PLATE BOUNDARY LOCALIZATION: WHAT PROCESSES ACTIVE ON EARTH DO NOT APPLY TO OTHER PLANETARY LITHOSPHERES?

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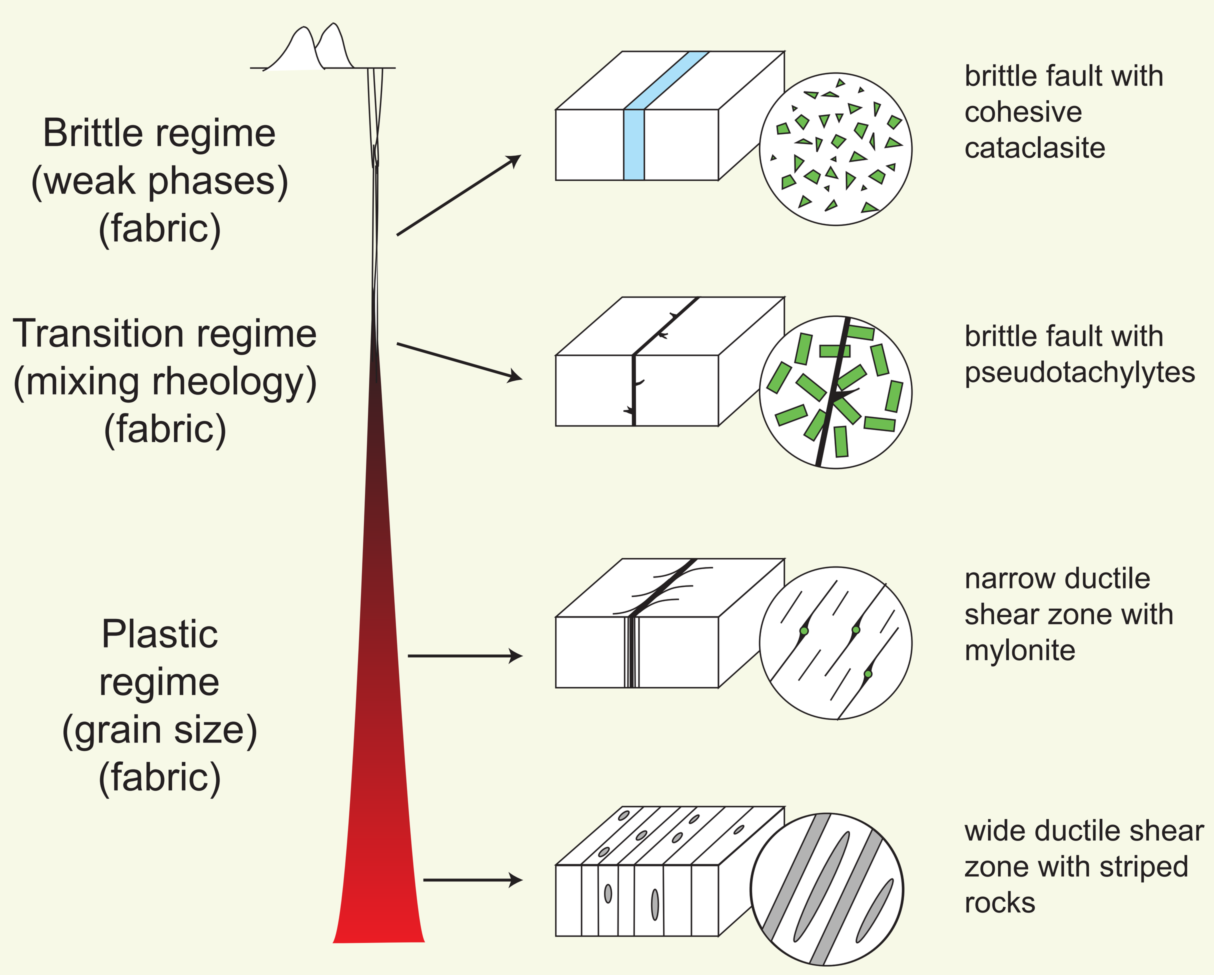
The challenge of Ductile Shear Zones

