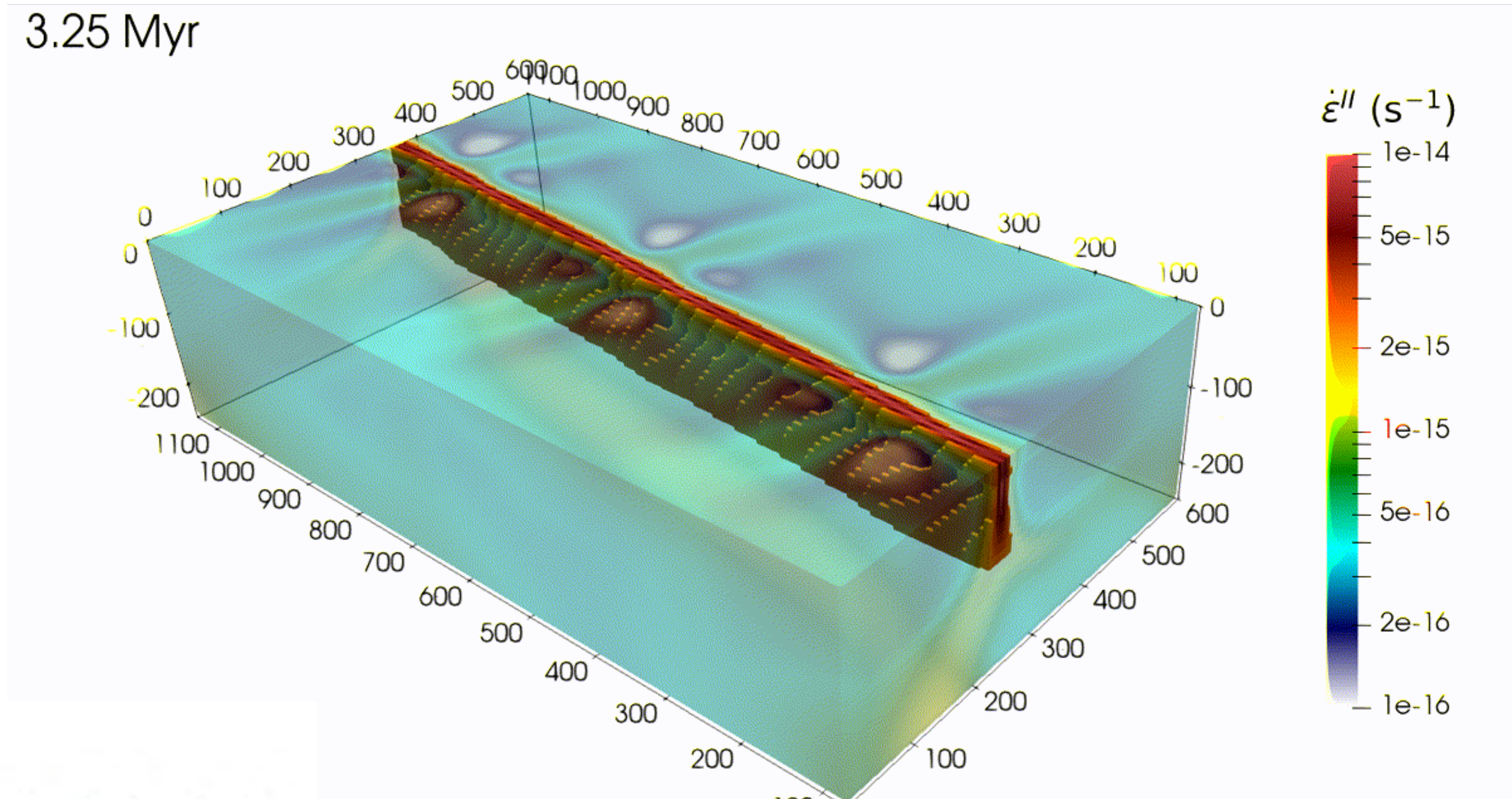
Quartz upper and lower crust



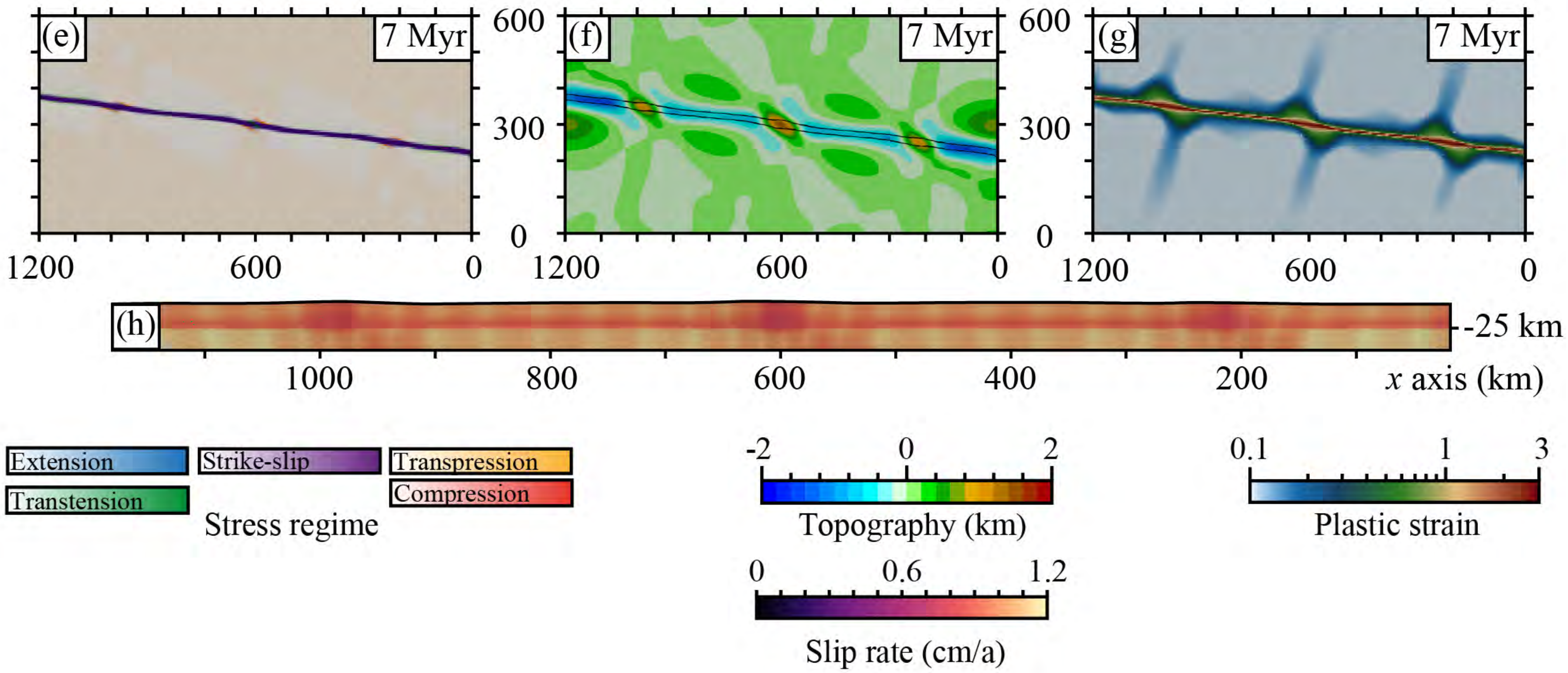
***Jourdon, Hayek, May, Gabriel* (2024). "Coupling 3D geodynamics and dynamic earthquake rupture: fault geometry, rheology and stresses across timescales", ArXiv: doi:10.48550/arXiv.2407.20609**

