The Structure and Rheology of Plate-Boundary Scale Shear Zones below the Brittle-Ductile Transition

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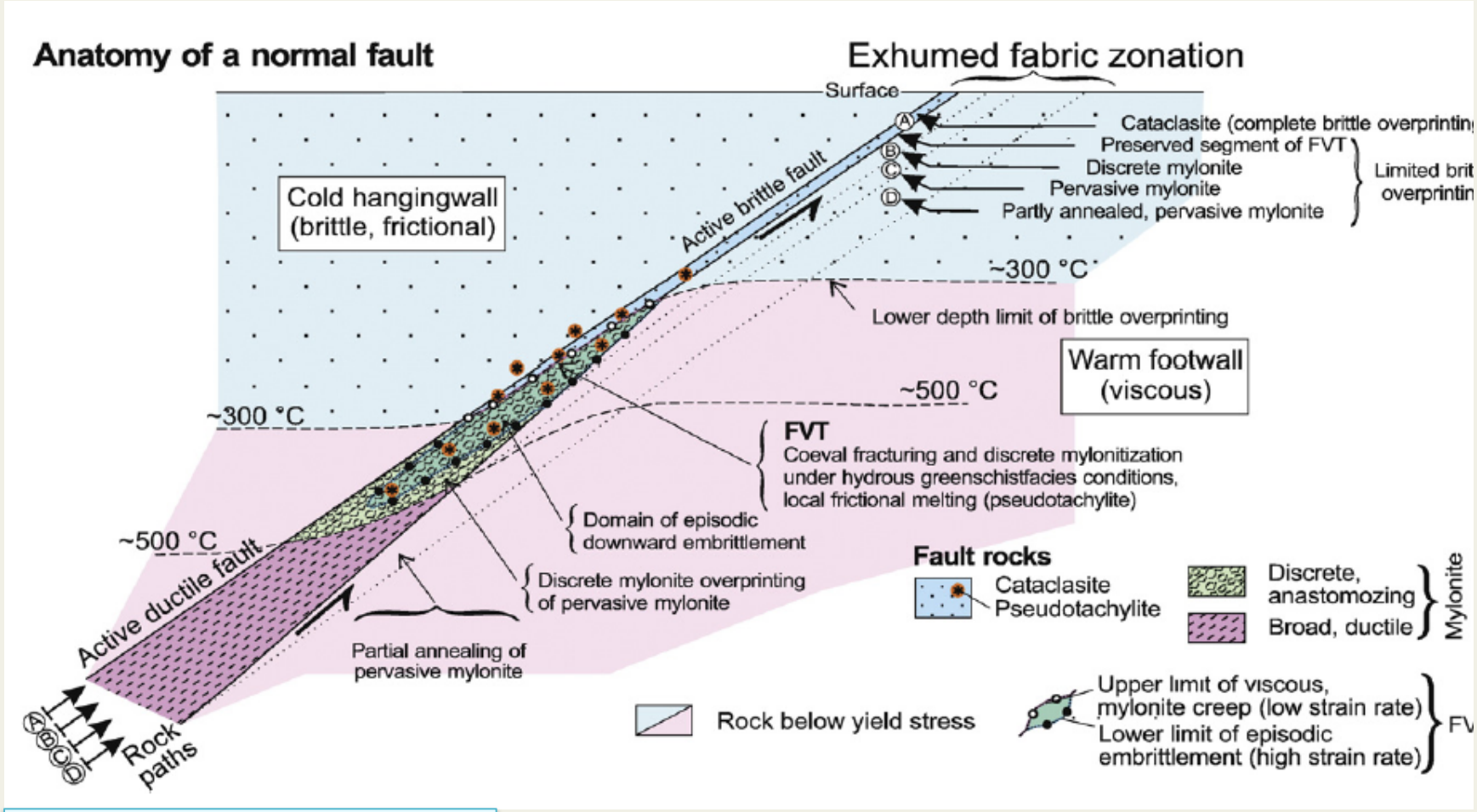
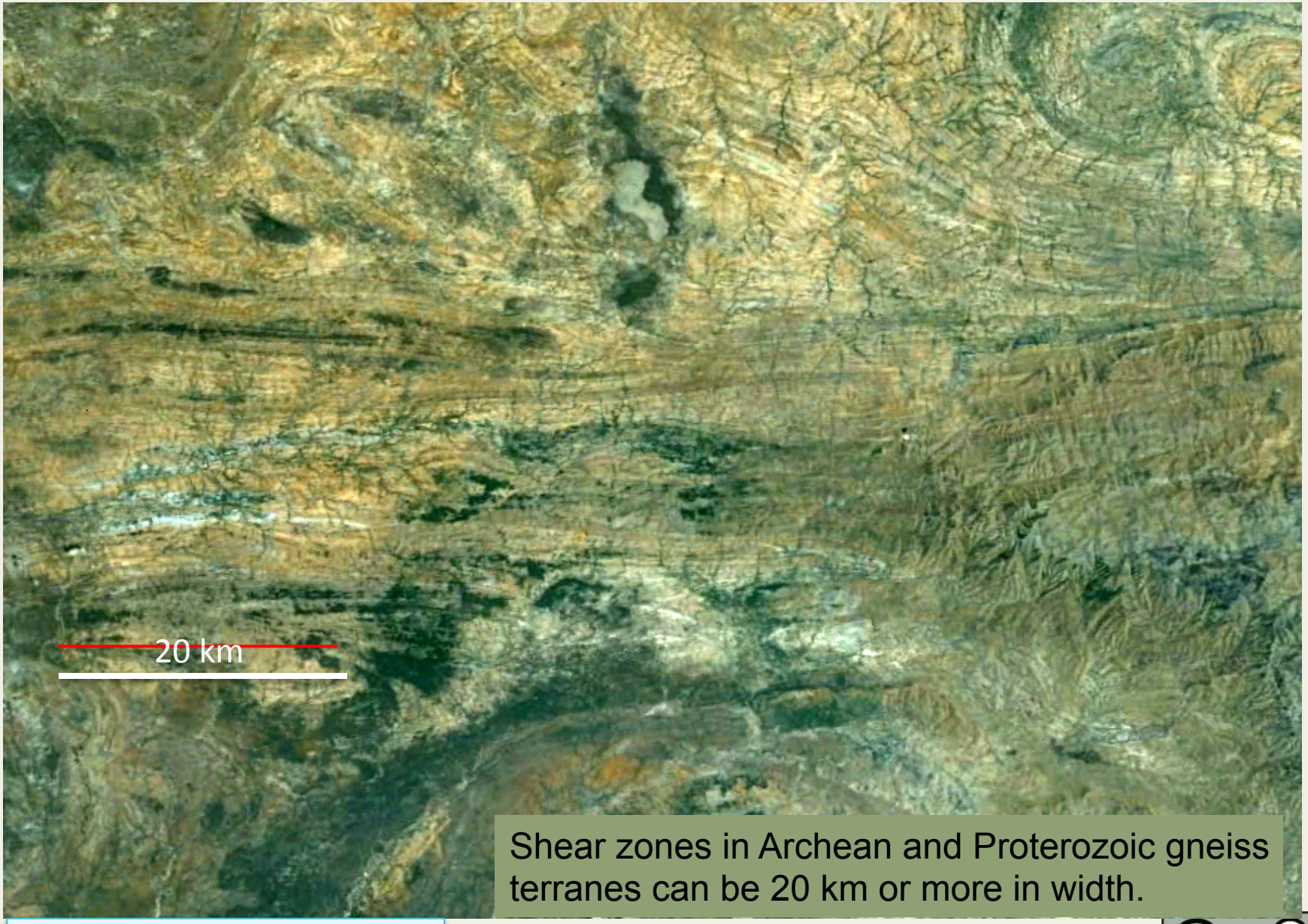
Brittle faults in the upper crust have very narrow slip zones (< 1 mm), surrounded by damage zones a few tens to hundreds of metres wide.



from Handy et al. 2007

Rick Sibson, Mark Handy and others have suggested faults broaden with depth, and the rheology changes. Can we quantify this?

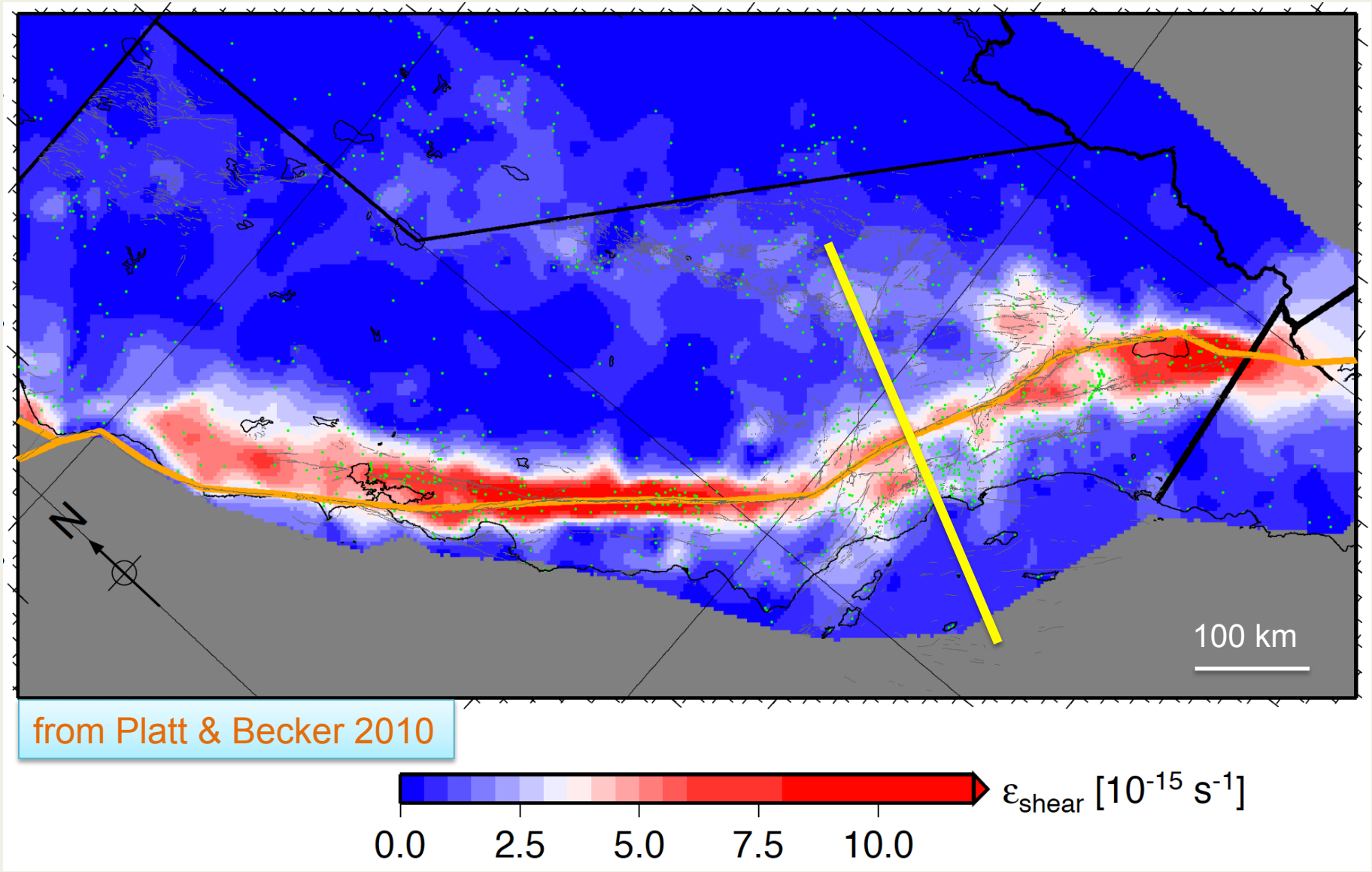
Antanimaro shear zone, southern Madagascar



Shear zones in Archean and Proterozoic gneiss terranes can be 20 km or more in width.

