EFFICIENCY OF DUCTILE SHEAR ZONE LOCALIZATION BY GRAIN SIZE REDUCTION ON EARTH, VENUS, AND MARS

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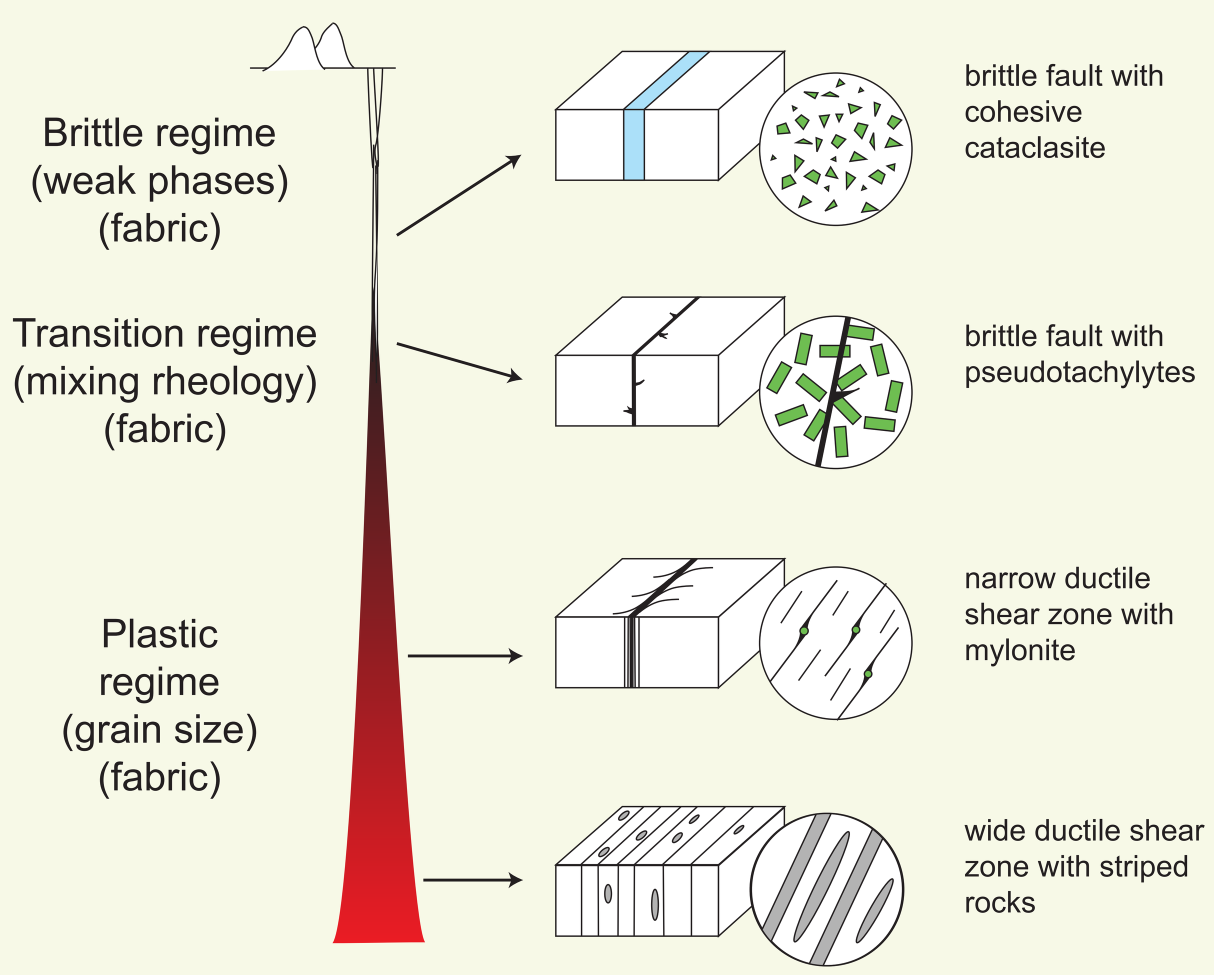
The Challenge of Ductile Shear Zones



