Modelling tectonics and seismicity due to slab retreat along the Northern Apennines thrust belt

ETH zürich · AlpArray · Utrecht University

Session T33D — Poster 0432

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1. Introduction and background

The link between lithospheric-scale structure and dynamics and the resulting short-term crustal tectonics has not been thoroughly investigated because of short observation timescales and of system complexity.

- Goal: clarifying the role of lithospheric rheology and temperatures in governing crustal stresses and seismicity through dynamics
- Study area: the Northern Apennines orogen. Tectonic domains: (1) shortening and compression in the subsiding, buried part of the belt and beneath the base of the range (2) extension and uplift in the mountain range.
- Hypothesis: the rheology and axis-parallel structure of the orogen can explain its first-order tectonics.

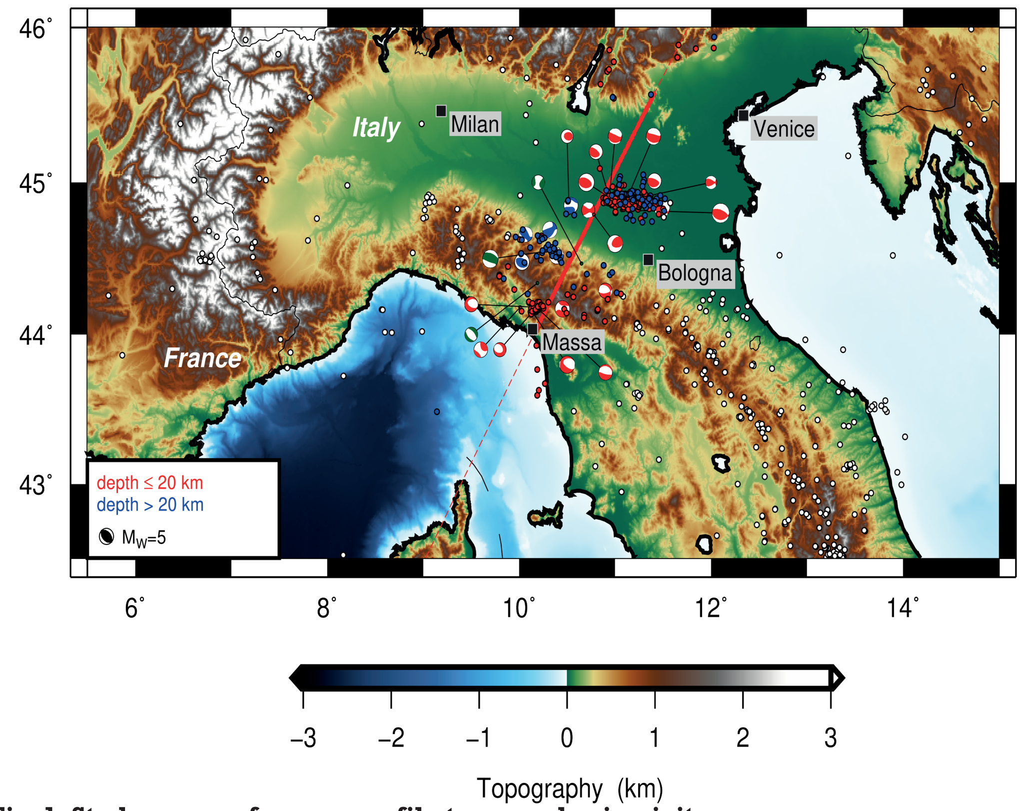
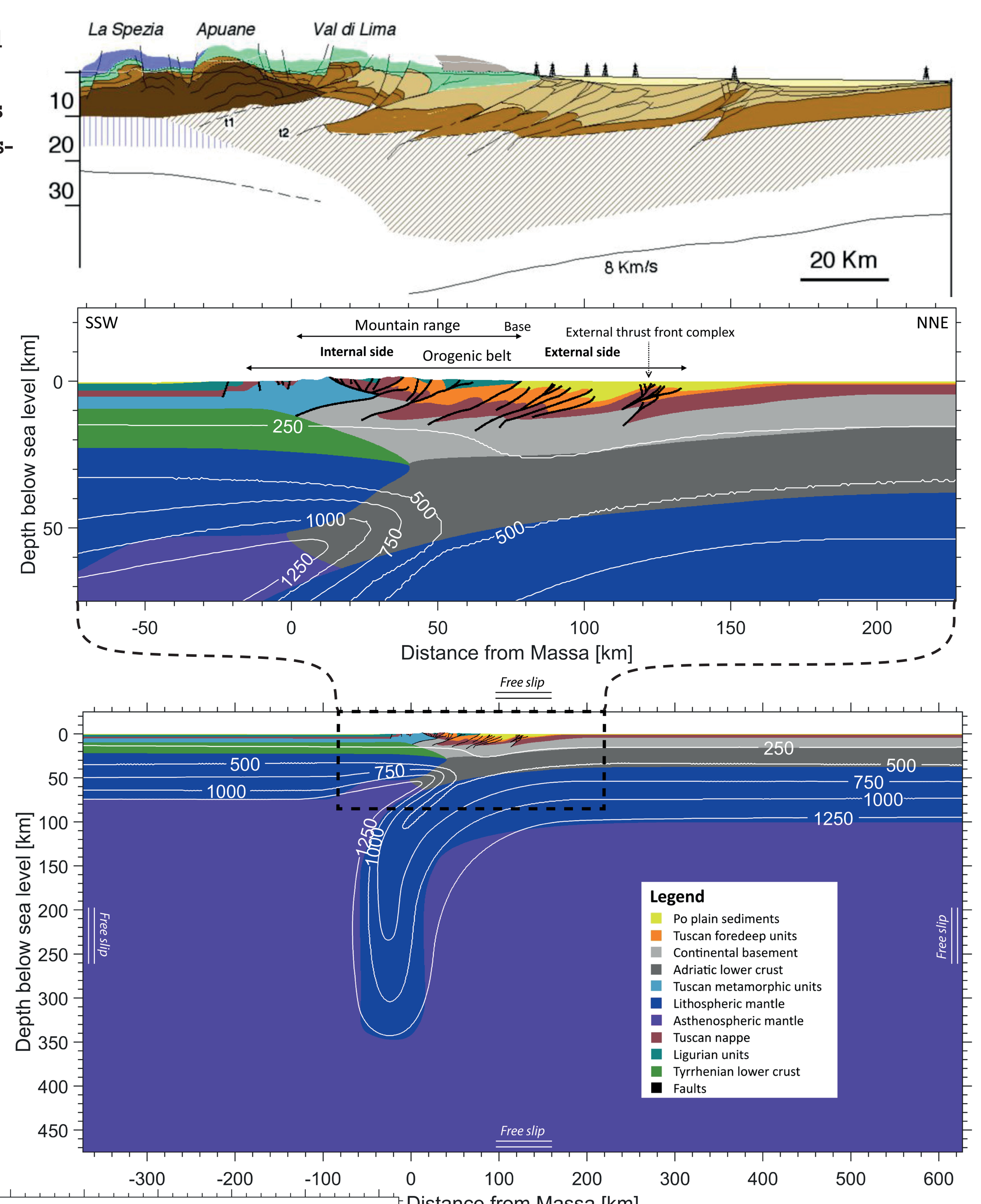