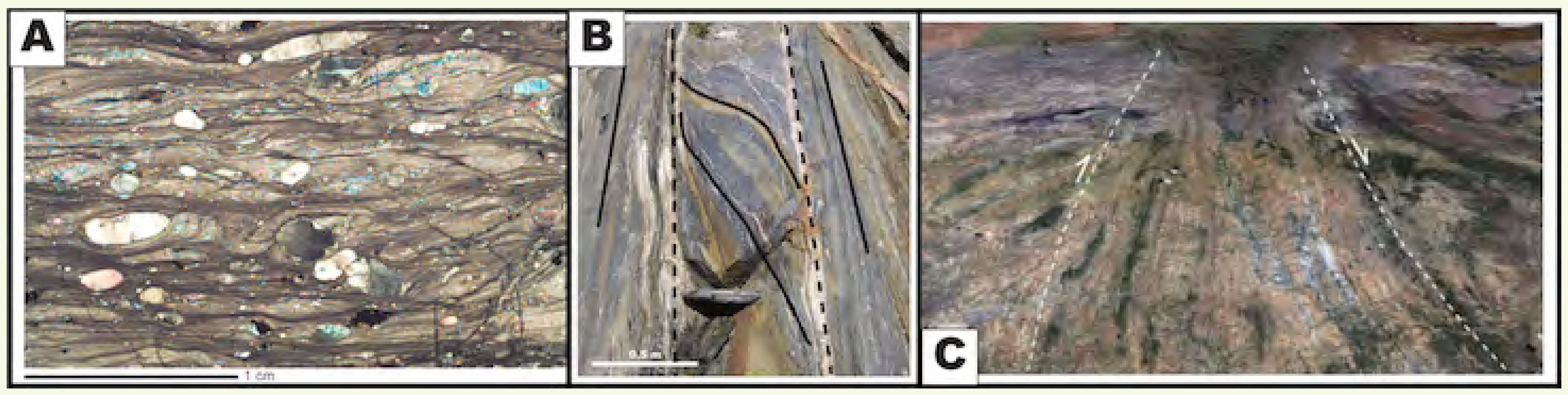


Geology and geophysics have long documented that deformation is localized to some extend at every depth in the lithosphere A characteristic feature of even the global tectonic regime of the Earth, localization is at the very definition of plate boundaries. However, we have as yet only a very limited understadning of the mechanics of ductile shear zones and their implications for tectonics.

The fundamental difficulty behind modeling ductile shear zones is that the plastic rheology active in these shear zones is fundamentally strain-rate hardening. Increased strain rate is associated with increased stress. Therefore, it is energetically favorable to deform a large region at a slow rate, the opposite of shear localizaiton.

To generate shear zones, it is necessary to appeal to the evolution of a ***state variable*** that is at a different value in the shear zone than in the surrounding rocks. The shear zone materials must be intrinsically weak.

Microstructural changes such as the development of a fabric in the middle crust, and grain size reduction in the mantle, are good candidates to explain localization (Montési, J. Struct. Geol., 2013). This structural changes for the strength profile of the continental lithosphere (Gueydan et al., Tectonophysics, 2014).



Examples of shear zones at all scale. A) Microscopic view of a harzburgite-hosted mylonite, showing the intense grain size reduction and the development of layers in a highly deformed mantle rock (Warren and Hirth, 2006). B) Outcrop-scale amphibolite facies shear zone from Dogleg Island in the Canadian Grenville Province showing phase segregation (following cracking and metasomatism) and layering (Gerbi et al., 2010) C) Oblique view of the 25 km wide Antanimora shear zone in tCe southern Madagascar (Google Earth-GeoEye 2011; Martelat et al., 1999; Vauchez et al., 2012).

Shear Zone Development

Numerical models follow the development of ductile shear zones and their effective viscosity at different levels in the continental lithosphere. Different localization processes are active at different depths and temperature, implying that different levels of the lithosphere localize by different amounts.