Intermediately-strong crust

- **Higher topography** with reliefs at fault bends and basins in between
- Deformation more **localized** in the crust and around the shear zone
- Higher long-term slip rate ~1 cm/a (2/3 of plate motion)
- Strike-slip stress regime with **compressional** stresses at fault bends



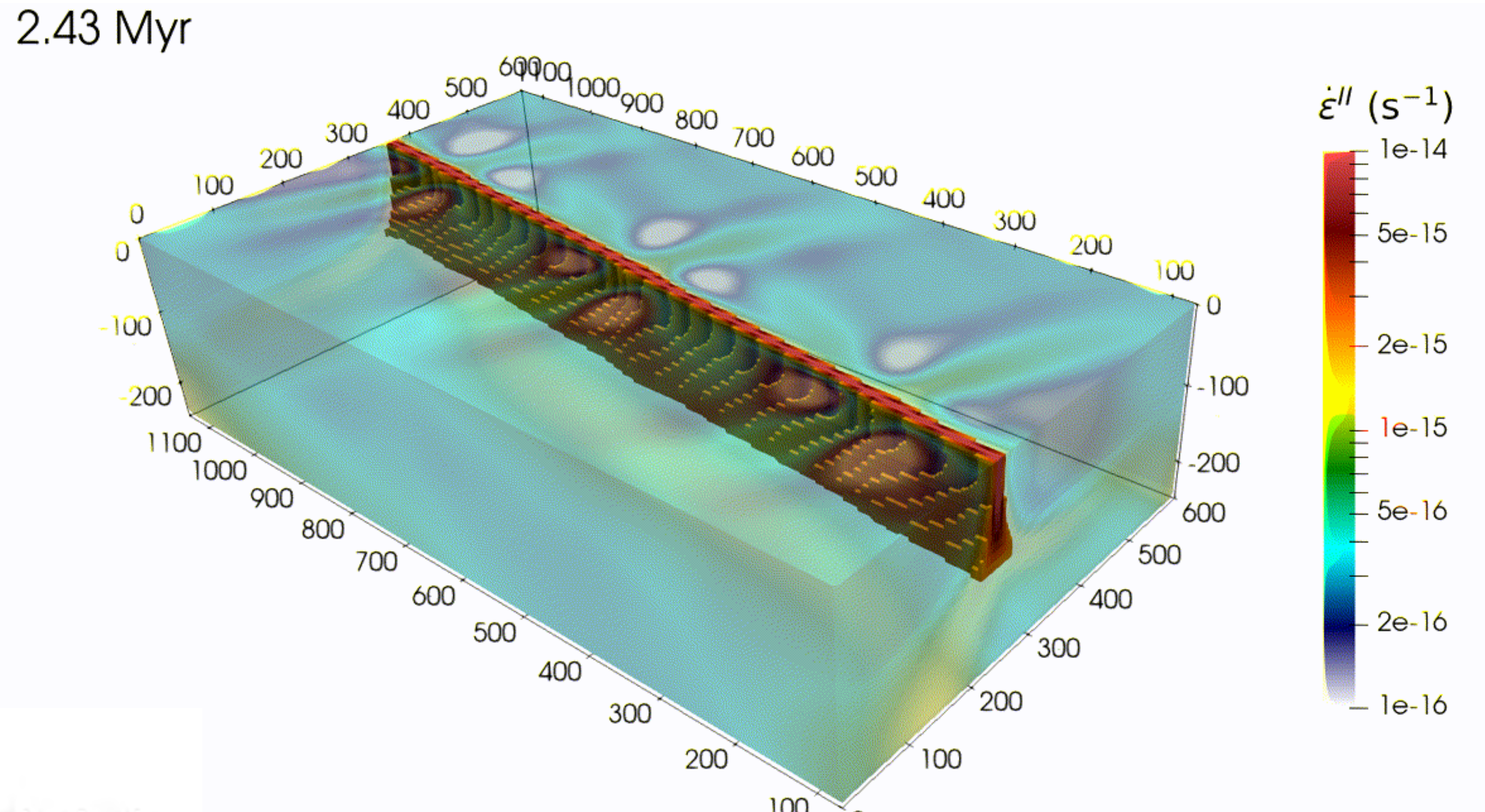
Quartz upper crust - anorthite lower crust



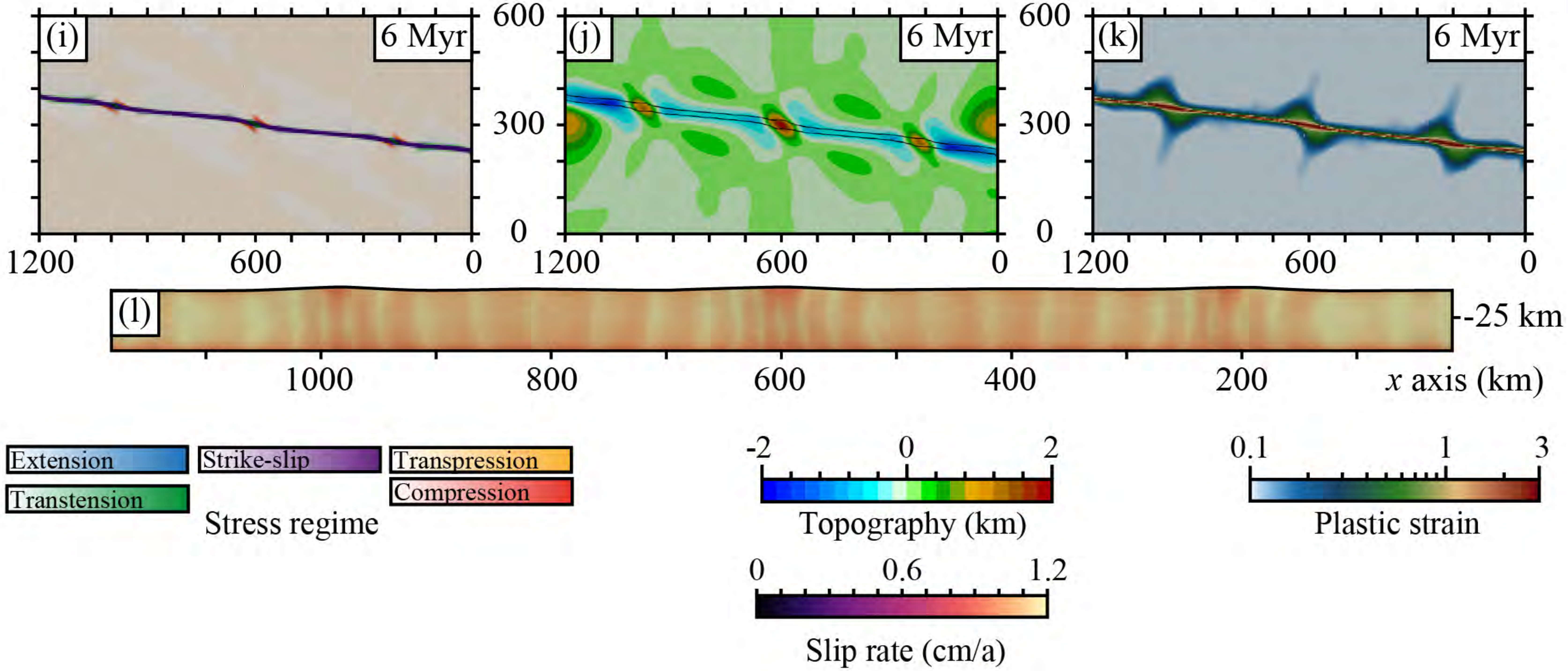
***Jourdon, Hayek, May, Gabriel* (2024). “Coupling 3D geodynamics and dynamic earthquake rupture: fault geometry, rheology and stresses across timescales”, ArXiv: doi:10.48550/arXiv.2407.20609**