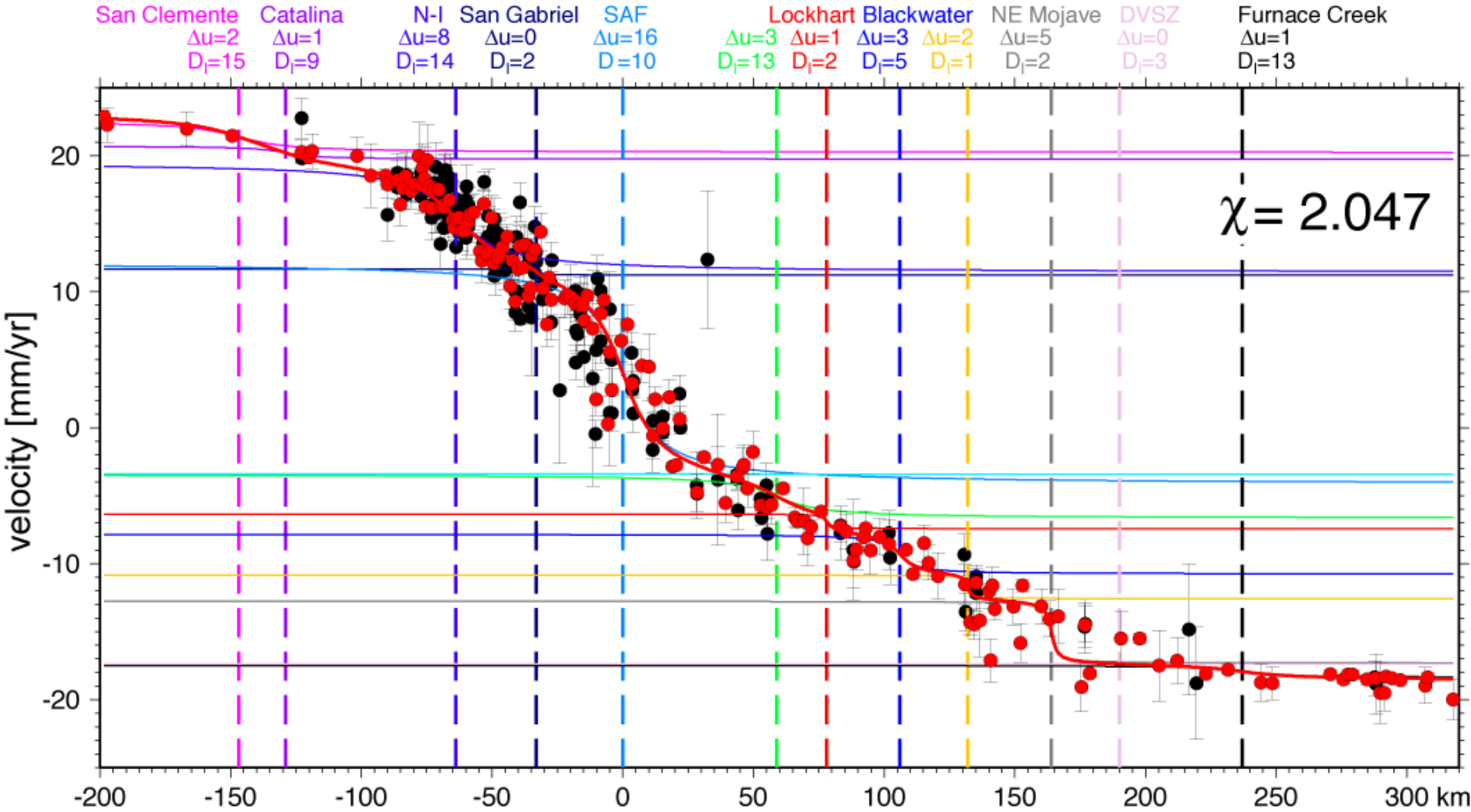
Google Earth image

Shear strain rate in California (second invariant of 2D strain-rate tensor)



The geodetic velocity field across the San Andreas fault is up to 400 km wide, encompassing many active faults. How is this expressed in the lower crust or the upper mantle?

Profile 2: Mojave



from Platt & Becker 2010

Velocity distribution across the San Andreas transform system in southern California

Cumulative width of a plate boundary shear zone

$$width = \frac{Velocity}{strain - rate}$$

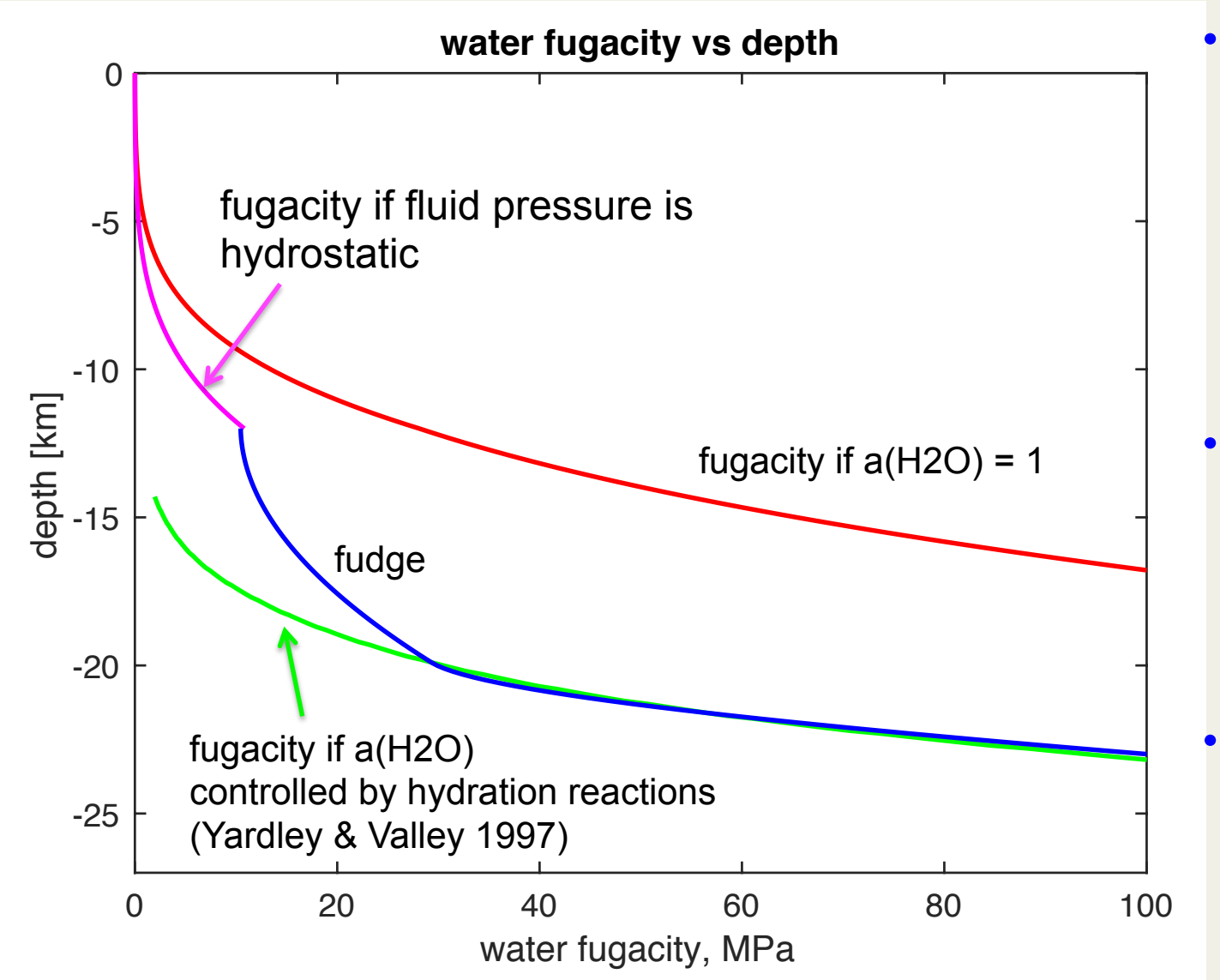
$$w = \frac{V}{2A\sigma^n D^m \exp(-Q/RT)}$$

The cumulative width of plate-boundary shear zones should be related to their rheology – but there are many poorly constrained variables.

- Strain rate is a function of:
  - mineral assemblage
  - temperature
  - water activity
  - metamorphic reactions
  - anisotropy
  - grain size
  - microstructure
  - stress

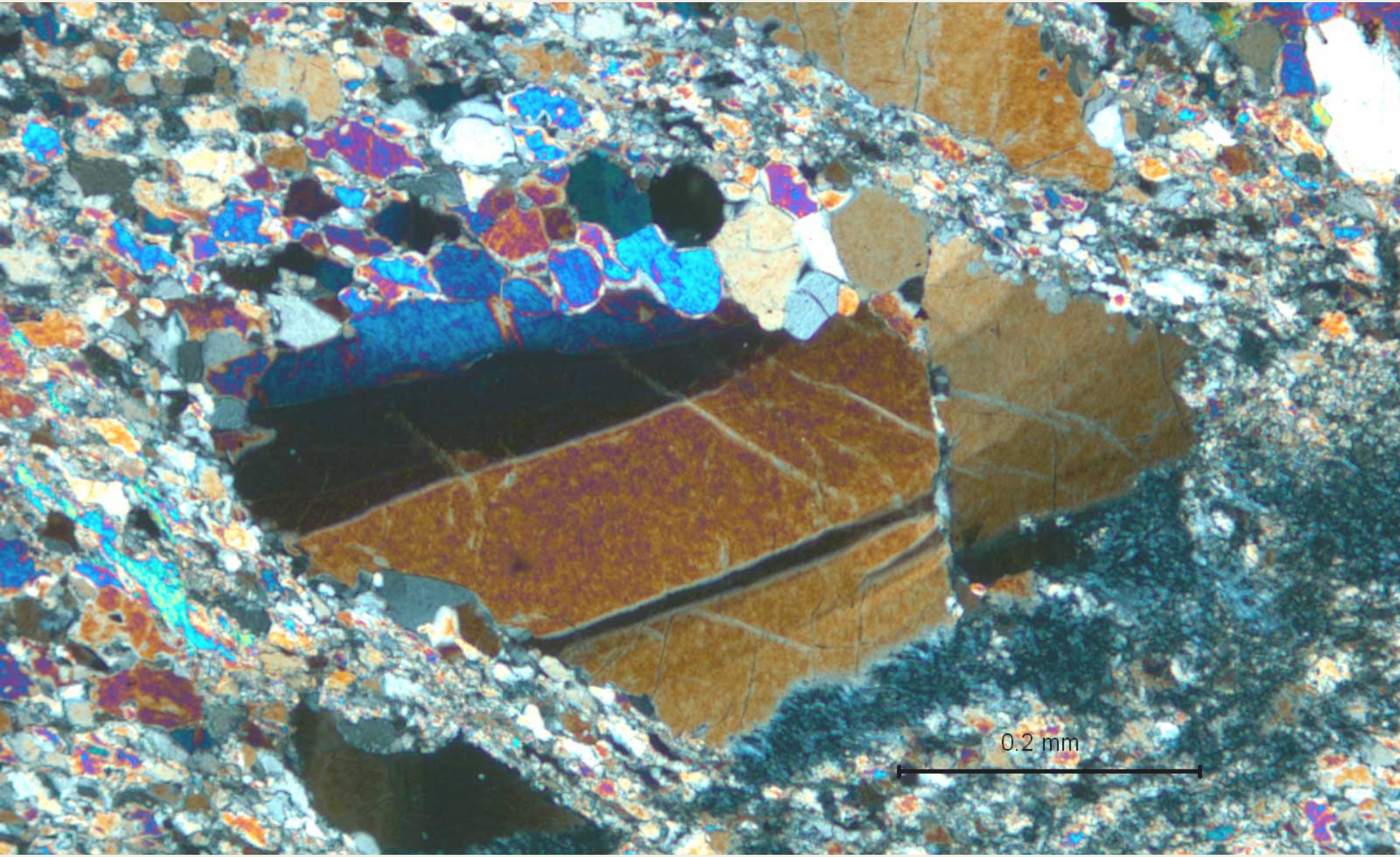
- let's discuss:
  - *water activity*
  - **grain size**
  - microstructure
  - stress