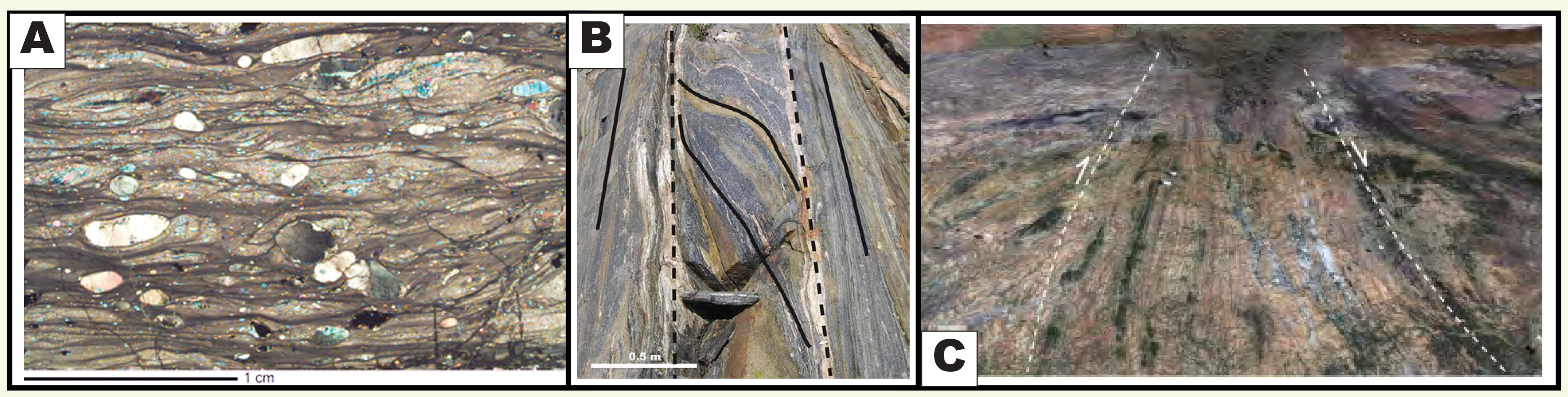
Modified from *Passchier and Trow (2005) Microtectonics*

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 Earth's continental lithosphere (*Gueydan et al., Tectonophysics, 2014*).



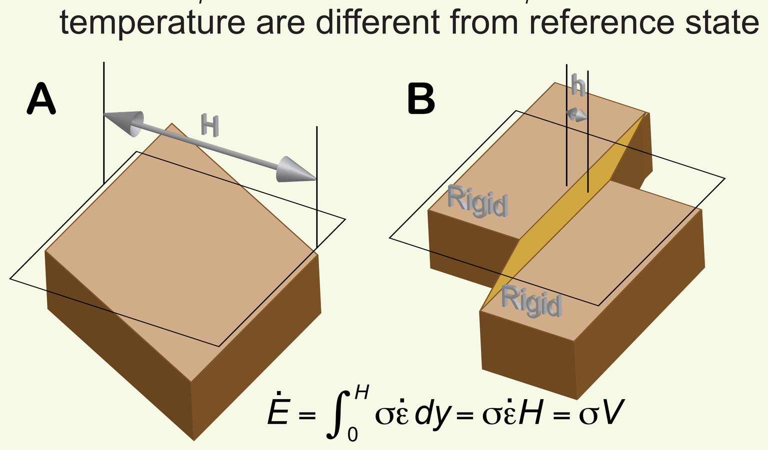
Examples of shear zones at all scale. A) Microscopic view of a harzburgite-hosted mylonite, showing the intense grain size reduction and the development of layers in a highly deformed mantle rock (*Warren and Hirth, 2006*). B) Outcrop-scale amphibolite facies shear zone from Dogleg Island in the Canadian 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 southern Madagascar (*Google Earth-GeoEye 2011; Martelat et al., 1999; Vauchez et al., 2012*).