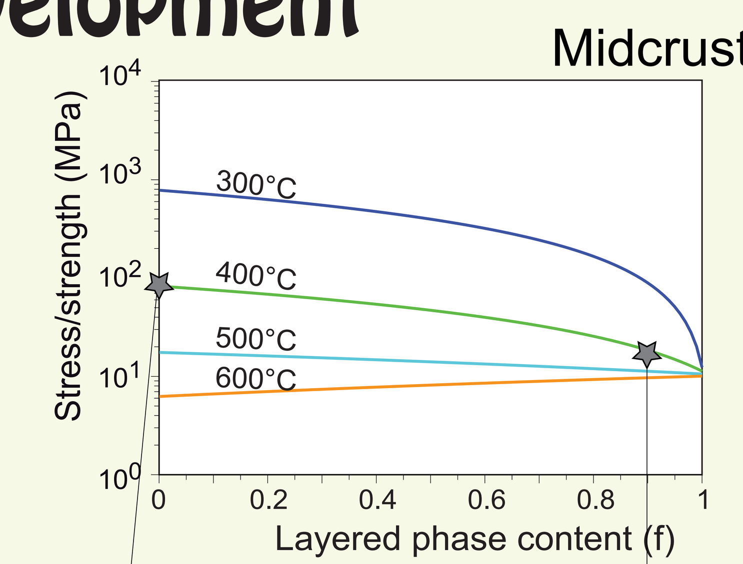
Model setup: 1-D layer sheared horizontally at a given strain rate and temperature but evolving fabric or grain size.High strain Finite Element Code SARPP (Gueydan et al., 2003). The simulations are pursued to an overall strain of 2.3. The local strain in the developing shear zone exceeds 100 in some cases.

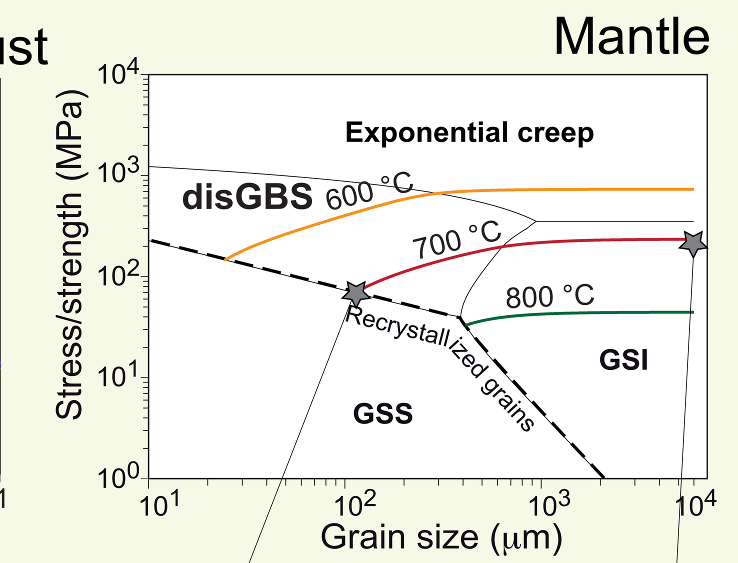
In the brittle crust: Weakening defined a priori by reduction of coefficient of friction from 0.6 to 0.1

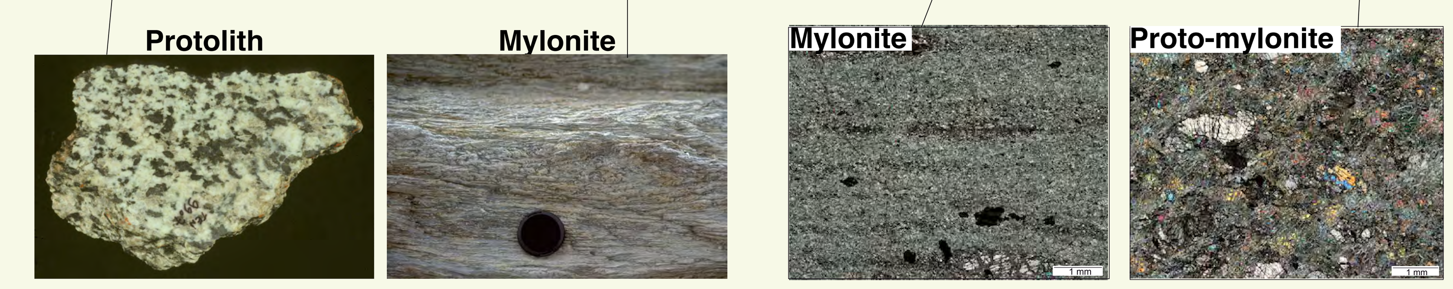
In the middle crust: The transition from an isotropic protolith (constant stress averaging) to a layered phyllonite induces significant weakening at temperatures less than 400°C.