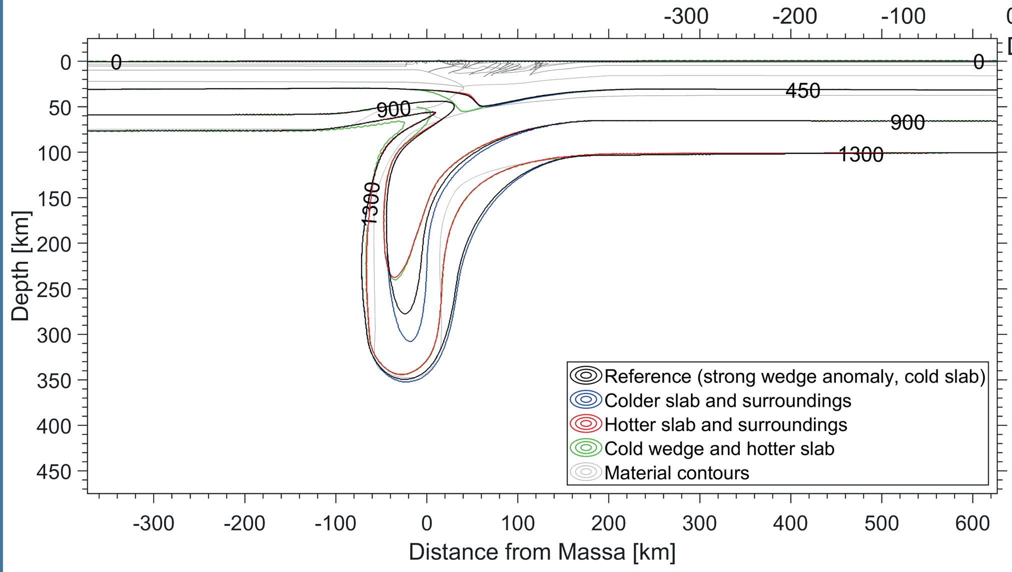
Fig. 1: Study area: reference profile trace and seismicity

2. Methods

- 2D seismo-thermo-mechanical (STM) modelling (Van Dinther *et al.*, 2013) combining viscous flow with fault loading and seismogenic ruptures.
  - Finite-difference, marker-in-cell numerical scheme.
  - Conservation of mass, momentum, and energy.
  - Maxwell viscoelastic rheology with flow law-based viscosity.
  - Brittle-plastic yielding with linear yield criterion and slip rate-dependent friction.
- Realistic 2D structure as a dynamic driver.
  - Slab pull providing driving force; no imposed shortening.
  - Initial setup based on geological and geophysical information (Fig. 2).
  - Thermal setups following a self-consistent simulation and lithospheric structure (Fig. 3).



Above—Fig. 2: reference geological-structural profile (Molli *et al.*, 2010) and model material setup based on it. Faults are predefined as thin zones with distinct (weaker) rheology, but any rock type can rupture.



Left—Fig. 3: isotherms of alternative model temperature setups. The designed contours are interpolated via biharmonic splines into a bitmap image used to set initial temperature.

3. Results and interpretation

I. Large-scale, long-term tectonics: delamination-retreat approximating observed regimes

The combination of a ductile lower crustal rheology and high temperatures in the mantle wedge and lowermost crust is required to produce realistic upper crustal tectonic regimes (Figs. 4—7). This happens through partial lithospheric delamination-retreat and wedge protrusion.

II. Short-term tectonics: stresses, earthquakes and surface displacement

- Earthquakes in the extensional mountain range and in the buried thrust belt, as observed (Fig. 7). Most observed intermediate depth (20—40 km) earthquakes not reproduced (Figs. 7, 8); bending-related earthquakes occur instead in the mantle.
- The long-wavelength trend in horizontal surface velocity agrees with observations (Fig. 9). Model vertical velocities define more consistent uplift and wider subsidence peak than observed.