Energetics of localization

Main idea: As a state variable evolves, the stress and/or the strain rate across the shear zone evolve so that the energy dissipation rate remains the same

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



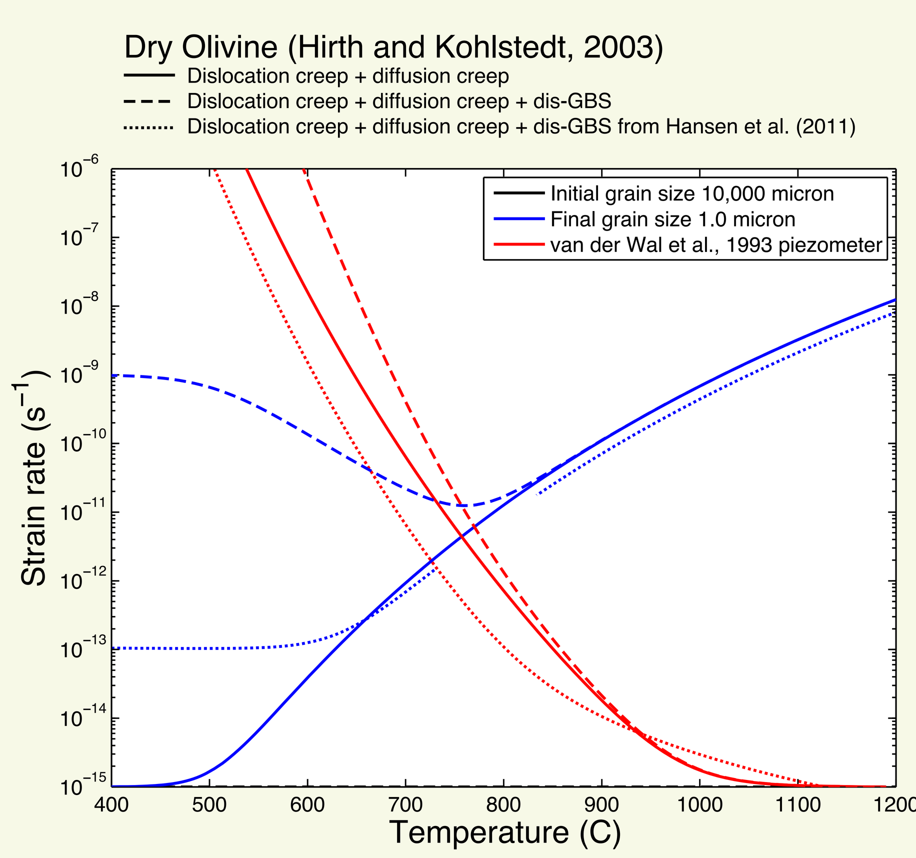
$$\dot{E} = \int_0^H \sigma\dot{\varepsilon}\,dy = \sigma\dot{\varepsilon}H = \sigma V$$

Two alternative assumption make it possible to determine the finals state:

A) Fixed velocity: The width of the deformation zone decreases from *H* to *h*. Accordingly, strain rate increases by a factor *L=H/h but stress remains the same* (same energy dissipation).

B) Fixed width: Assuming that the structural change takes place in a shear zone of predetermined width, both stress and strain rate change so that their product remains the same.

We will consider two possible changes in state variables: ***1) grain size reduction*** and ***2) brittle weakening*** associated with the appearance of hydrated minerals and foliation in a fault gouge.



Strain rate in a olivine shear zone after grain size reduction as a function of temperature (constant velocity assumption). Initial grain size of 10 mm and strain rate of 10^{-15} s^{-1}.

Blue: grain size is reduced to 1 micron. Localization is observed at high temperature, where grain size reduction leads to a transition to diffusion creep. However, stress is so low that grain size reduction is unlikely under these conditions. At low temperature, a grain size sensitive regime is encountered only if dis-GBS is active.

Red: grain size reduction to the predictions from the van der Wal et al., (1993) piezometer. Localization is observed at low temperature, but it would require unrealistically small grain size (less than 1 nm). At high temperature, no grain size reduction is expected.