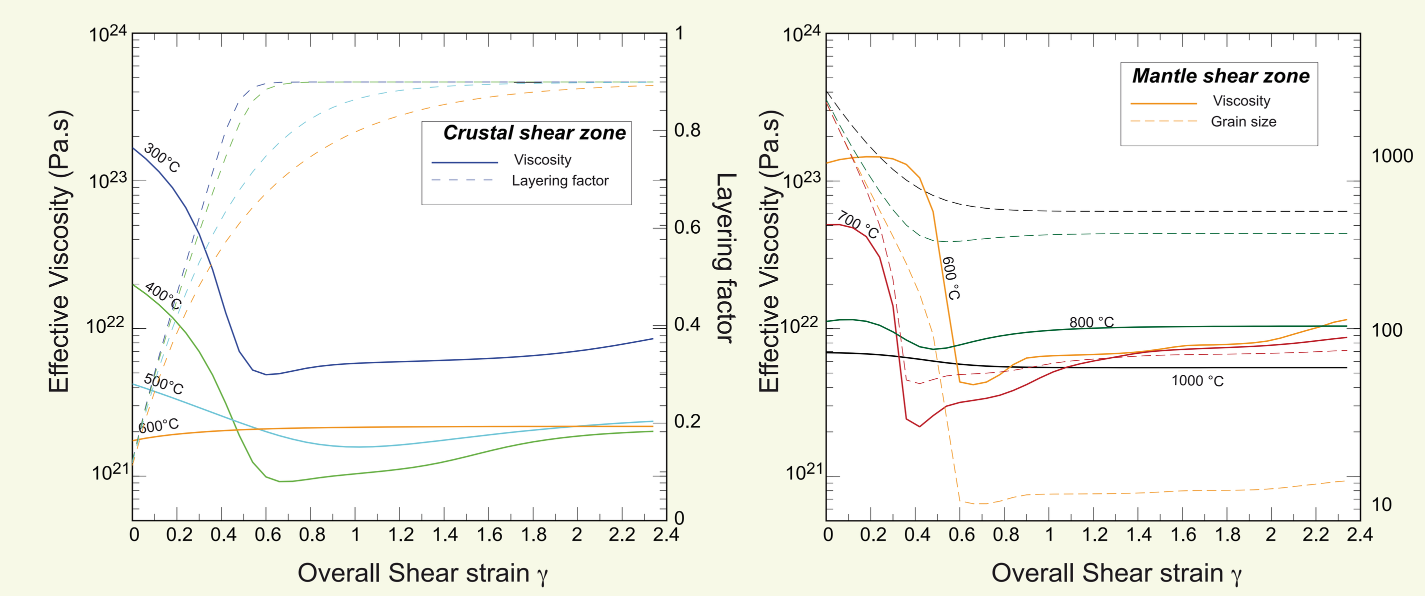
In the lower crust: High temperature prevent renders inefficient the other localization processes explored here. Shear heating and melt infiltration may produce weakening, although less intense than in other layers.