➢ water activity



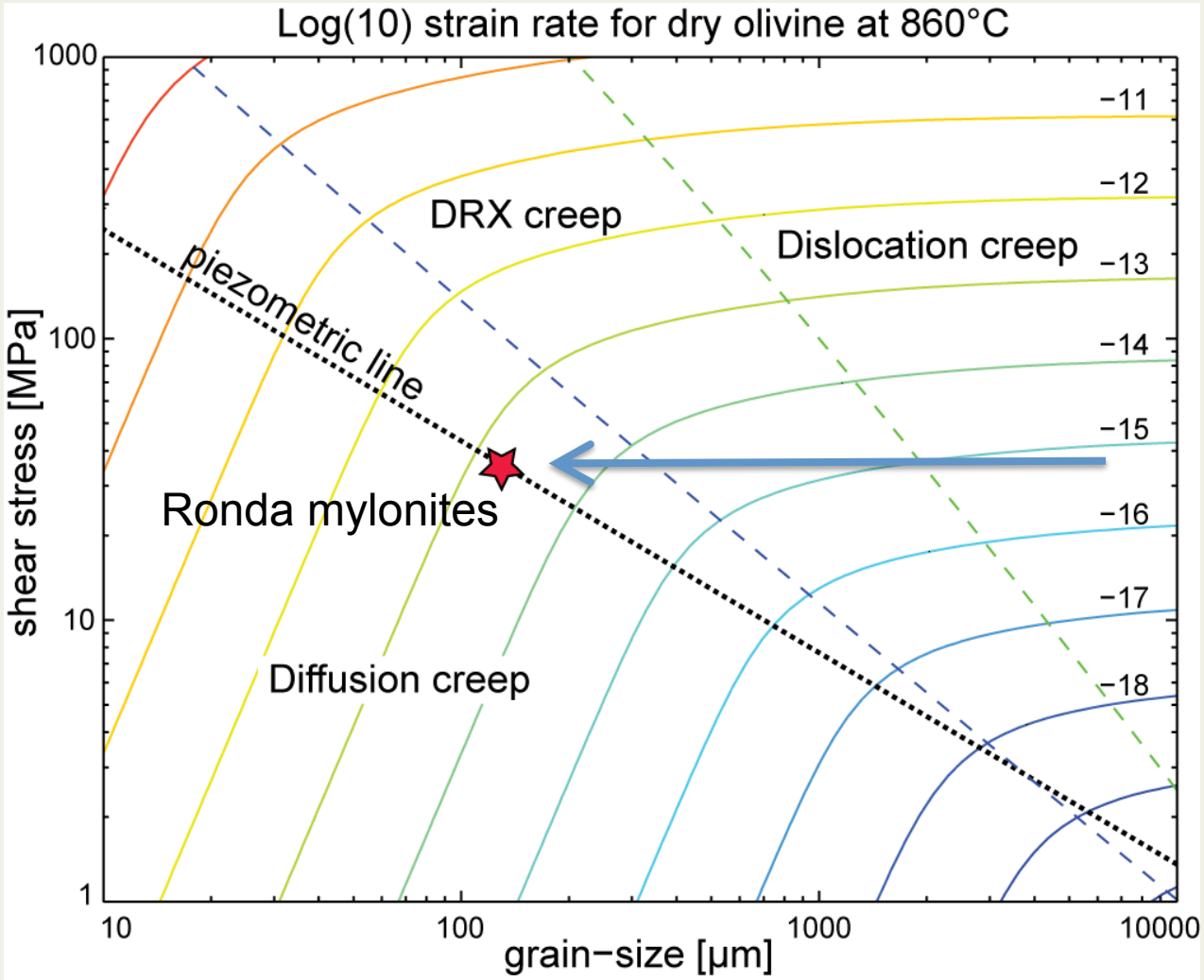
- Flow laws are commonly written with a dependence on water fugacity.
- Water fugacity depends on water activity, P and T.
- Water activity is controlled by metamorphic reactions

Grain-size reduction as a weakening mechanism



Olivine porphyroclast system in mylonitic peridotite, Finero Massif

Switch to grain-size sensitive creep in olivine



Grain-size reduction due to dynamic recrystallization in olivine readily induces a switch to grain-size sensitive creep, with an increase in strain-rate at constant stress of ~100.

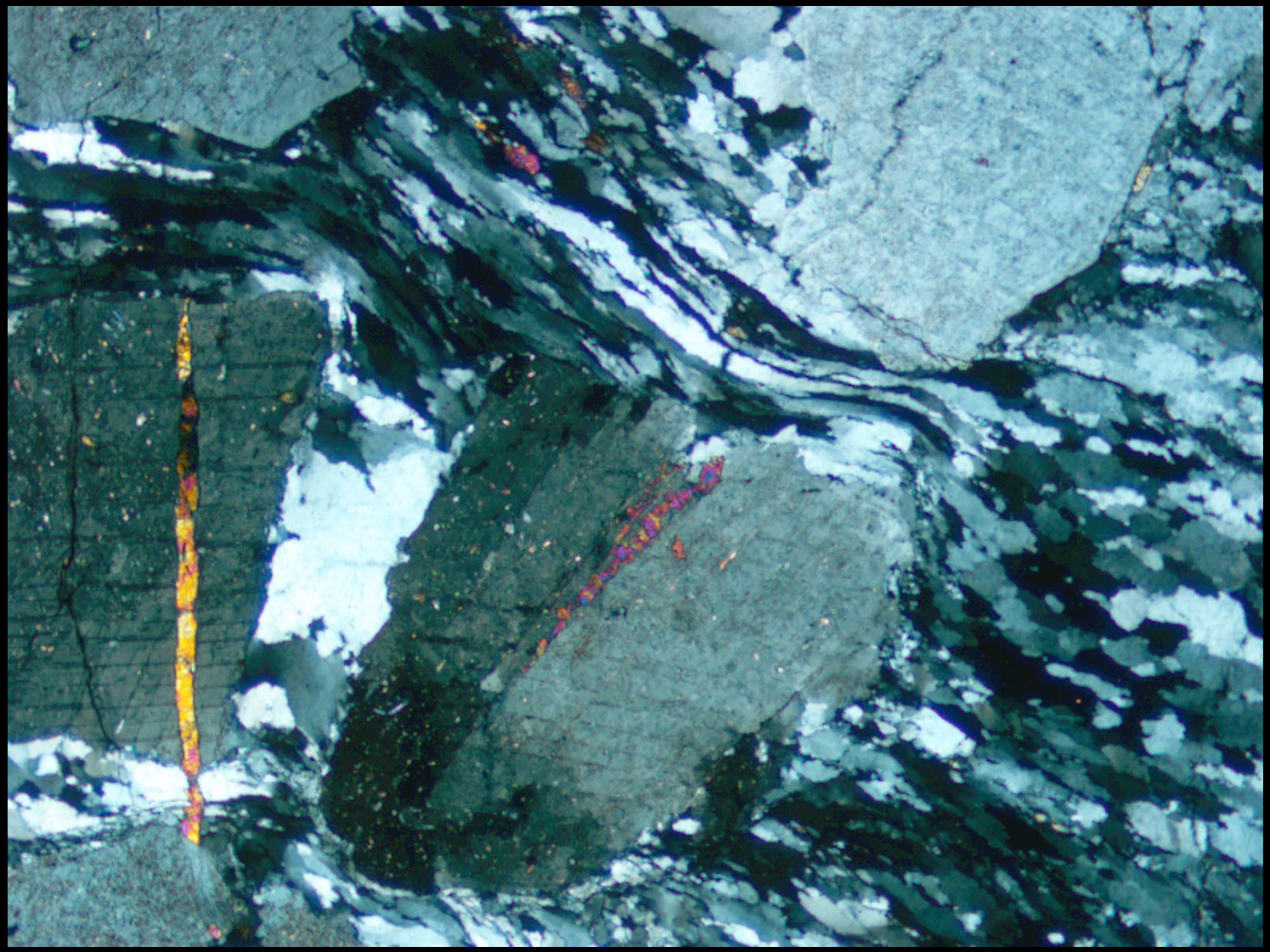
Olivine piezometer from van der Wal et al 1993; olivine flow laws from Hirth and Kohlstedt 2003; DRX flow law from Platt & Behr 2011.