Summary: localization by grain size reduction is limited by a well-known conundrum: grain size reduction has a strong effect on strength only under conditions where it is not expected to take place. Dis-GBS may be the key for localization but is a poorly understood and controversial regime.

Local Approach

Numerical models are used to simulate shear zones development at specific depths in the lithosphere. Grain size reduction produces shear zones in the mantle as long as the dis-GBS regime is encountered, i.e., at temperature less than 800°C.

Considering a terrestrial continental lithosphere, shear localization is observed:

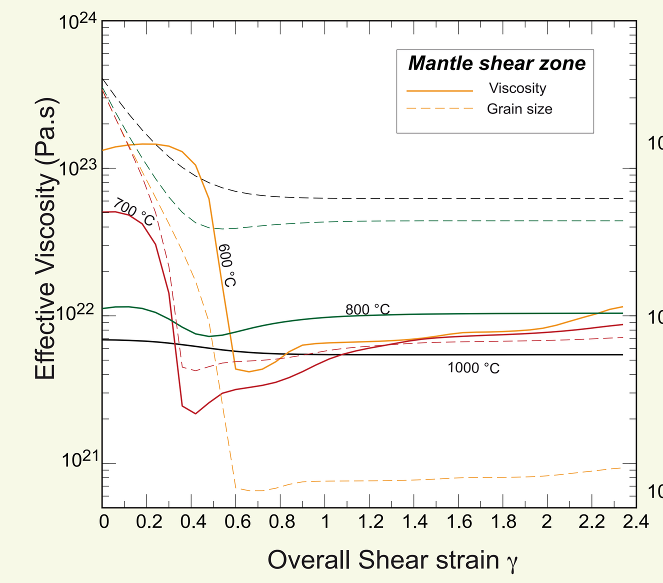
In the brittle crust: as the coefficient of friction decreases from 0.6 to 0.1

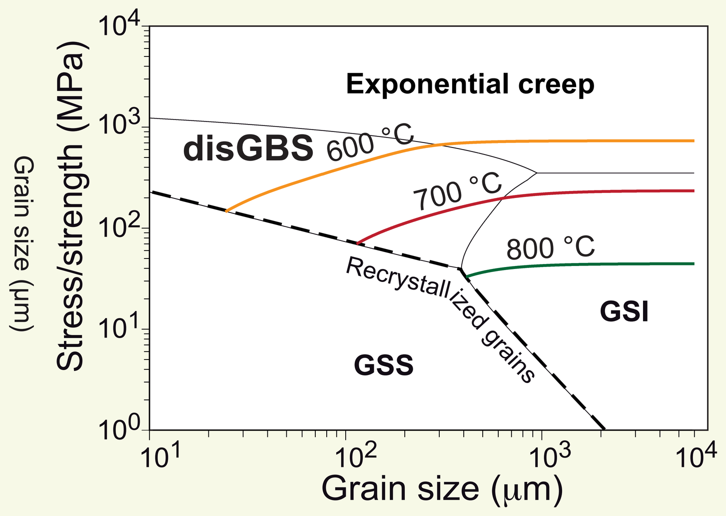
In the middle crust: as phyllosilicates become interconnected