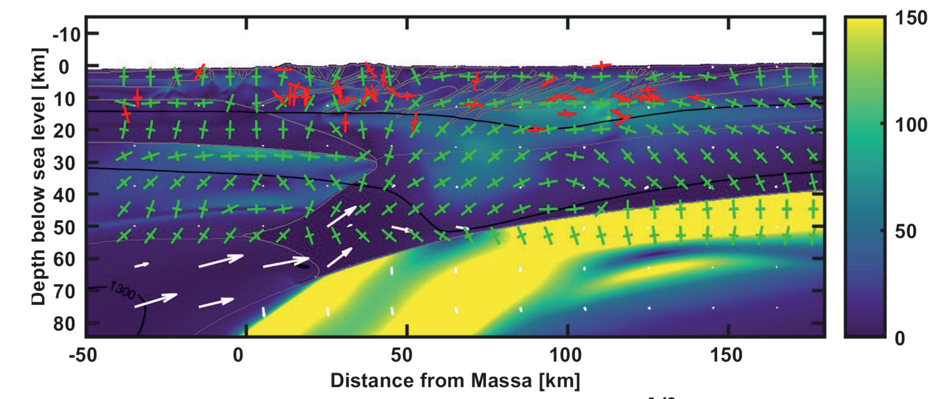


Fig. 4: Reference model—effective stress $\sigma'_{II}{}^{1/2}$ and principal stress axes orientations, green from the model, red from World Stress Map data (projected onto the plane). The compressive axis is longer.

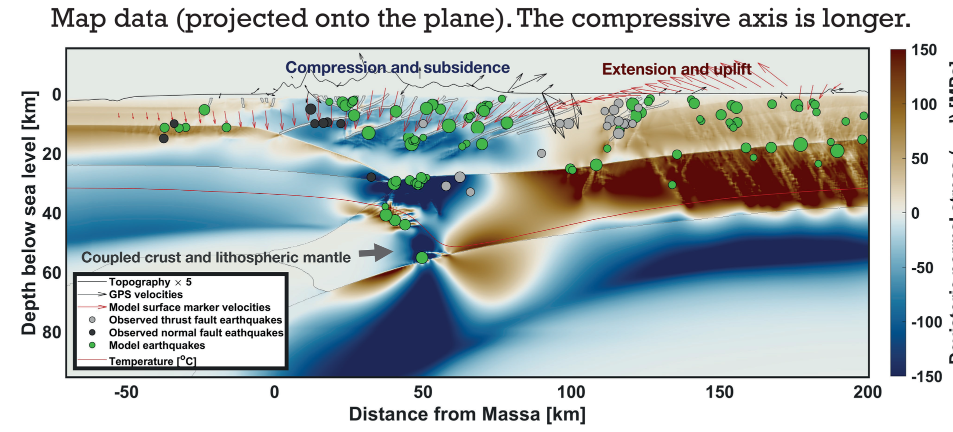


Fig. 5: Model with mafic granulite lower crusts—tectonic features: horizontal normal stresses, earthquakes, velocities

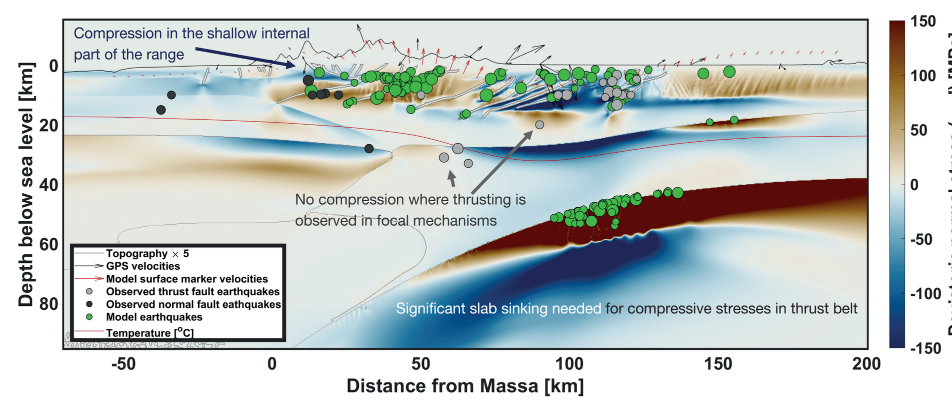


Fig. 6: Model with plagioclase lower crusts and hotter lithosphere, otherwise like the reference—**tectonic features:** normal stresses, earthquakes, velocities