Strong crust

- **No flat shear zone in the lower crust**
- Even higher long-term slip rate ~1.2 cm/a (80% of plate motion)



Anorthite upper and lower crust



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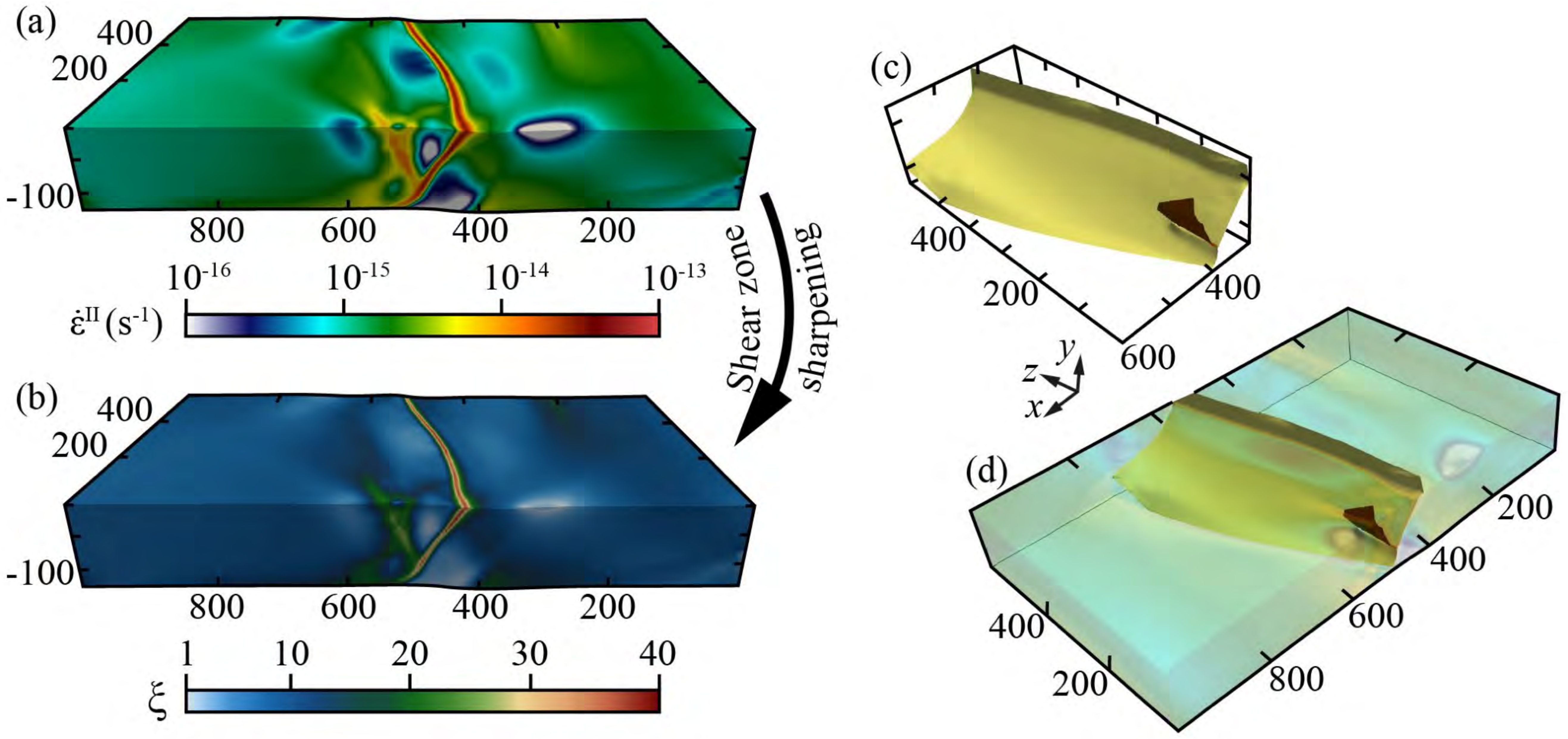
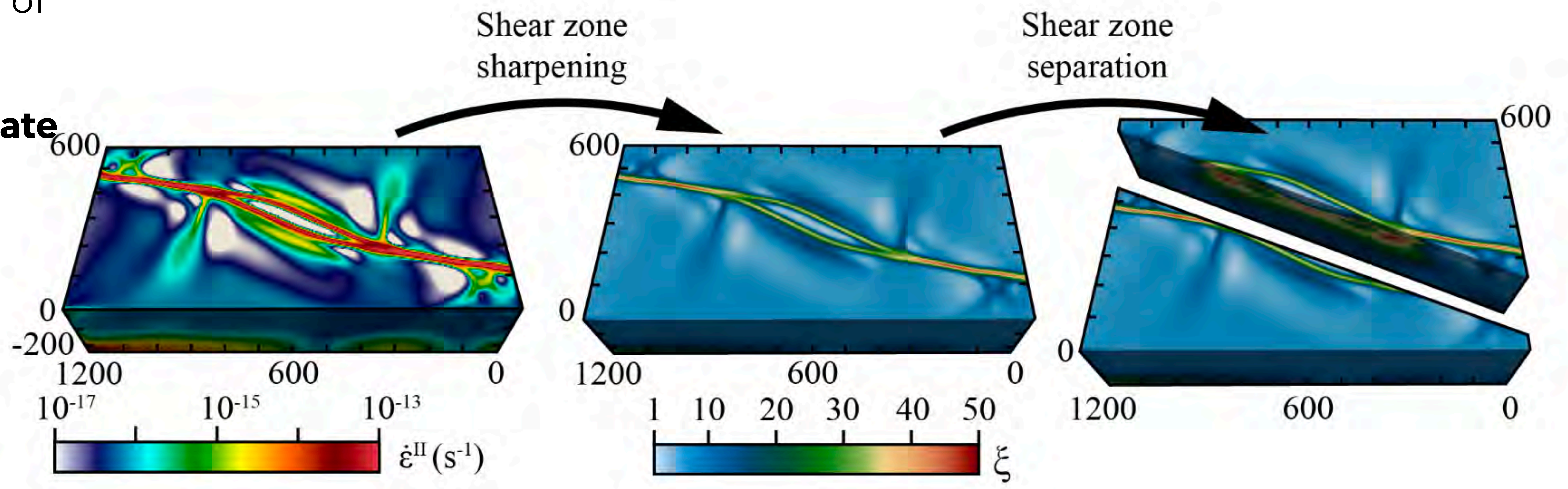
New fault-reconstruction approach