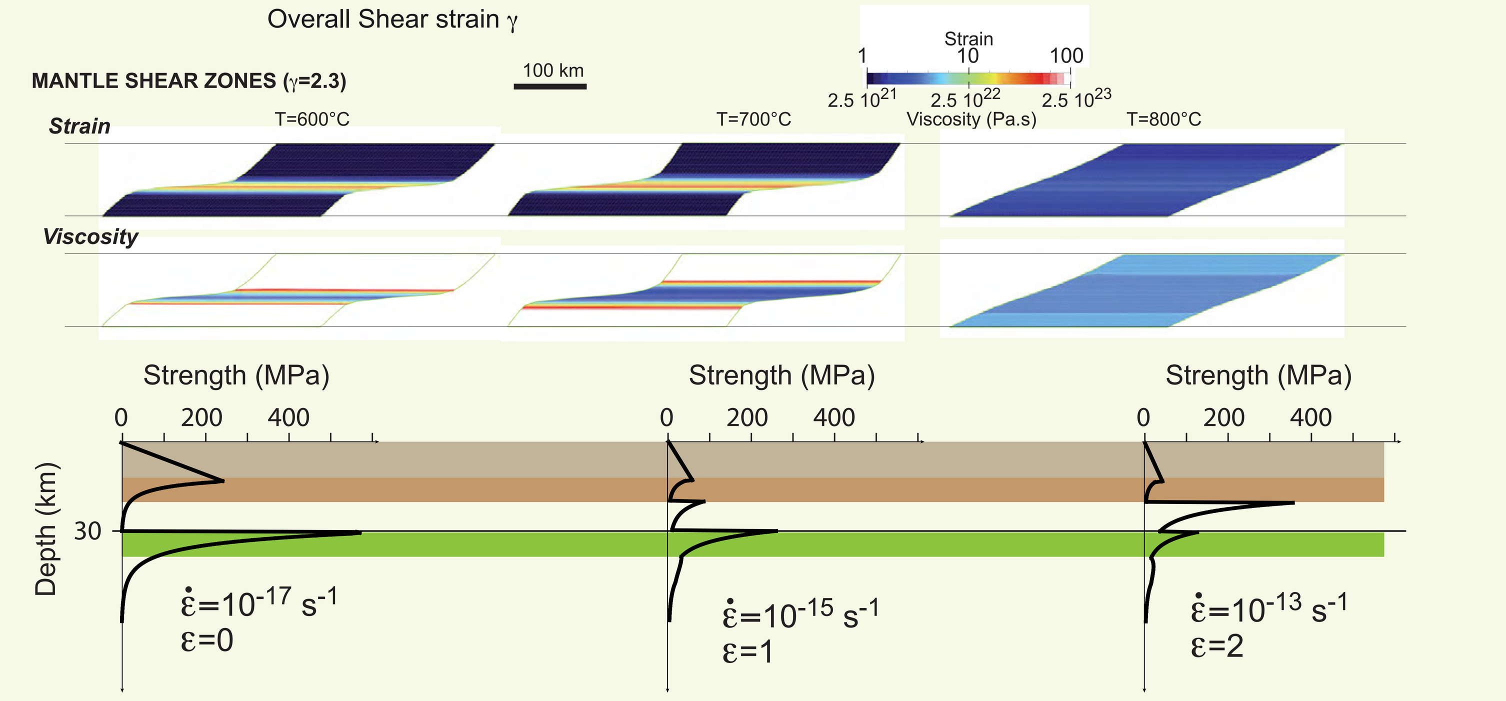
In the upper mantle: as grain size decreases

As the only layer that does not undergo weakening, the lower crust changes from strength minimum to strength maximum. Strain rate increases (here. arbitrary) to compensate for the oveall loss of strength