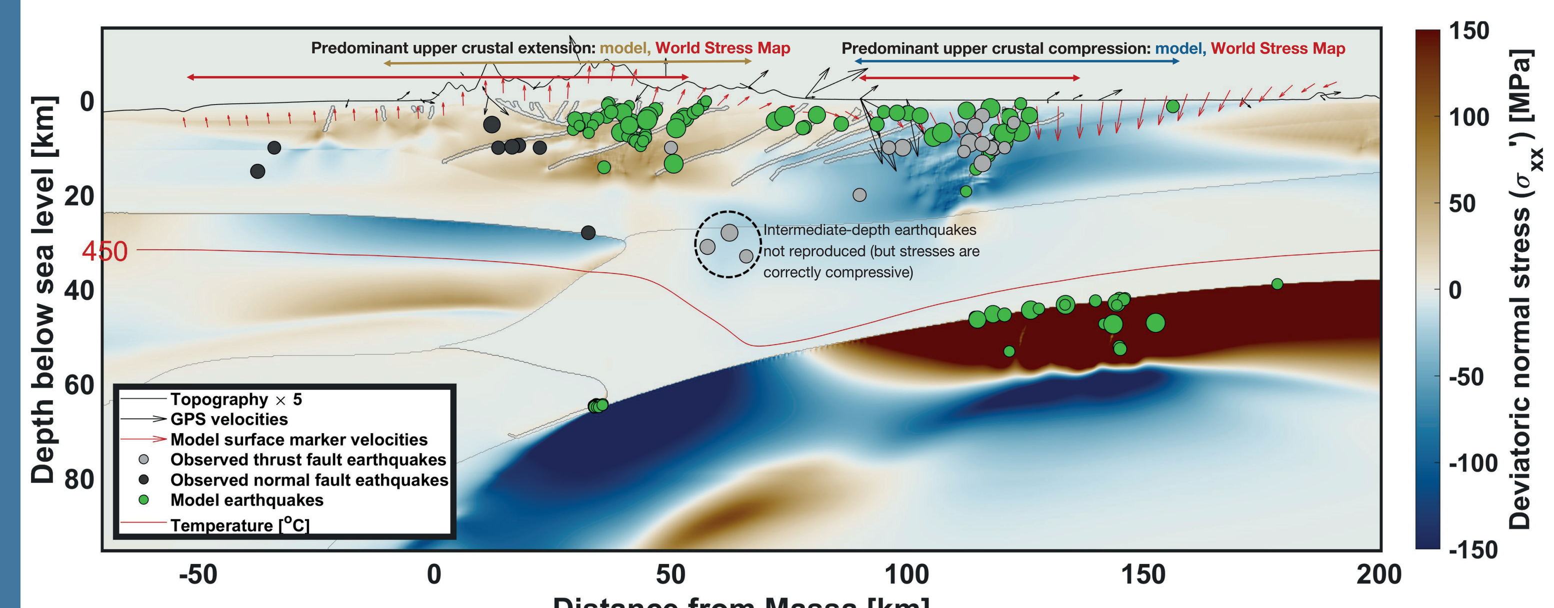
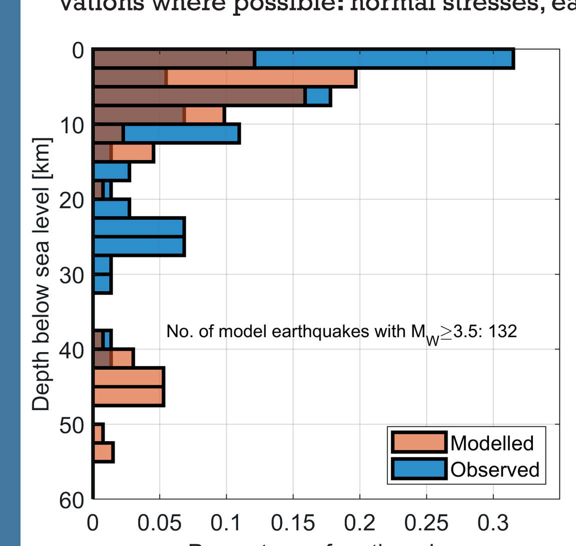
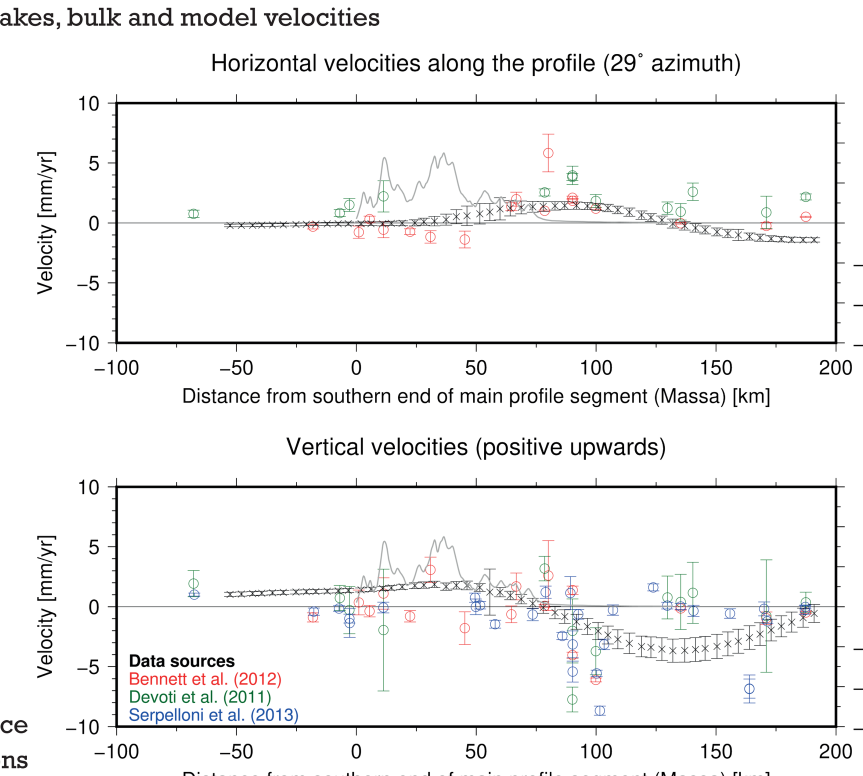