- These models may evolve **complex multi-shear zone geometries and oblique stress states**
- **2D multi-fault reconstruction from 3D shear zones** required but long-standing challenge (also in industry for, e.g., seismic horizons)
- New automatic method based on **medial axis transformation (“skeletonization”) of strain rate norm,** capturing the essential geometric features of volumetric shear zones while reducing its representation to simplified 2D surfaces even of **multiple, complex, intersecting faults**
- Allows for the **evaluation of long-term slip rate** across the faults



ocean-continent subduction model producing two distinct shear-zones, a megathrust, and a conjugate thrust fault

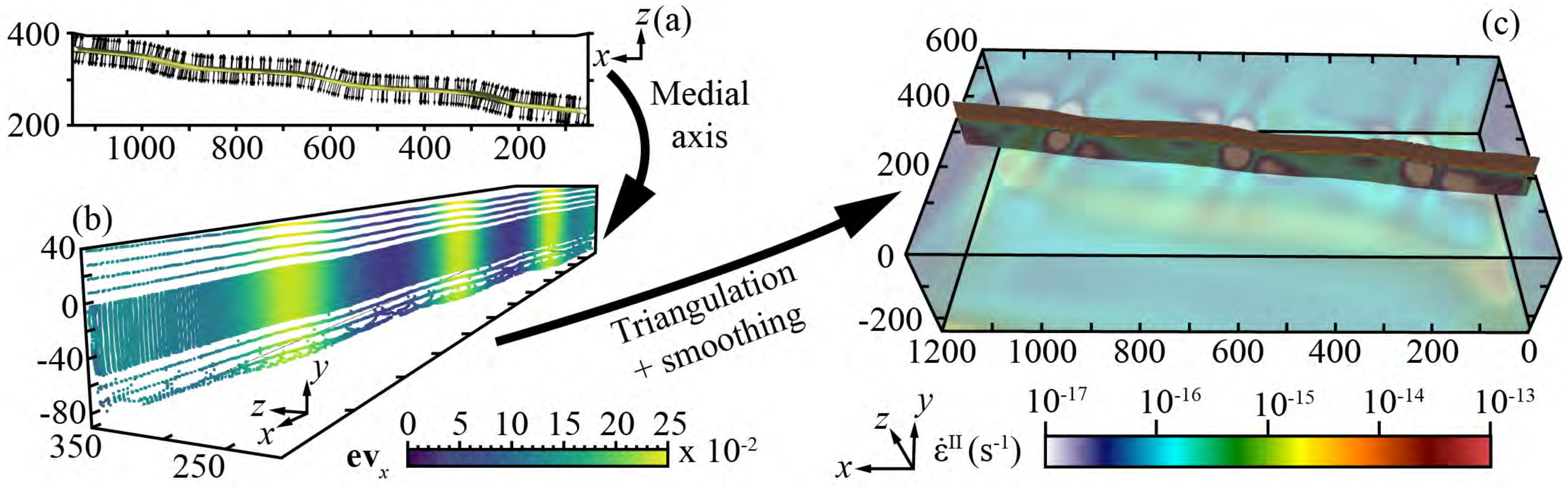


strike- slip shear zone splitting into two branches

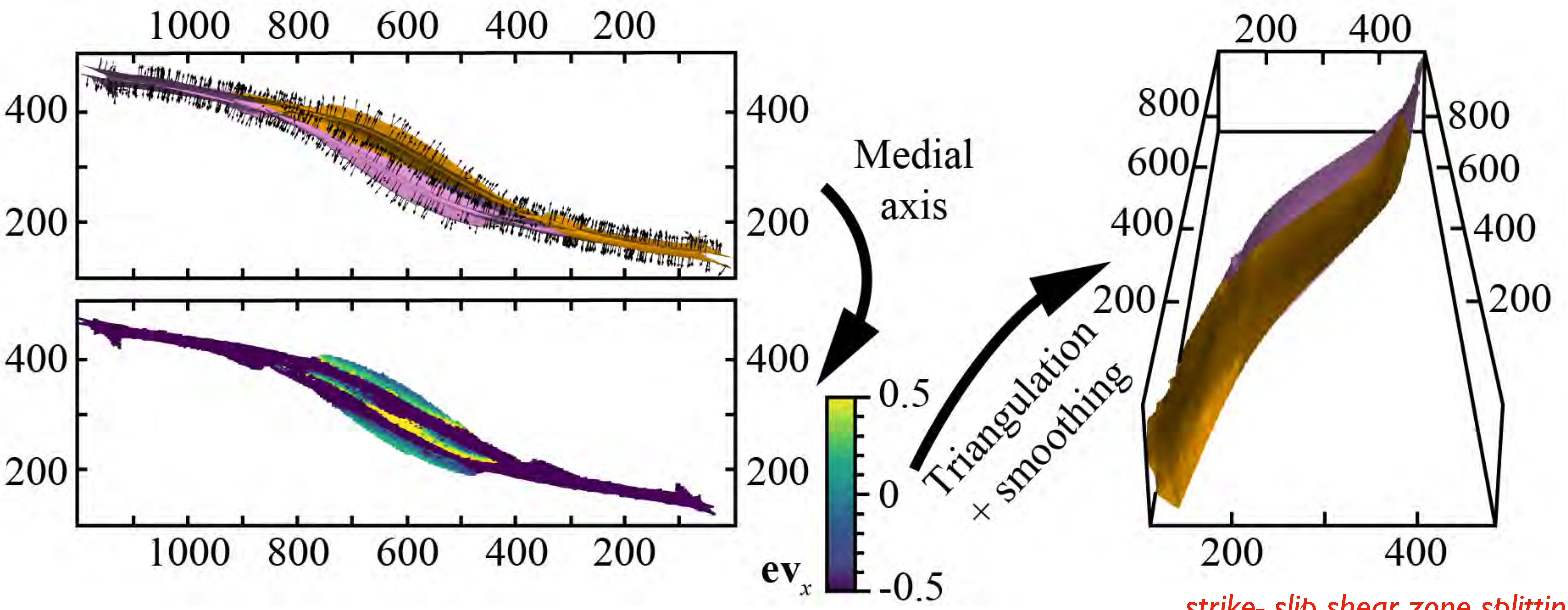
***Jourdon, Hayek, May, Gabriel* (2024). “Coupling 3D geodynamics and dynamic earthquake rupture: fault geometry, rheology and stresses across timescales”, ArXiv: doi:10.48550/arXiv.2407.20609**

New fault-reconstruction approach

- Dimensional reduction is followed by fault-normal **Laplacian smoothing**, **Delaunay triangulation** and **volume splitting**