Grain size is controlled by the piezometric relationship

$$D = K\sigma^{-p}$$

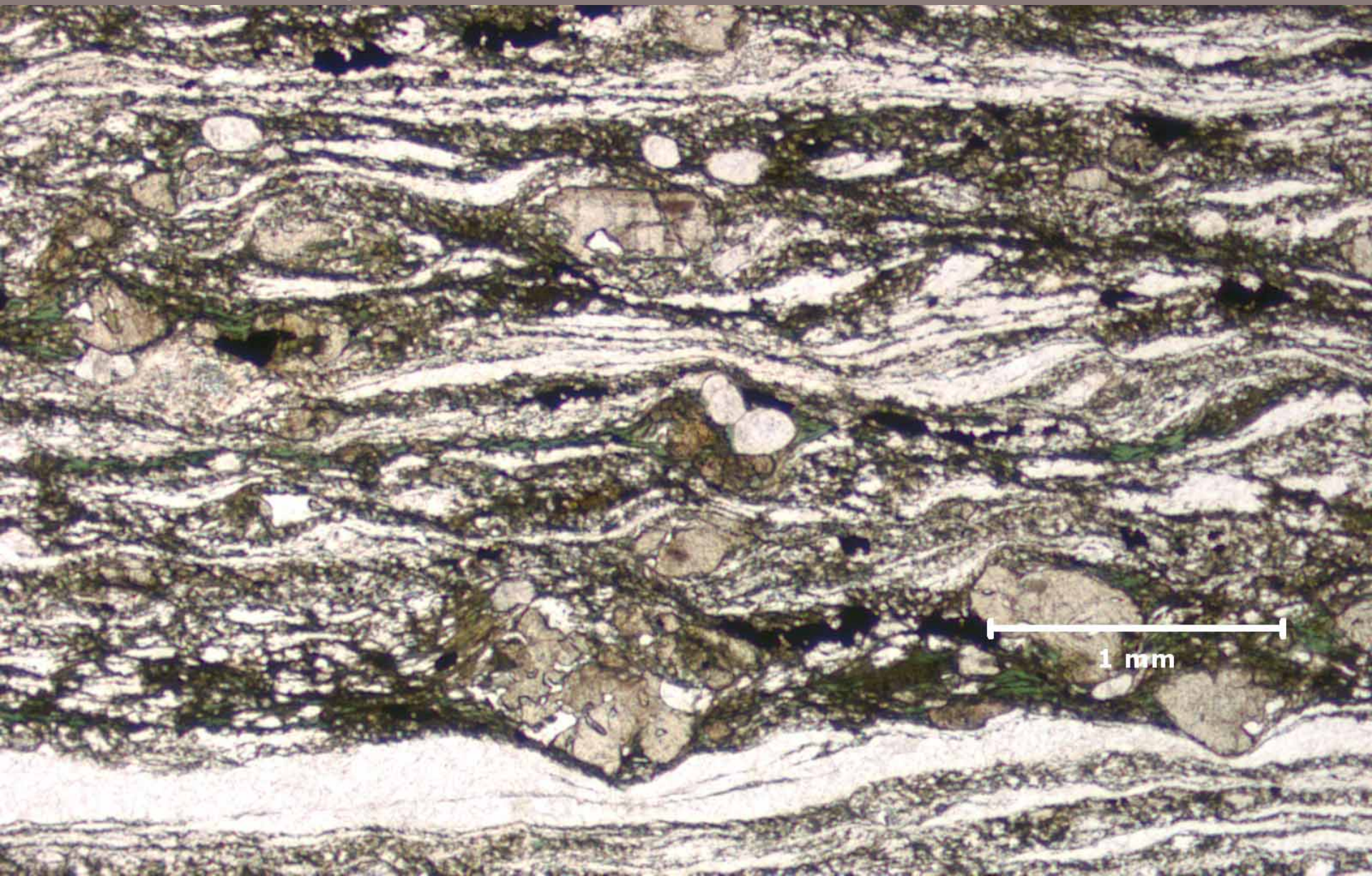
- Quartz: Stipp & Tullis 2003 p = 1.26
- K-Feldspar: Speciale & Behr in prep p = 1.59
- Opx: Linckens et al. 2014 p = 1.308
- Olivine: Van der Wal 1993 p = 1.33

Microstructure

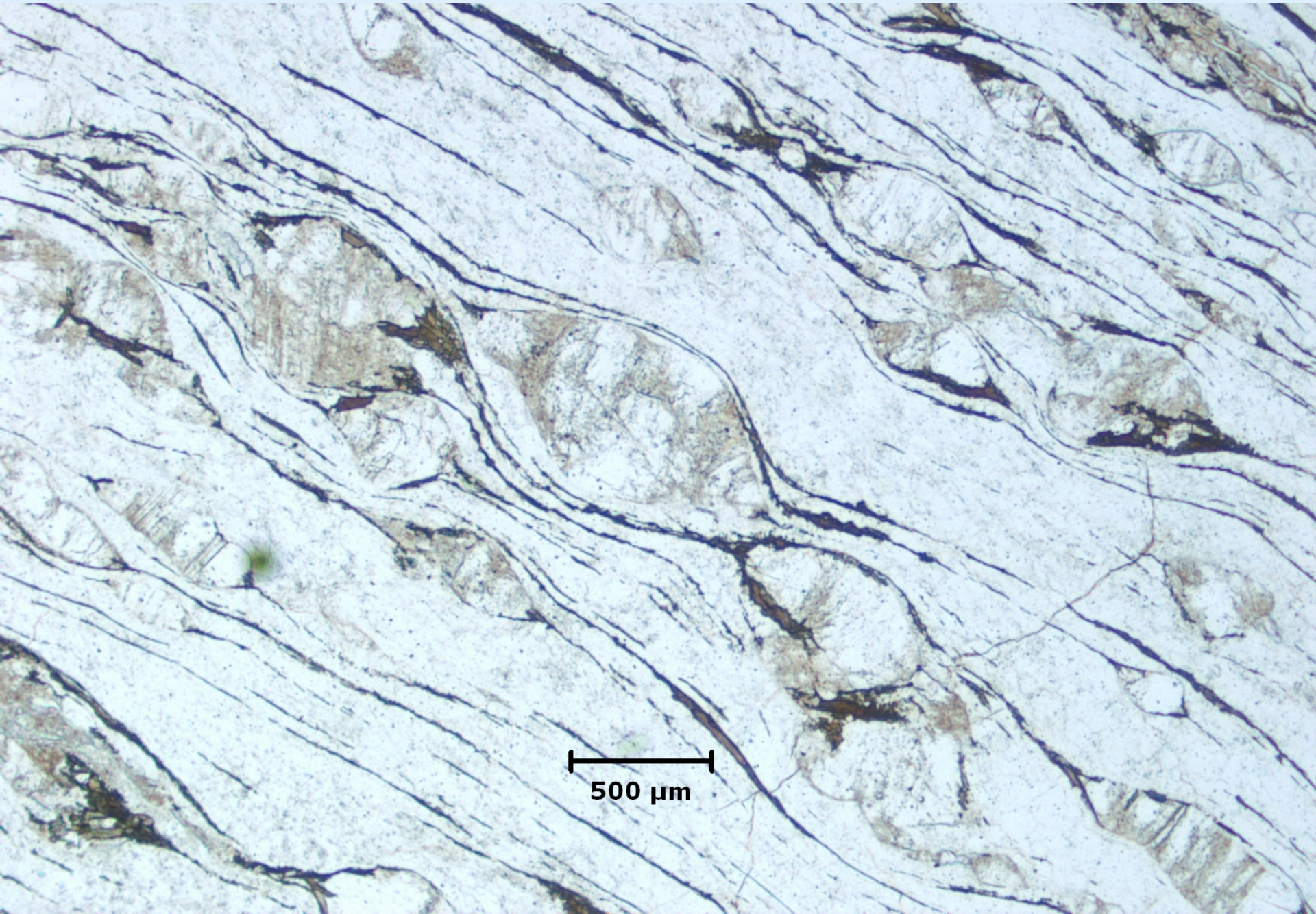


If the strong phase in a polyphase aggregate forms a load-bearing framework, the strength of the aggregate approximates the strength of the strong phase (another concept we owe to Mark Handy)

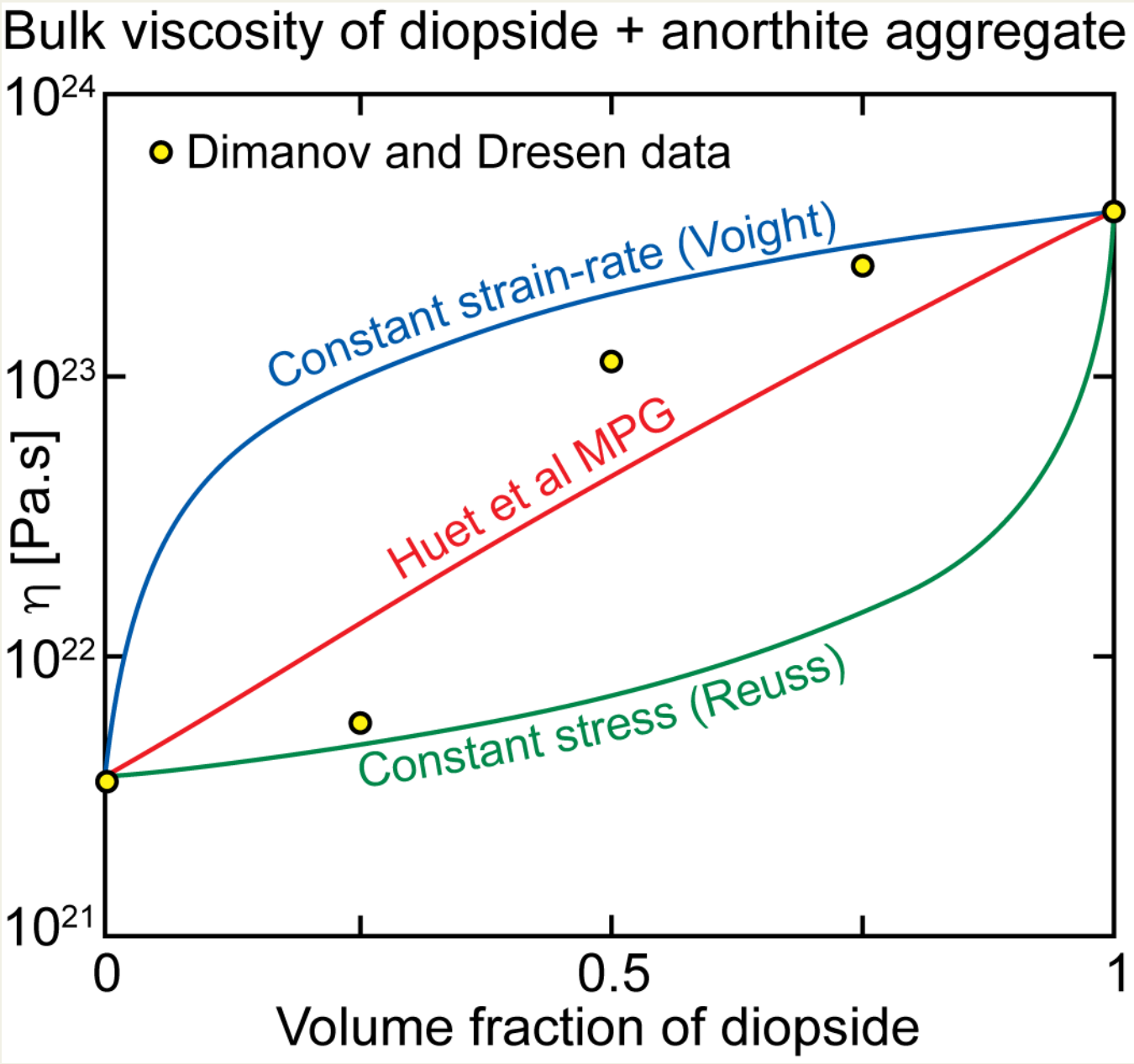
Whipple Mtns mylonitic gneiss. The quartz forms interconnected weak layers and the bulk strength is close to that of the weaker phase.