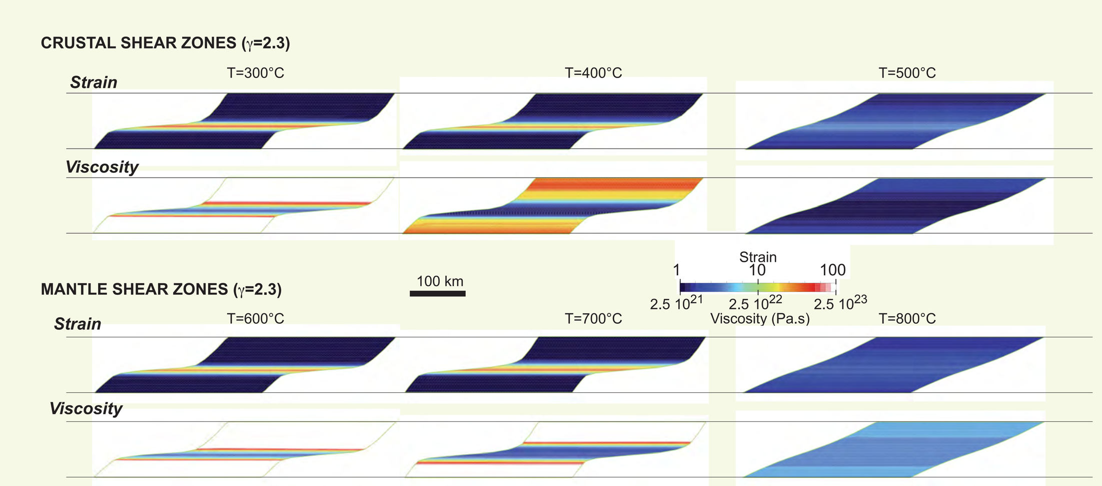
In the upper mantle: Grain size reduction (recrystallization) and grain-size sensitive creep coexist in the dis-GBS regime,enabling possible localization the temperature is less than 800°C.









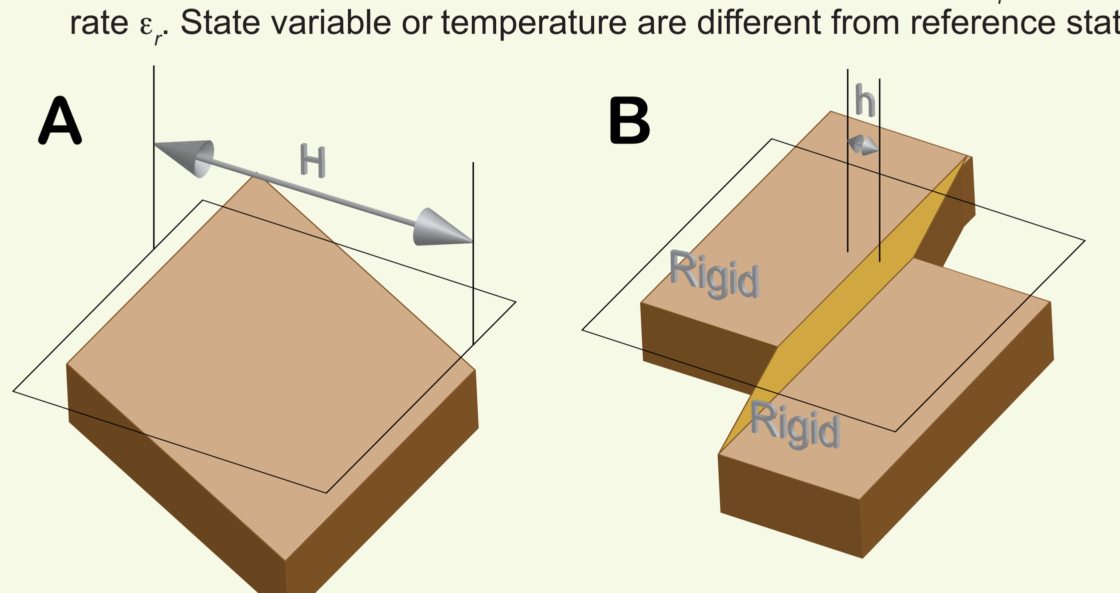


Localization Potential

Main idea: The favored deformation state is the one that dissipates the least energy.

A) Reference state: Wide deformation zone (H), stress σ_r, corresponding strain rate ε_r, velocity $V=H\varepsilon_r$, and Energy $E=V\sigma_r$