Simple yet non-planar strike-slip fault embedded in weak, intermediately strong or strong crust



strike- slip shear zone splitting into two branches

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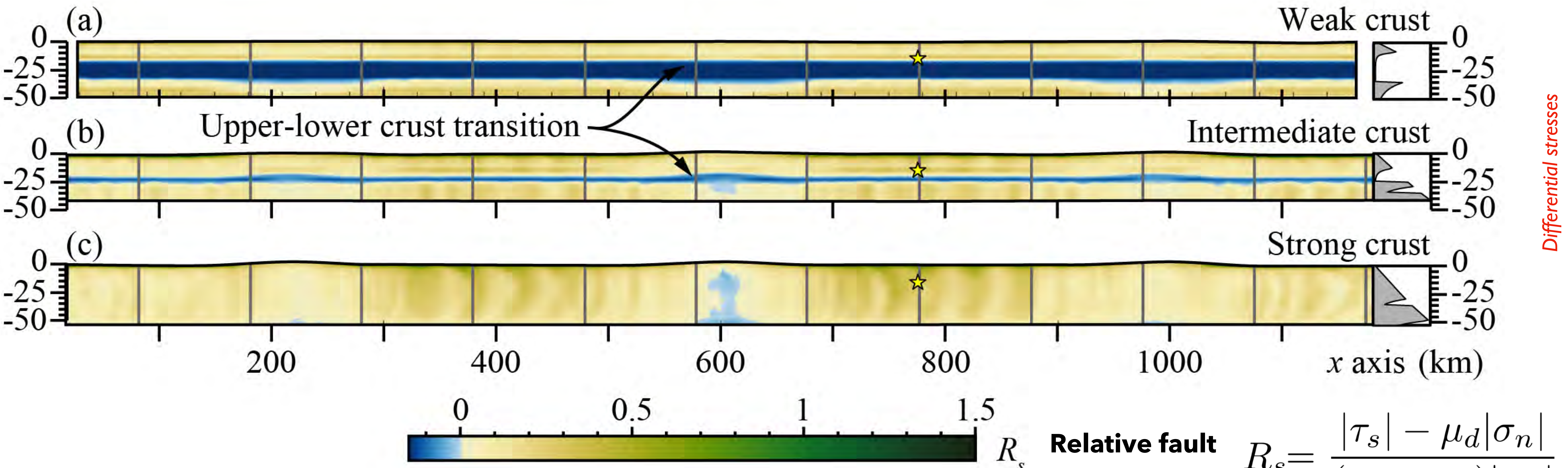
Topography, fault geometry, stress, off-fault cohesion & density from long-term geodynamic models as initial conditions for dynamic rupture models

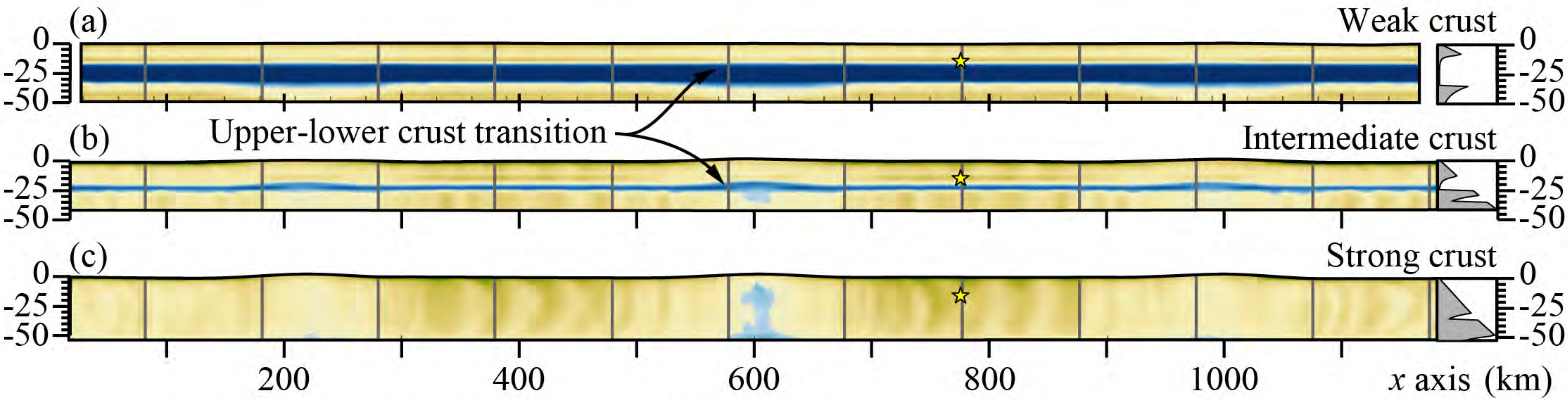


Relative fault strength ratio:

$$R_s = \frac{|\tau_s| - \mu_d|\sigma_n|}{(\mu_s - \mu_d)|\sigma_n|}$$

- **Long-term stress computed from long-term rheology shows that relative fault strength ratio (max. Stress drop/full frictional breakdown strength) is influenced by the crust composition**
- **Brittle-ductile transition** is well marked in the stress state
- Fault's strength Rs < 0 where shear stress < normal stress ➔ corresponds to **viscous deformation in the long-term model**

Topography, fault geometry, stress, off-fault cohesion & density from long-term geodynamic models as initial conditions for dynamic rupture models