➢ Microstructure: Ruby mountains granitic mylonite



2-phase rheology



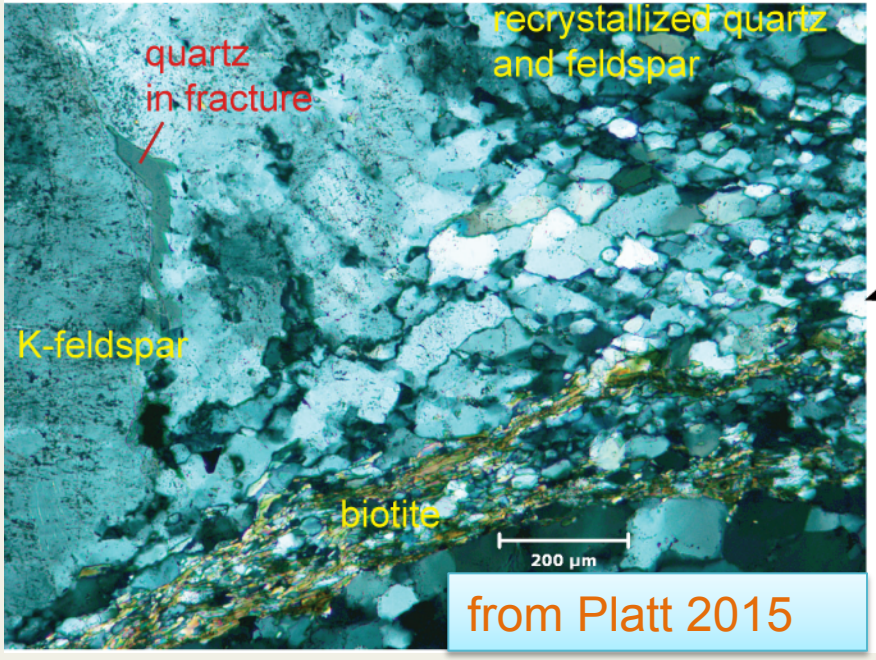
Experimental data approximates constant strain rate law at high volume fractions of strong phase, and constant stress law at low volume fractions

from Dimanov & Dresen 2005, Huet et al. 2014

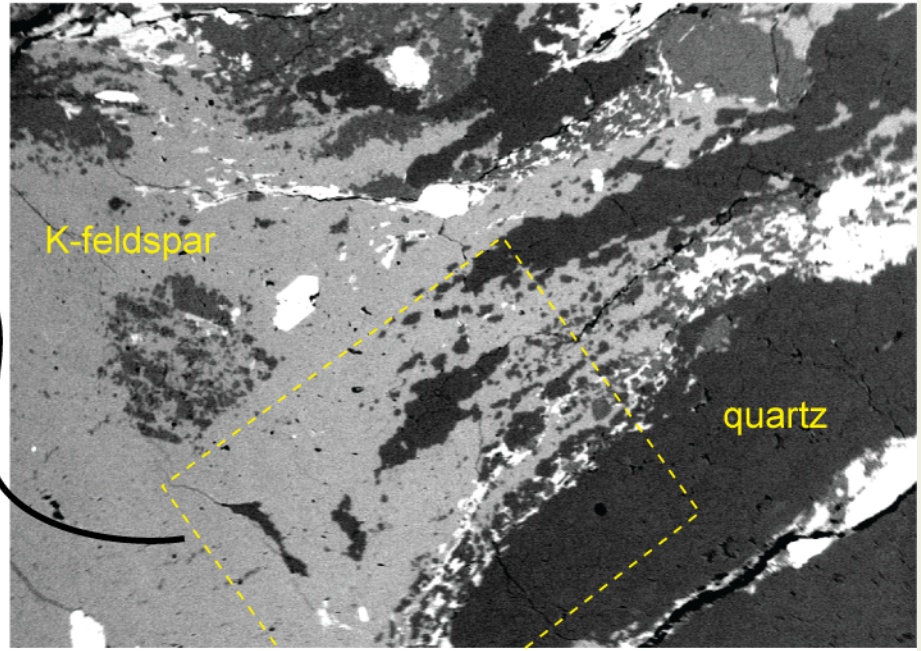
2-phase mixing laws

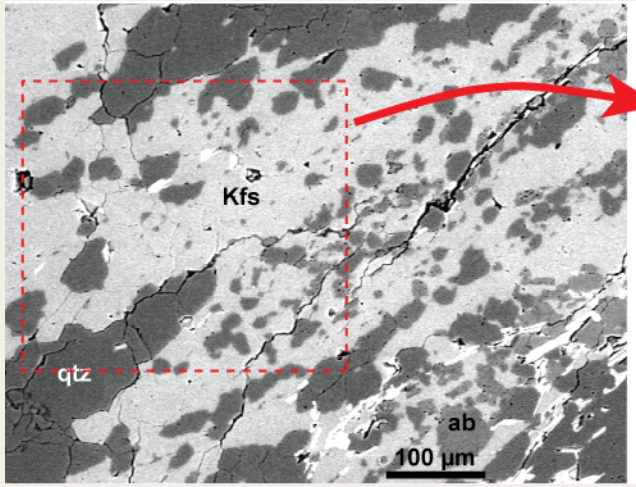
- For dislocation creep with high volume fractions of strong phase (e.g., granite), bulk behavior may be LBF, approximates Voigt upper bound.
- But granitic gneiss has IWL microstructure, may approximate Reuss lower bound.
- Low volumes fractions of strong phase (e.g., peridotite) may approximate Reuss lower bound.
- Intermediate volume fractions are best approximated by Huet et al. mixing law.
- What about ultramylonites???