Fig. 7: Reference model (wet quartzite lower crusts and hot mantle wedge)—tectonic features, compared with observations where possible: normal stresses, earthquakes, bulk and model velocities



Above—Fig. 8: Relative vertical distribution of earthquake hypocenters in the reference model and in instrumental observations



Right—Fig. 9: Surface velocities in the reference model and from GPS observations

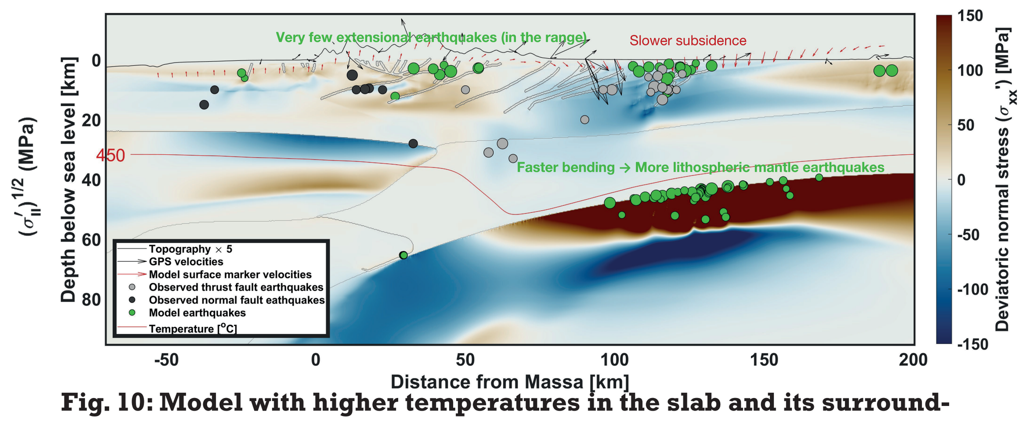


Fig. 10: Model with higher temperatures in the slab and its surroundings, otherwise like the reference—**tectonic features:** normal stresses, earthquakes, velocities