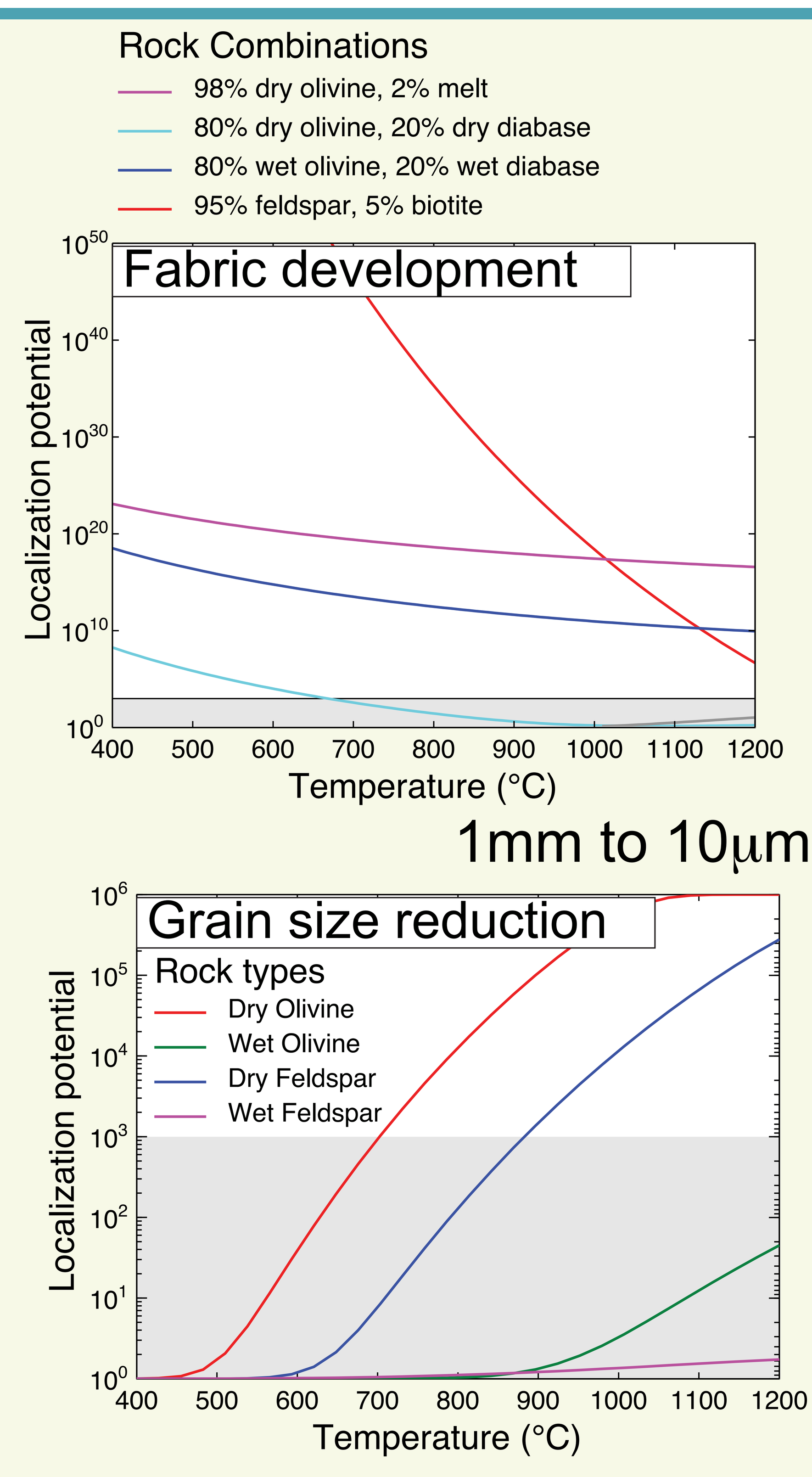
B) Localized state: narrow deformation zone (h), stress σ_l and strain rate ε_r. State variable or temperature are different from reference state



$$\dot{E} = \int_0^H \sigma\dot{\varepsilon}\,dy = \sigma\dot{\varepsilon}H = \sigma V$$

Assuming ***constant velocity***, as the width of a deformation zone decreases from H to h, strain rate increases by a factor $L=H/h$. If there is no change in deformation conditions or state variables, stress and energy dissipation increase. The localized state is favored if the change of state variable compensates strengthening due to the increase of strain rate. The ***localization potential*** induces by a change of state variable of deformation conditions is the maximum increase of strain rate for which the energy dissipation is $V\sigma_r$, i.e., the ratio of strain rate in the localized and reference conditions for the same stress σ_r deformation conditions.