Two-phase mixing in mylonitic granite

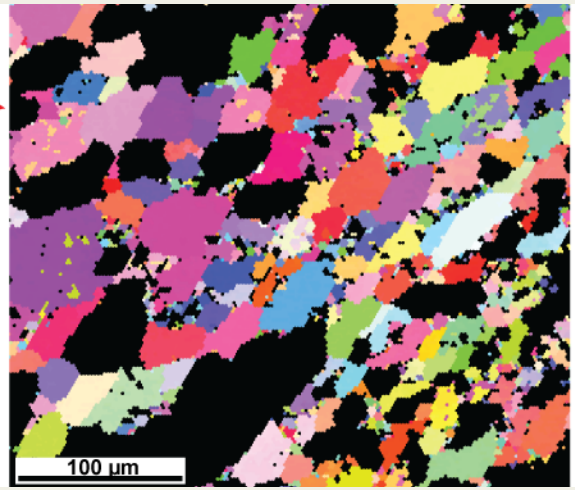


from Platt 2015

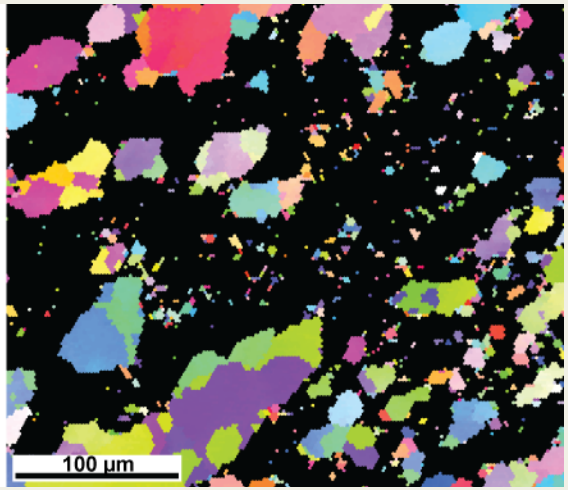




backscatter

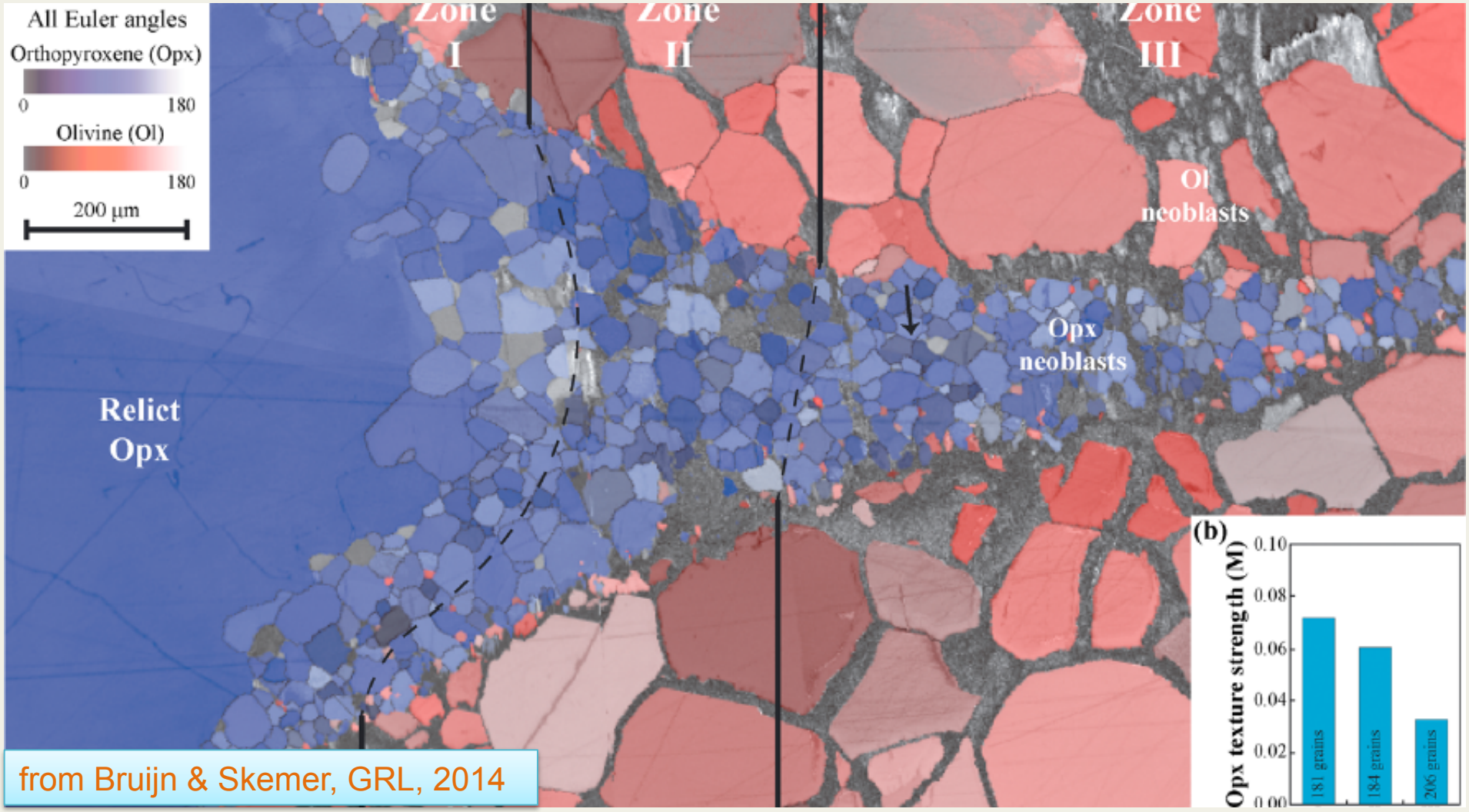


EBSD map, feldspar



quartz

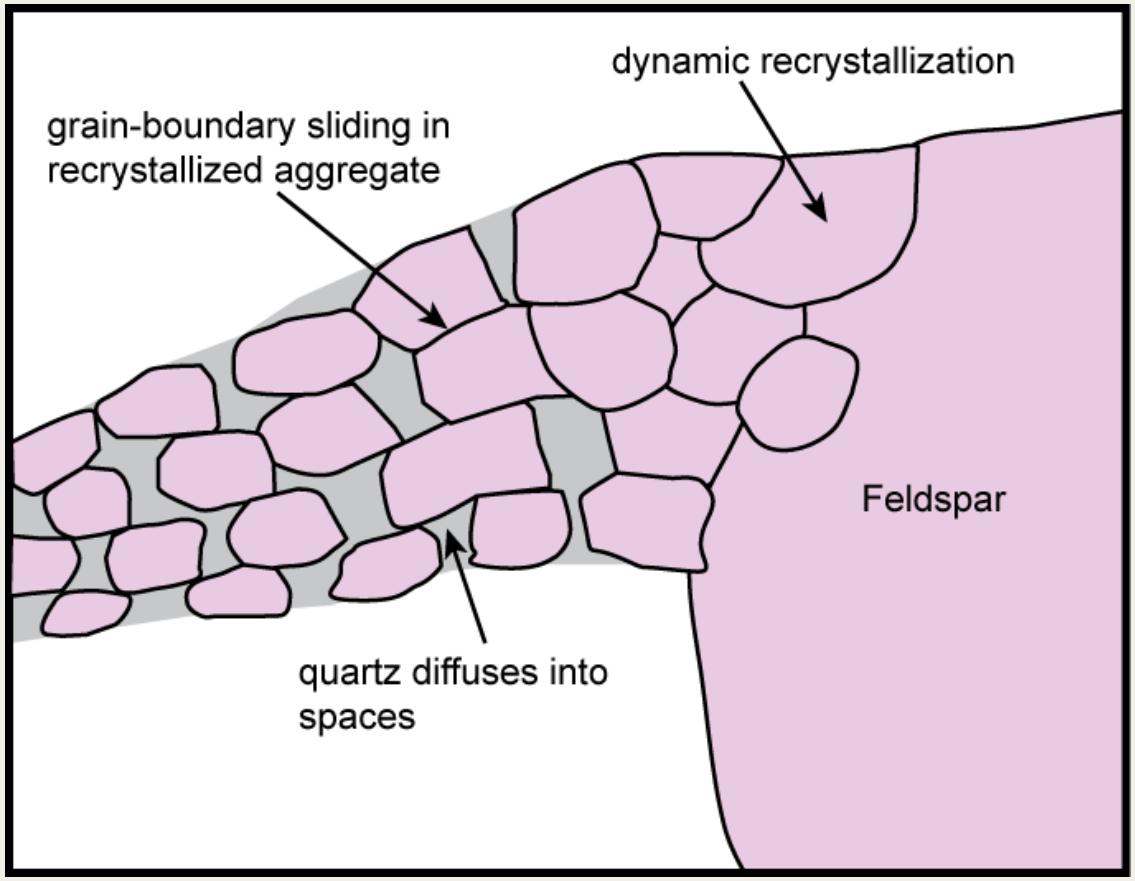
Orthopyroxene porphyroclast system in mylonitic peridotite



from Bruijn & Skemer, GRL, 2014

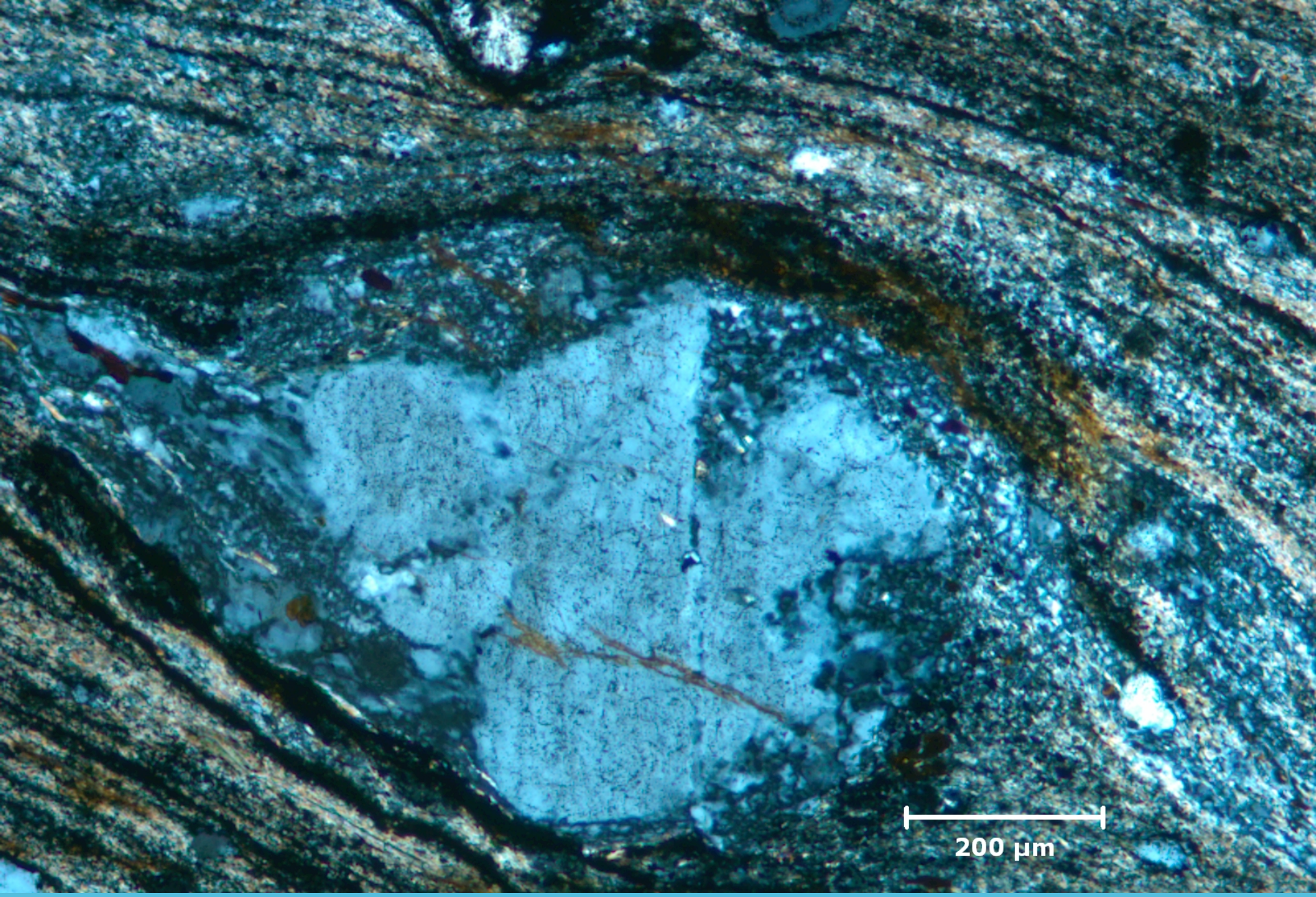
Orthopyroxene (blue) is dynamically recrystallized in the tail of a large porphyroclast. Olivine (red) has diffused into the tail creating a two-phase mixture.

Two-phase mixing in a granitoid



from Platt, JSG, 2015

- Dynamic recrystallization in feldspar → piezometric grain size
- quartz diffuses by pressure solution into spaces created by grain-boundary sliding
- bulk flow is pressure solution creep of quartz, diffusion creep of feldspar, controlled by grain-size of feldspar



Two phase mixing can also occur by chemical processes. This plagioclase porphyroclast is being altered to fine-grained K-feldspar + quartz in the tail.

The width of lithospheric shear zones

The cumulative width *w* of a system of plate boundary shear zones is controlled by:

imposed plate velocity

$$w = \frac{V}{2A\sigma^n D^m \exp(-Q/RT)}$$

flow law for shear zone

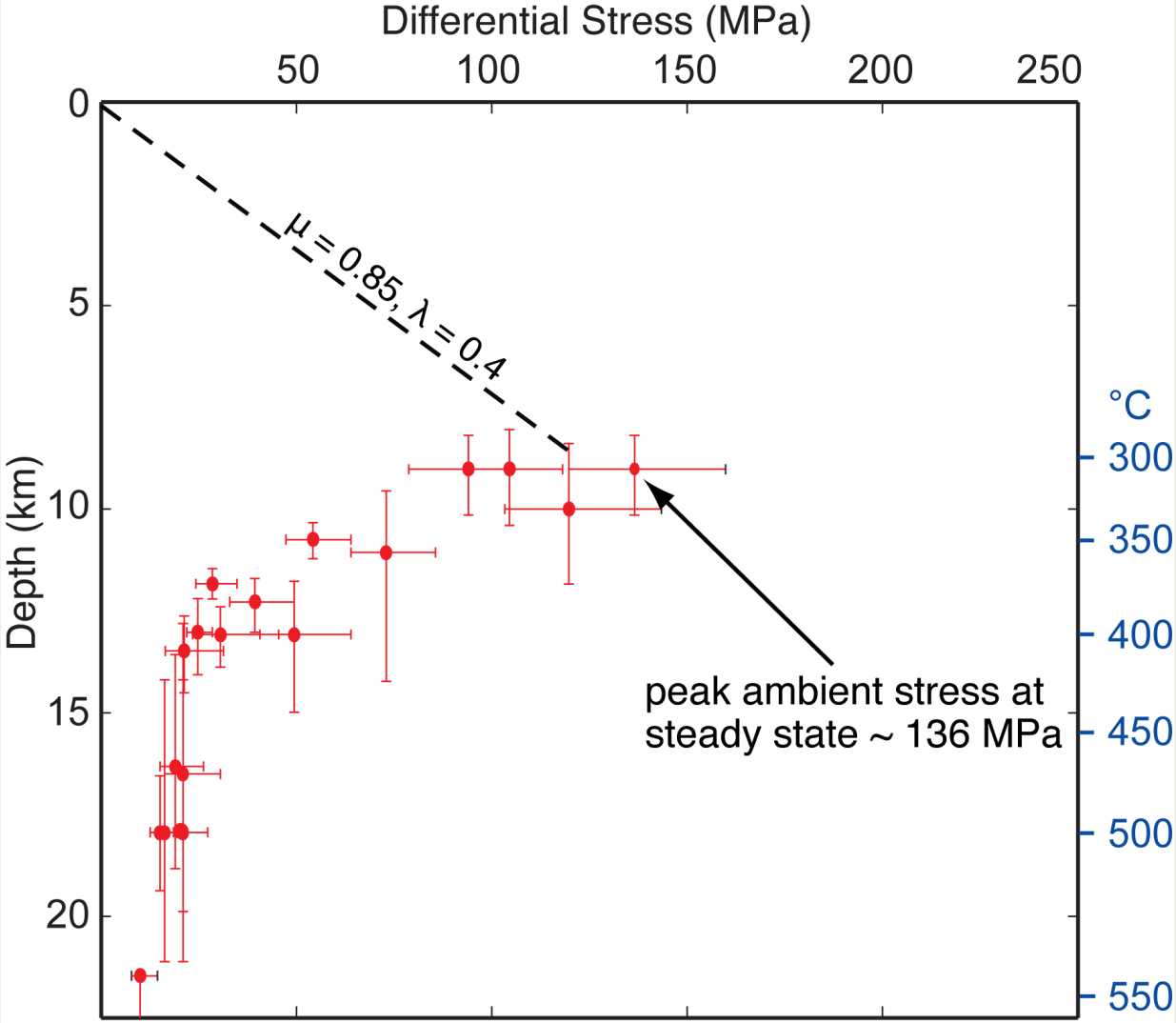
flow stress

Strain-rate in shear zone

- *A* depends on mineral properties and water content
- *D* is grain-size, which for dislocation creep is a function of stress
- *Q* is activation energy for creep, and may be sensitive to pressure

➢ How do we constrain stress ?