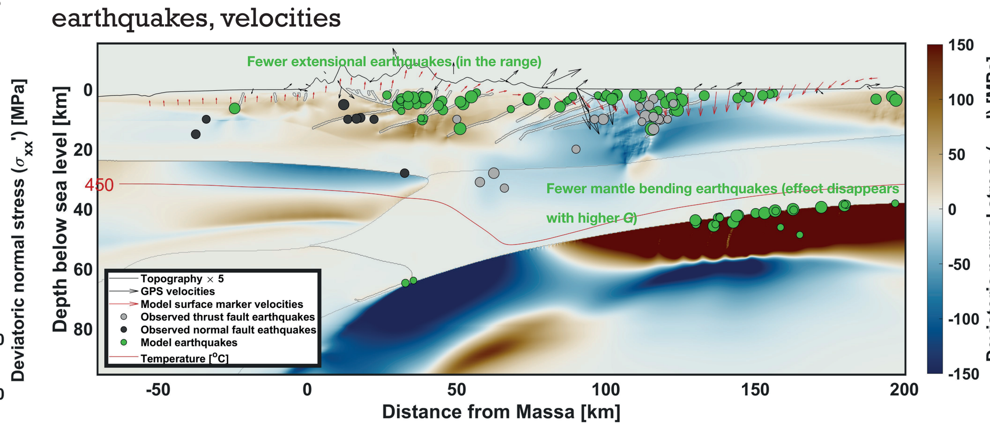


Fig. 11: Model with shear modulus *G*=67 GPa in the lithospheric mantle, otherwise like the reference—**tectonic features:** normal stresses, earthquakes, velocities

III. Control of seismicity distribution by slab pull and elasticity

- Decreasing or increasing temperatures in the slab and its surroundings respectively increases or decreases the seismic rate in the crust (Figs. 10, 12a). The extensional regime is more susceptible. The mantle exhibits the opposite trend.
- Increasing the shear modulus of the lithospheric reduces the seismic rate in the extensional mountain rainge (Figs. 11, 12b). The seismic rate in the bending lithospheric mantle results from a combination of reduced bending and greater bending-induced stresses.