$$L = \frac{H}{h} = \frac{\dot{\varepsilon}_s}{\dot{\varepsilon}_r}$$



Planetary Lithospheres

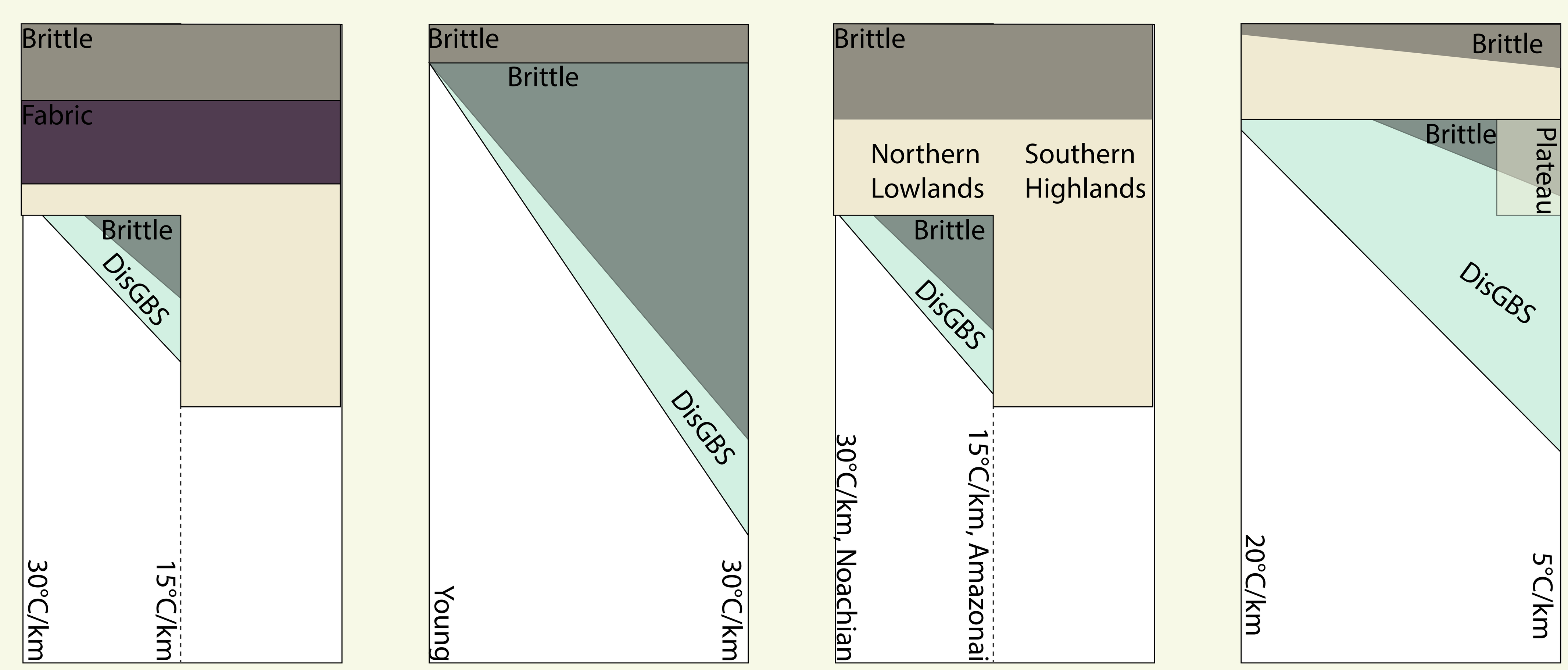
Shading indicates conditions where brittle failure is expected. Green indicates the mantle, where localizing by grainsize reduction combined with disGBS. Purple indicates localizing crust with phyllosilicates; Brown indicates non-localizing crust

Continental Lithosphere

Oceanic Lithosphere

Mars

Venus



Continental Lithosphere: Localization possible in the middle crust. Localization in the mantle unless the geotherm is high (Western U.S.) or the crust is thickened (Tibet)

Oceanic Lithosphere: Thin crust hardly a factor at lithospheric scale. Brittle or localizing mantle for most of the plate

Mars: Thick brittle layer in the crust; Phyllosilicate unlikely in mafic crust. Localization in the mantle underneath lowland crustal thickness, except in the Noachian. Similarities to the continental crust.

Venus: Only a thin veneer of brittle crust; No micas and ductile localization in the crust. Localization possible in the mantle but surrounded my non-localizing layers