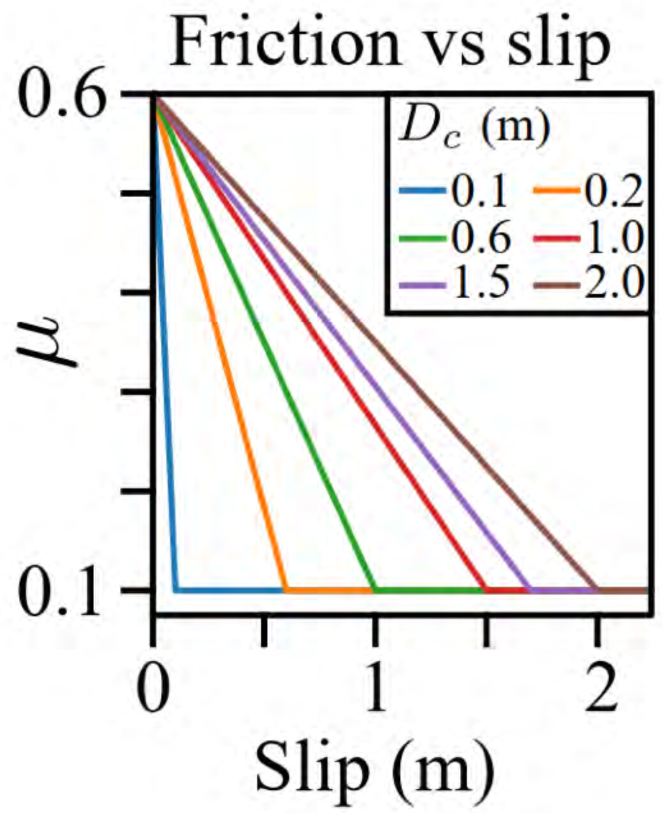


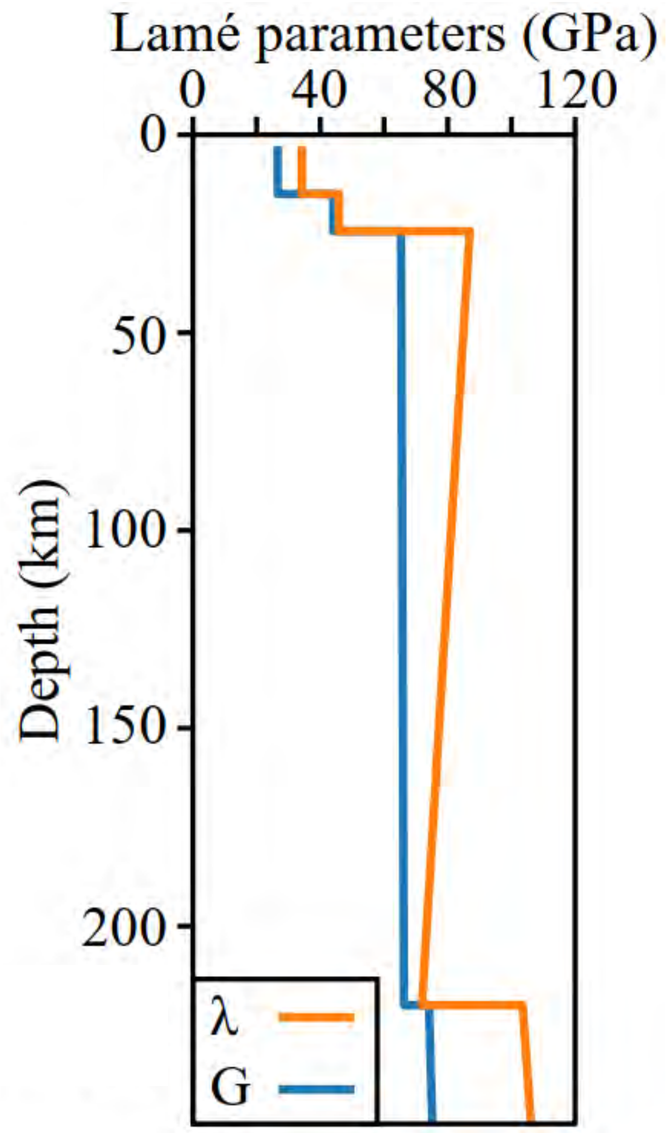
Differential stresses

Static friction $\mu_s = 0.6$

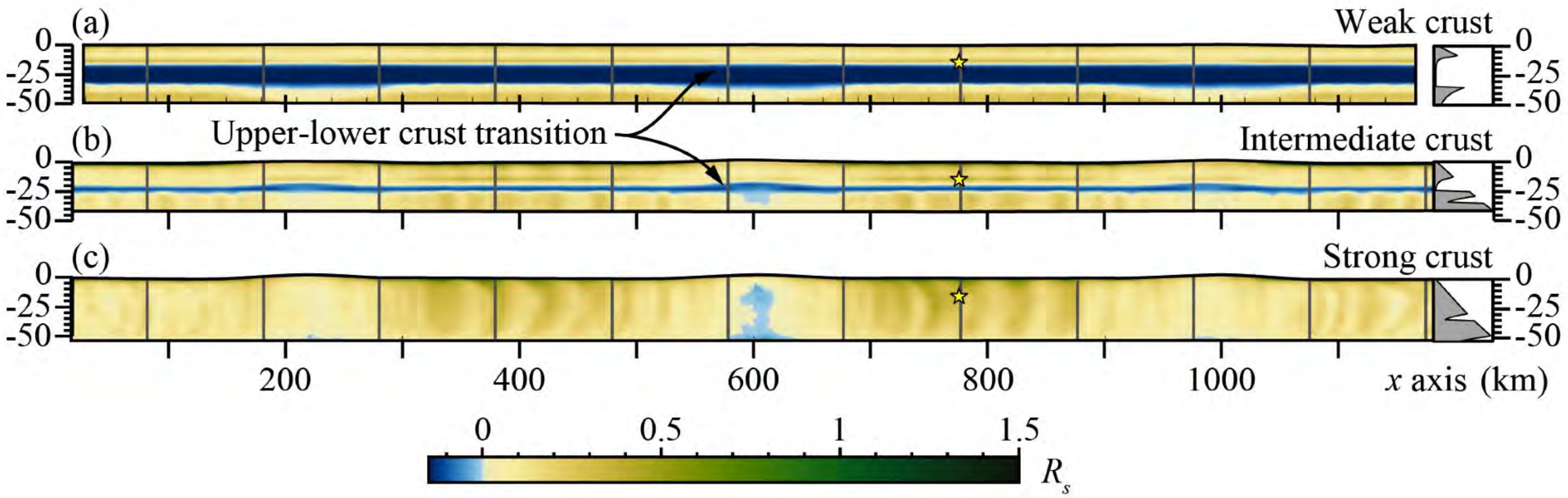
Dynamic friction $\mu_d = 0.1$

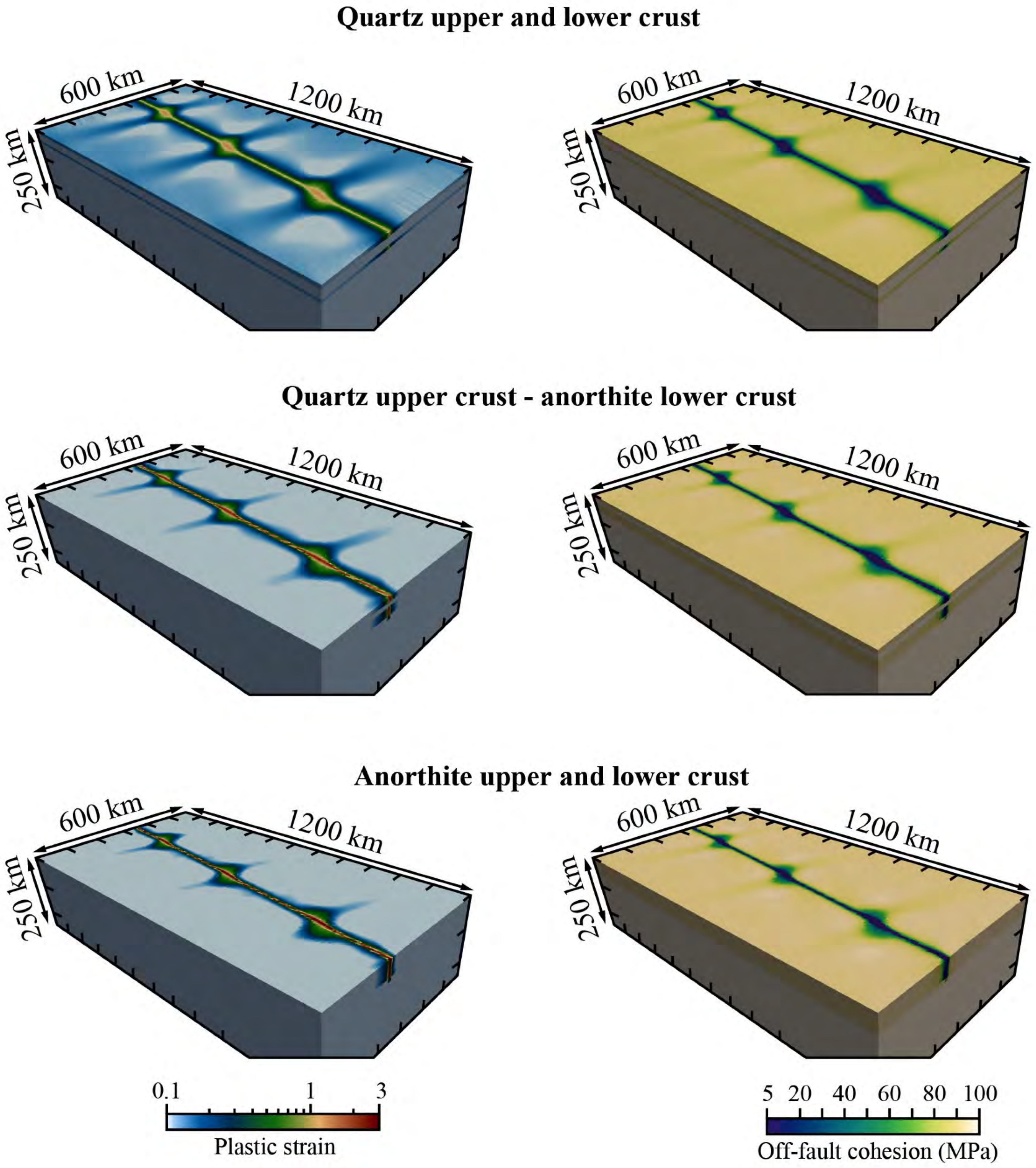
- **Linear slip-weakening** friction framework, with varying Dc
- Depth-dependent seismic velocity structure (~PREM)