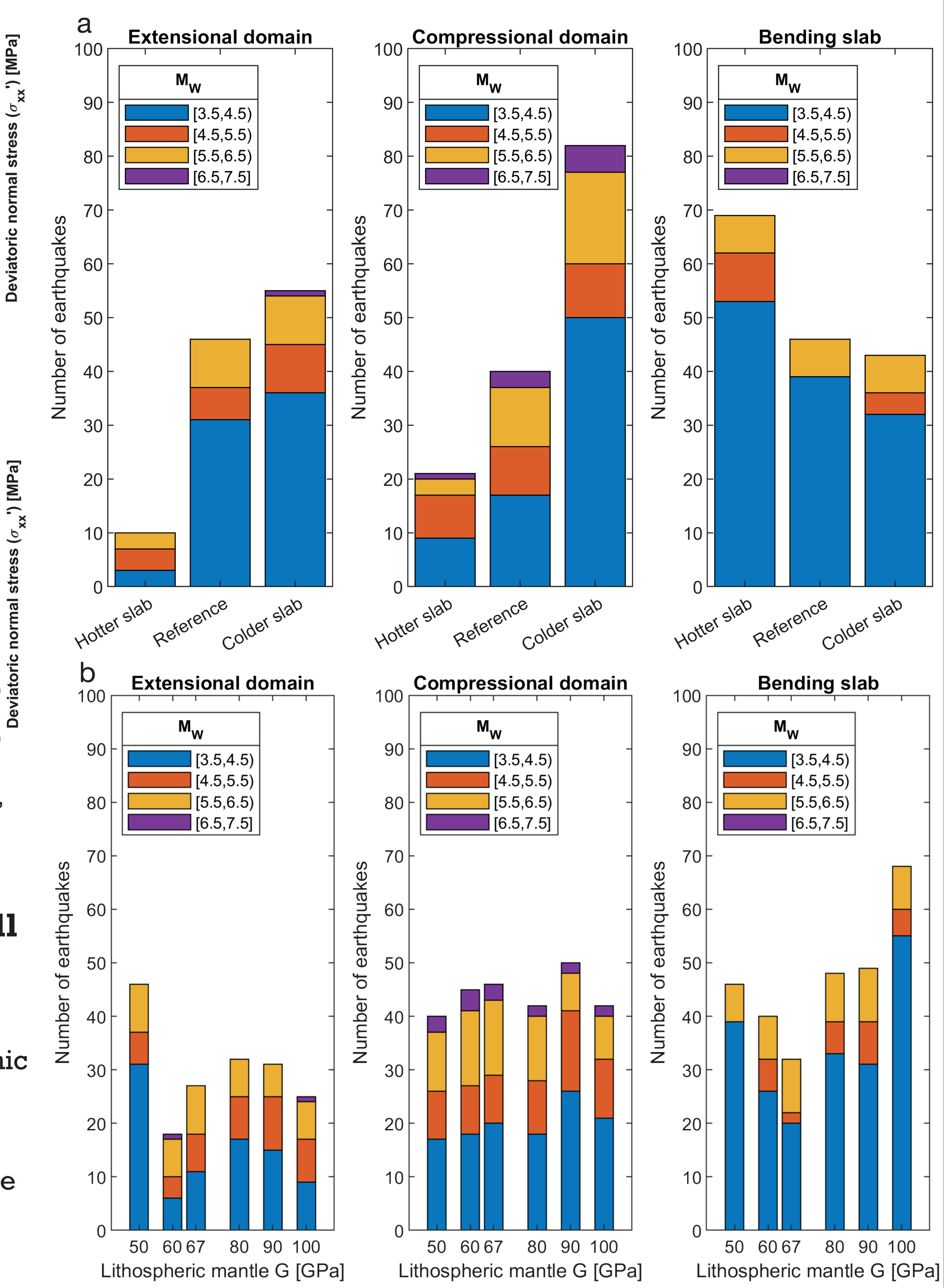


Fig. 12: Number of earthquakes in the main tectonic regimes with different slab temperatures (a) and lithospheric mantle shear modulus *G* (b).

4. Discussion, implications and conclusions

- **STM modelling can successfully link large-scale geodynamic and small-scale tectonics.** It allows the use of tectonic regimes as observed from the surface as constraint on likely lithosphere dynamics.
- **The temperature and buoyancy at depth as well as bulk rheological properties such as slab stiffness control the seismic rate in different regimes and thus the spatial distribution of earthquakes through the lithosphere.** This is the case even with a fixed network of imposed faults and with relatively constant macroscopic flow pattern, stresses and surface velocities. Therefore, future studies should accurately constrain physical parameters before drawing conclusions on likely geodynamics on the basis of modelled seismicity. Also, rupture simulations on fault networks should consider the effect of off-fault yielding and inhomogenous loading on the spatio-temporal features of seismicity.
- **Lower crustal ductility (resulting from rheological law and temperature) is crucial in enabling the development of tectonic regimes consistent with observations.** The lack of modelled intermediate-depth earthquakes indicates that the rheological structure of the crust is not fully captured in the models. In reality, the stable middle and lower crust is probably brittle and deforms through thrusting and underplating, while the suture zone is probably ductile as in the models.
- **Geodynamics driven solely by slab buoyancy and governed by lithospheric rheology can explain the first-order features of Northern Apennines tectonics through lithospheric delamination, slab retreat and wedge protrusion.** Unlike in the models, consistent uplift of the mountain range and of long-wavelength subsidence in the northwesternmost sector of the orogen are presently lacking along the reference profile, unlike further to the southeast. This suggests a possible lack of active delamination-retreat, which would leave the stresses and seismicity unexplained, or unquantified effect of 3D orogen structure near its terminus.

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