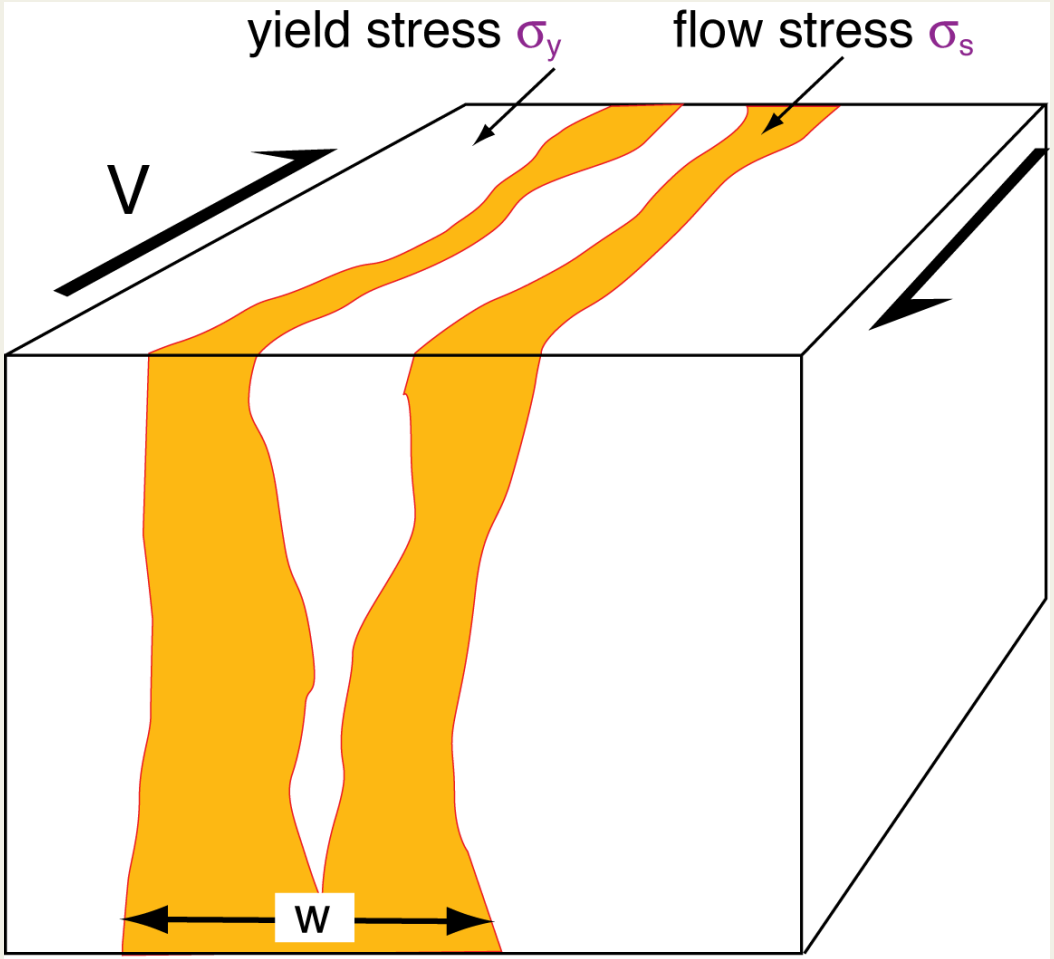
Paleostress-depth profile, Whipple Mtns



- Stress from dynamically recrystallized grainsize paleopiezometry
- T from Ti in quartz
- depth from thermal modeling
- progressive localization allows preservation of older (deeper) parts of the history

Behr & Platt, 2011, EPSL

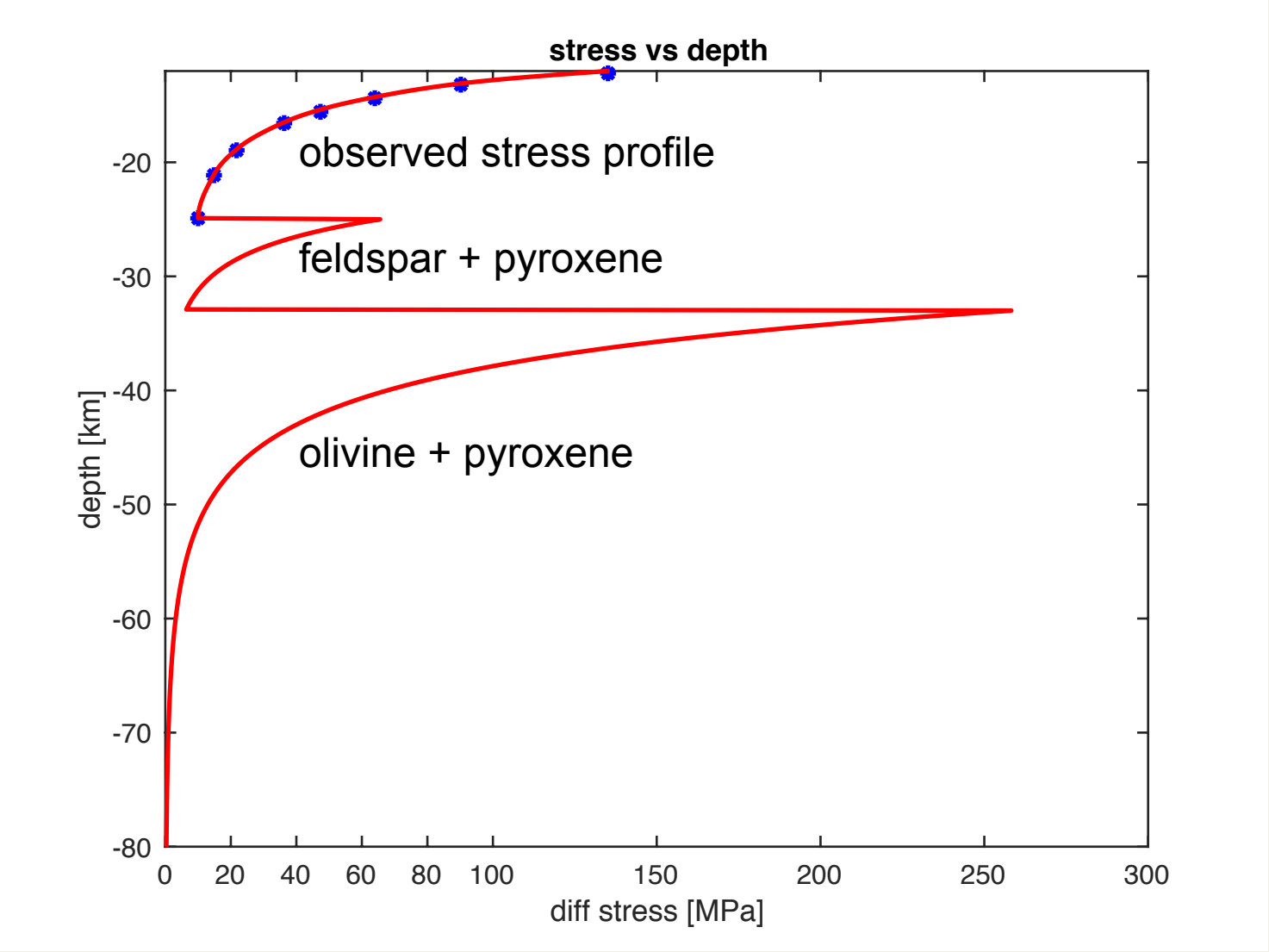
Stress in ductile shear zones



V is the imposed relative plate velocity
w is the cumulative width of the shear zones

- Narrow shear zones require high strain rates, and hence high flow stress, to accommodate *V*
- Shear zones get wider if flow stress exceeds yield stress of surrounding rock
- Shear zones cease to widen once that condition is reached.
- Hence flow stress in shear zones equals yield stress