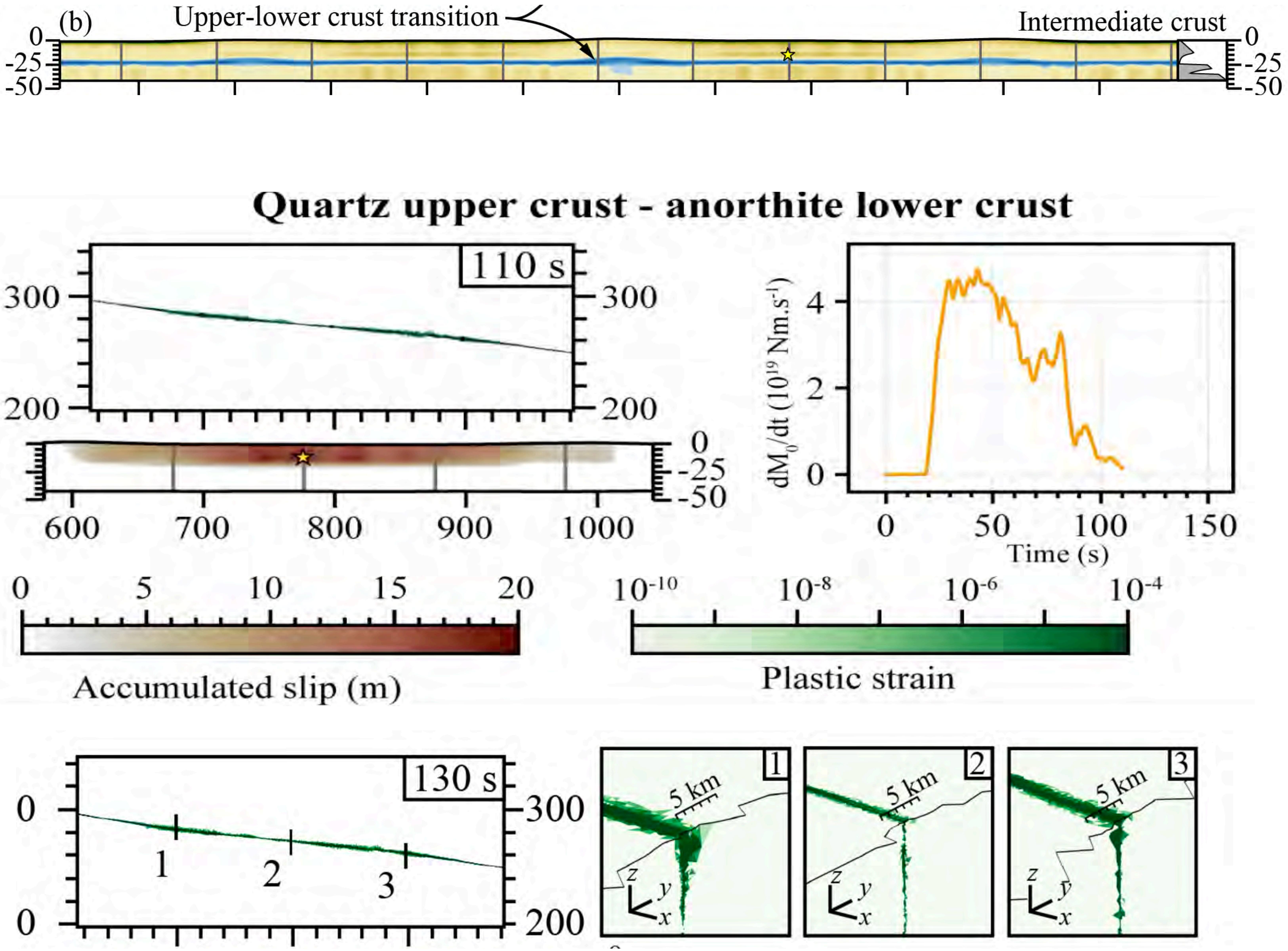
Topography, fault geometry, stress, off-fault cohesion & density from long-term geodynamic models as initial conditions for dynamic rupture models





- **Off-fault plasticity** accounting for 3D stress state and long-term plastic strain evolution