Gueydan et al. (2014), Tectonophysics



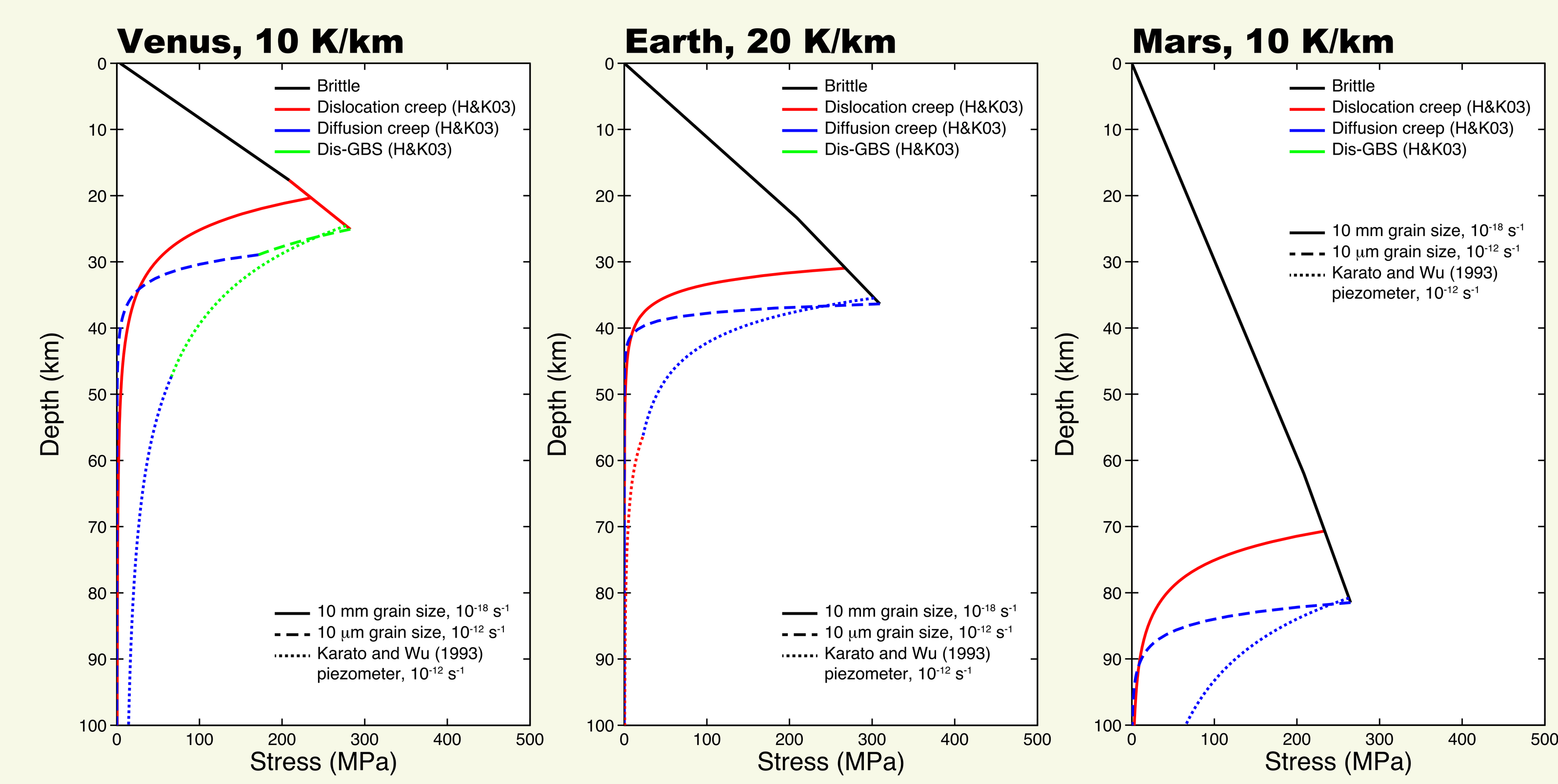


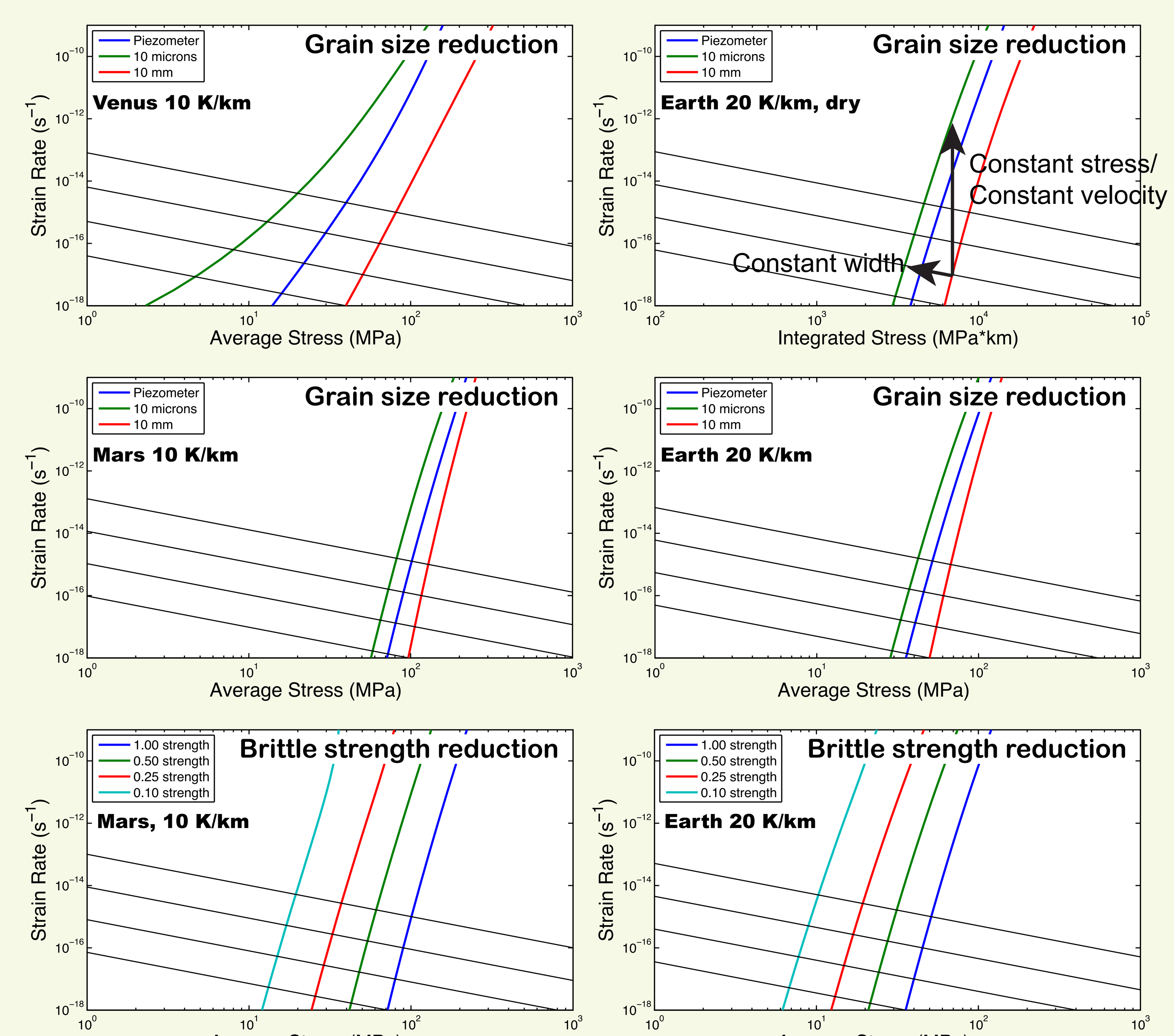


Lithospheres Scale

As grain size decreases, the total strength of the lithosphere decreases too. To keep the same energy dissipation, strain rate increases. The strength profiles to the right show that an initial strain rate of 10^{-18} s^{-1} transforms roughly into 10^{-12} s^{-1} after grain size reduction and that the deformation regime changes from dislocation creep to grain size sensitive creep (diffusion creep or dis-GBS).

Olivine flow law parameters from Hirth and Kohlstedt (2003) (dry for Venus).





The final strain rate is linked to the initial strain rate by the constant stress/constant velocity (see diagrams) or constant width (black lines) assumption. Strain rate increase is often a factor of 10^5 to 10^6 for constant stress, so that mantle circulation would localize on meter-wide shear zone! For constant width, the strain rate, and therefore the overal shear zone velocity, increase by less than a factor of 10.

Surprisingly, strain rate increases more on Venus than on Earth and for dry conditions. This would imply that shear localization is more efficient in Venus' mantle than in Earth's. This is because, for low geotherm expected from stagnant lid convection, the top of the ductile mantle is cool enough for dis-GBS creep.

For Mars and the Earth localization is also possible by reducing brittle strength. Although the uppermost ductile mantle of Venus may be more localizing that Mars and Earth, the near-surface levels are more localizing on Earth. It remains to be seen if the absence of strongly localizing brittle layers explains the lack of plate tectonics on Venus.