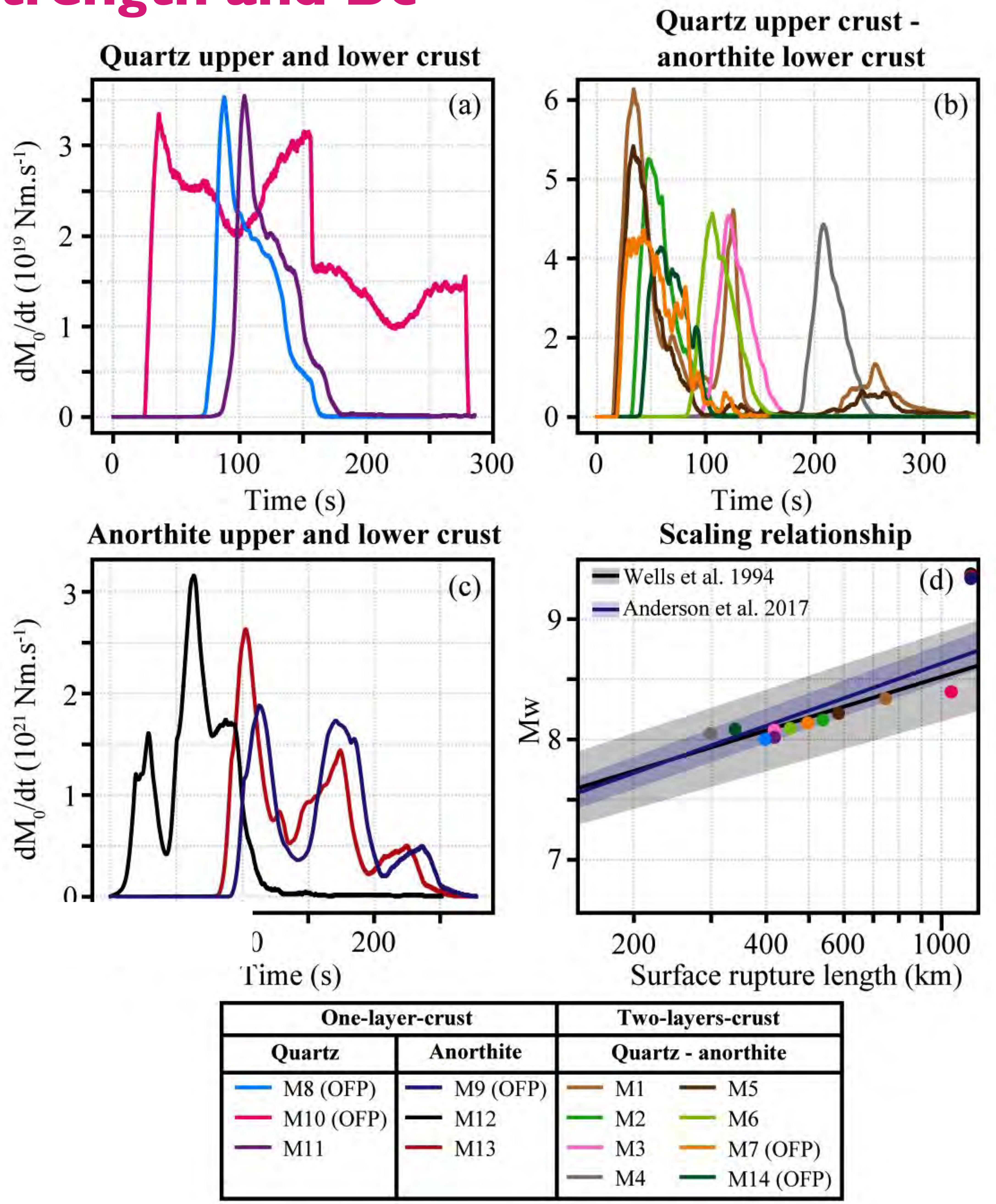
Dynamic rupture models: intermediately strong crust, elasto-plastic medium



- Rupture propagates bilaterally until it reaches fault bends causing **multi-peak moment release**
- Rupture velocity and accumulated slip **decrease near fault bends**
- **In weaker crusts stresses are lower and rupture arrests upon reaching fault geometrical heterogeneity while in sufficiently strong crusts rupture passes**
- Along-strike **variable off-fault deformation / fault zone width**

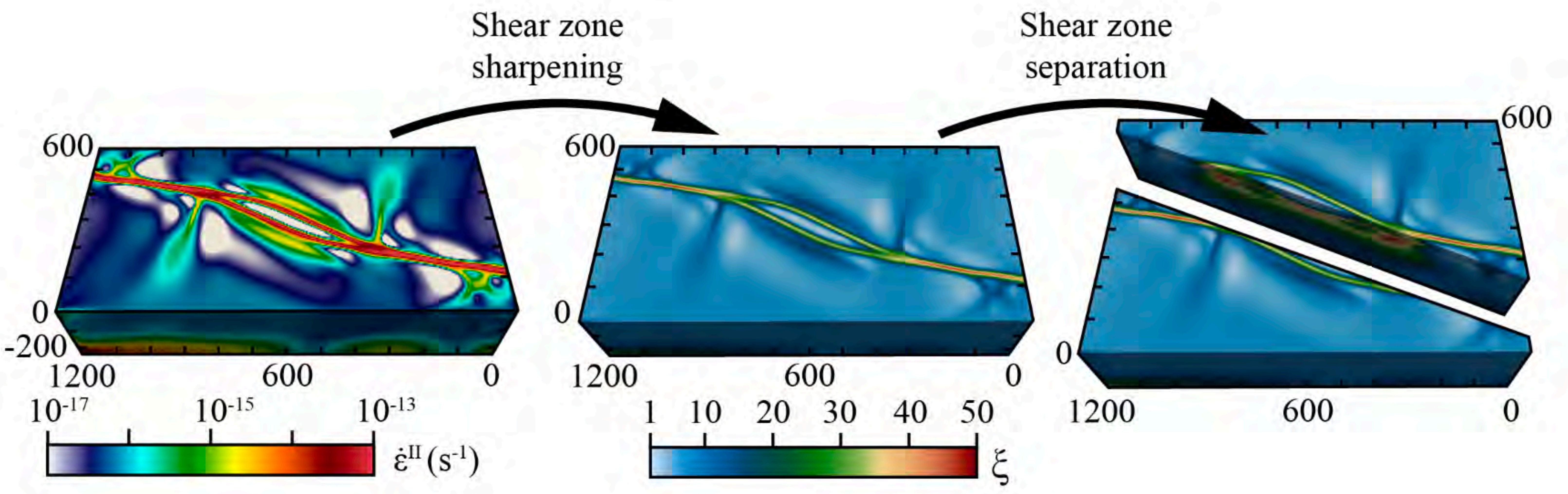
14 Dynamic rupture models varying crust strength and Dc

- Our suite of dynamic rupture models shows that for the geodynamic system considered, the geometry of the fault, the rheology of the crust, and the long-term stress-state, **a suitable critical slip weakening distance falls within Dc** ∊ **[0.6, 1.5].**
- Crusts with a **thicker ductile layer promote a lower stress state** that will produces smaller magnitude strike-slip earthquakes with shorter surface rupture length, smaller rupture surface area, and less accumulated slip
- Dynamic slip on fault segments **better aligned with the regional long-term plate motion is favored** and even **minor fault bends can dynamically arrest rupture in stronger crust**
- In **stronger crusts**, because feldspar-rich rocks do not readily flow at crustal temperatures, the total stress accumulated along the fault is **higher**, enabling rupture propagation through geometric variations also where fault orientation changes and producing **larger** earthquakes
- Geodynamically informed single earthquake scenarios on a simple, large strike-slip fault **match scaling relations**
- **The models yield high moment magnitudes** which may result from lack of accounting for shorter-term (seismic cycle) heterogeneity smaller events during the seismic cycle



Conclusions

- **Novel "Nitsche" geodynamic boundary conditions allows for self-consistent formation of strongly oblique systems of strike-slip shear zones minimizing boundary effects**
- **New fault surface reconstruction from volumetric shear zones based on medial axes transformation, Laplacian smoothing and Delaunay triangulation also allows for the evaluation of long-term slip rate across the faults**
- **Long-term rheology and evolution of fault geometry and pre-stress states crucially affect earthquake dynamics and coseismic off-fault plastic strain localization**



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