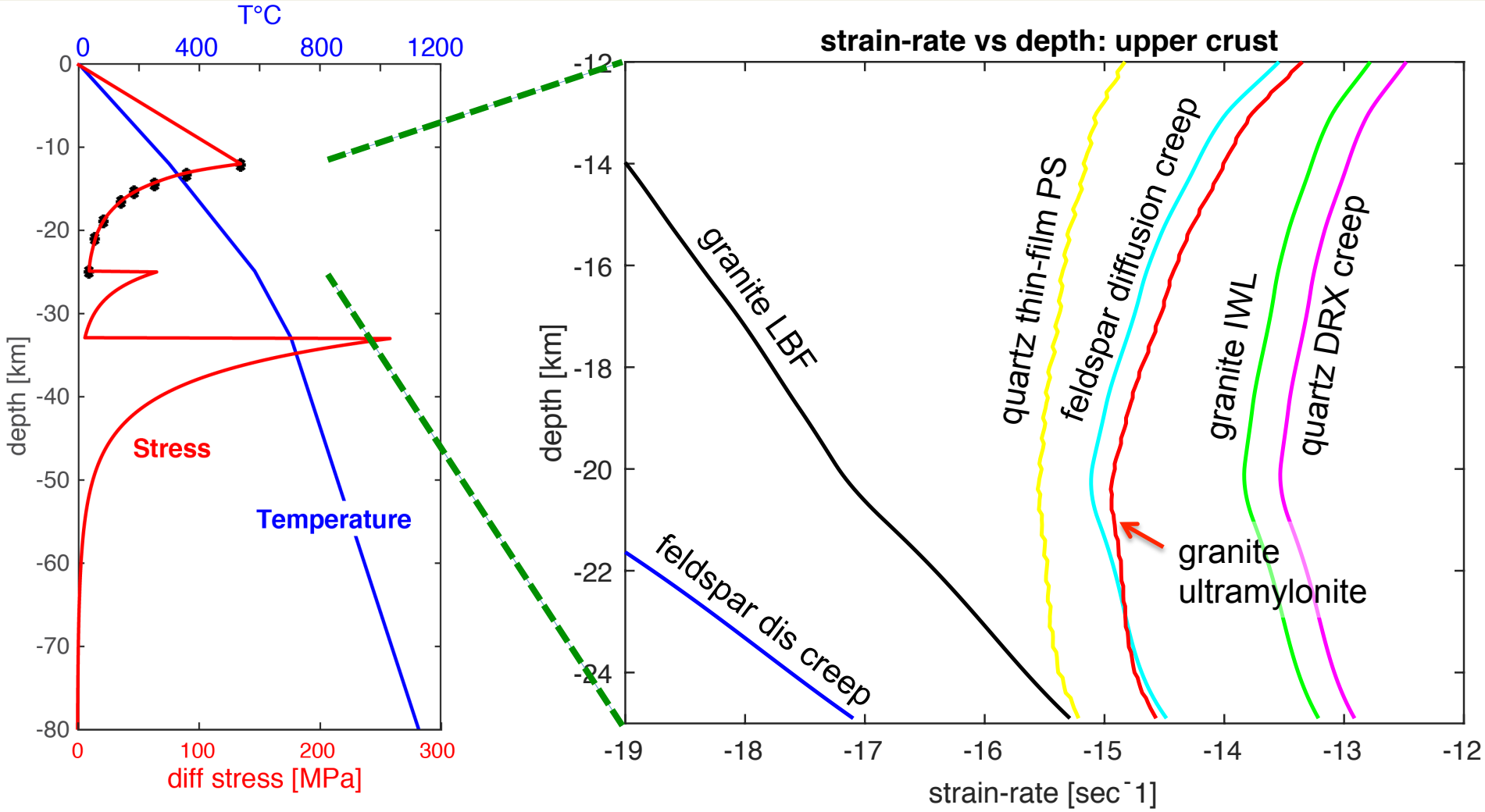
Lithospheric strength profile



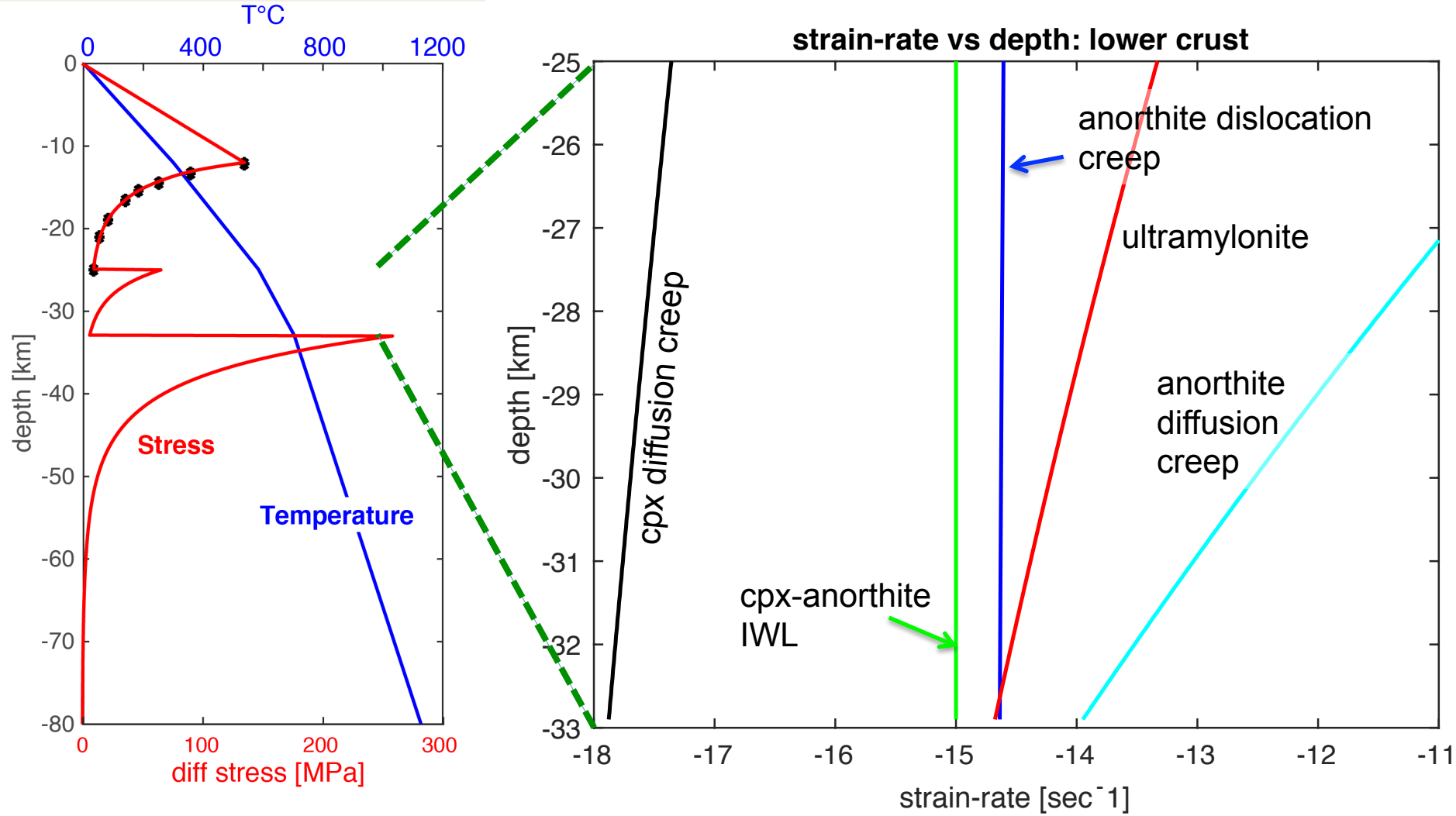
Stress profiles calculated assuming dislocation creep in two phase aggregates, and bulk strain rate of 10^{-15} s^{-1}

Strain rate vs depth

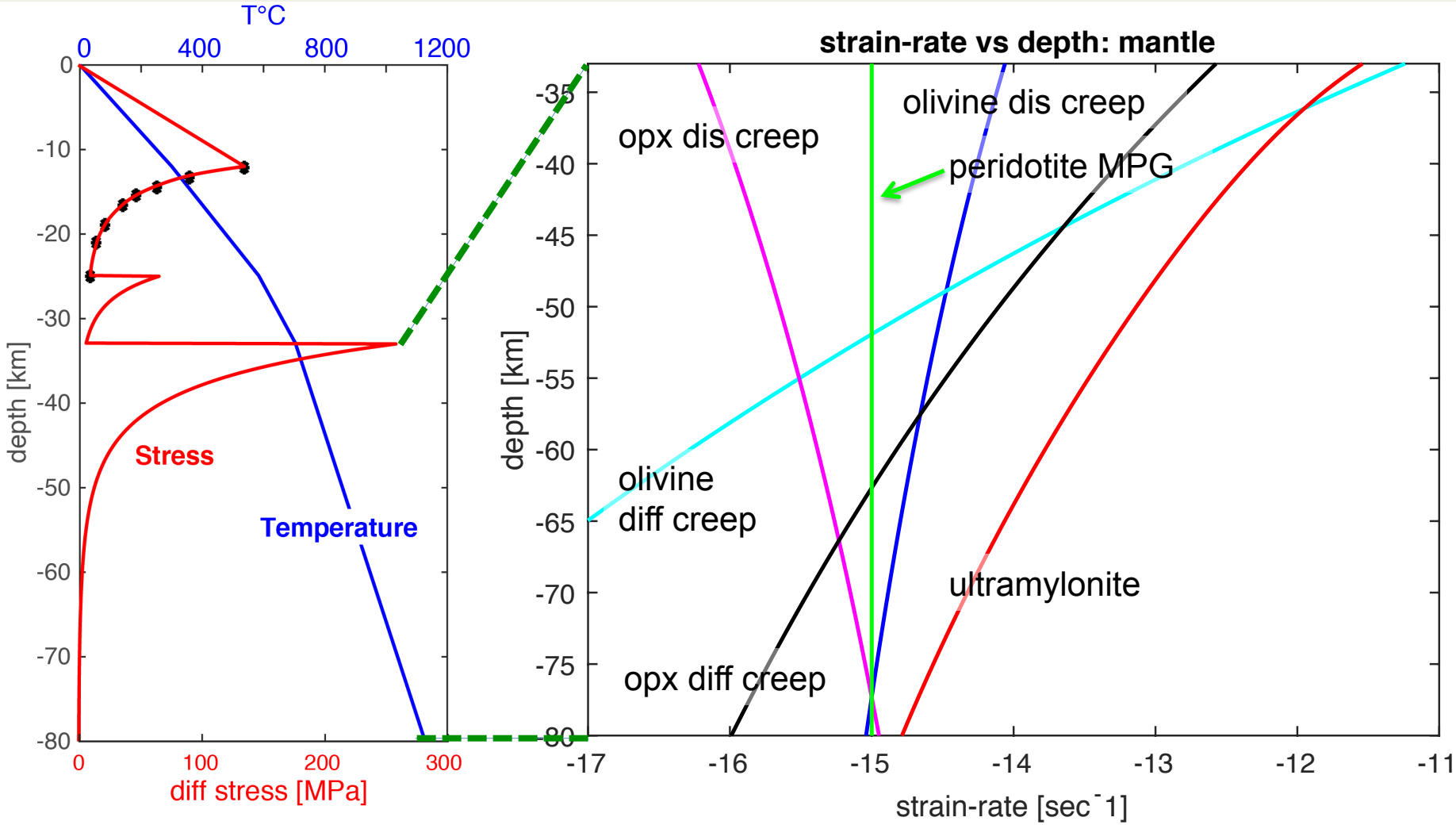
Upper crust: 50% feldspar, 50% quartz



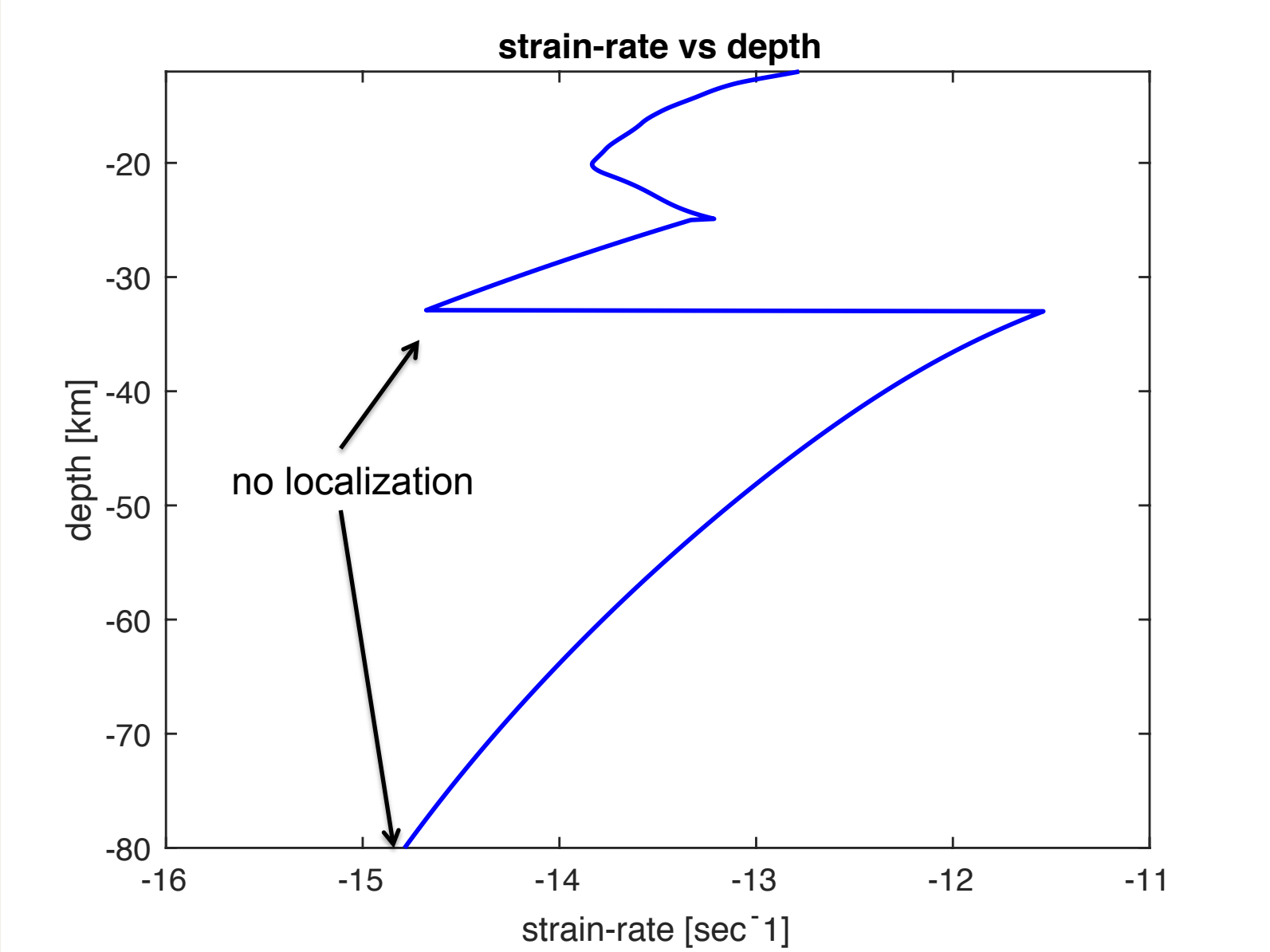
Lower crust: 70% anorthite, 30% diopside



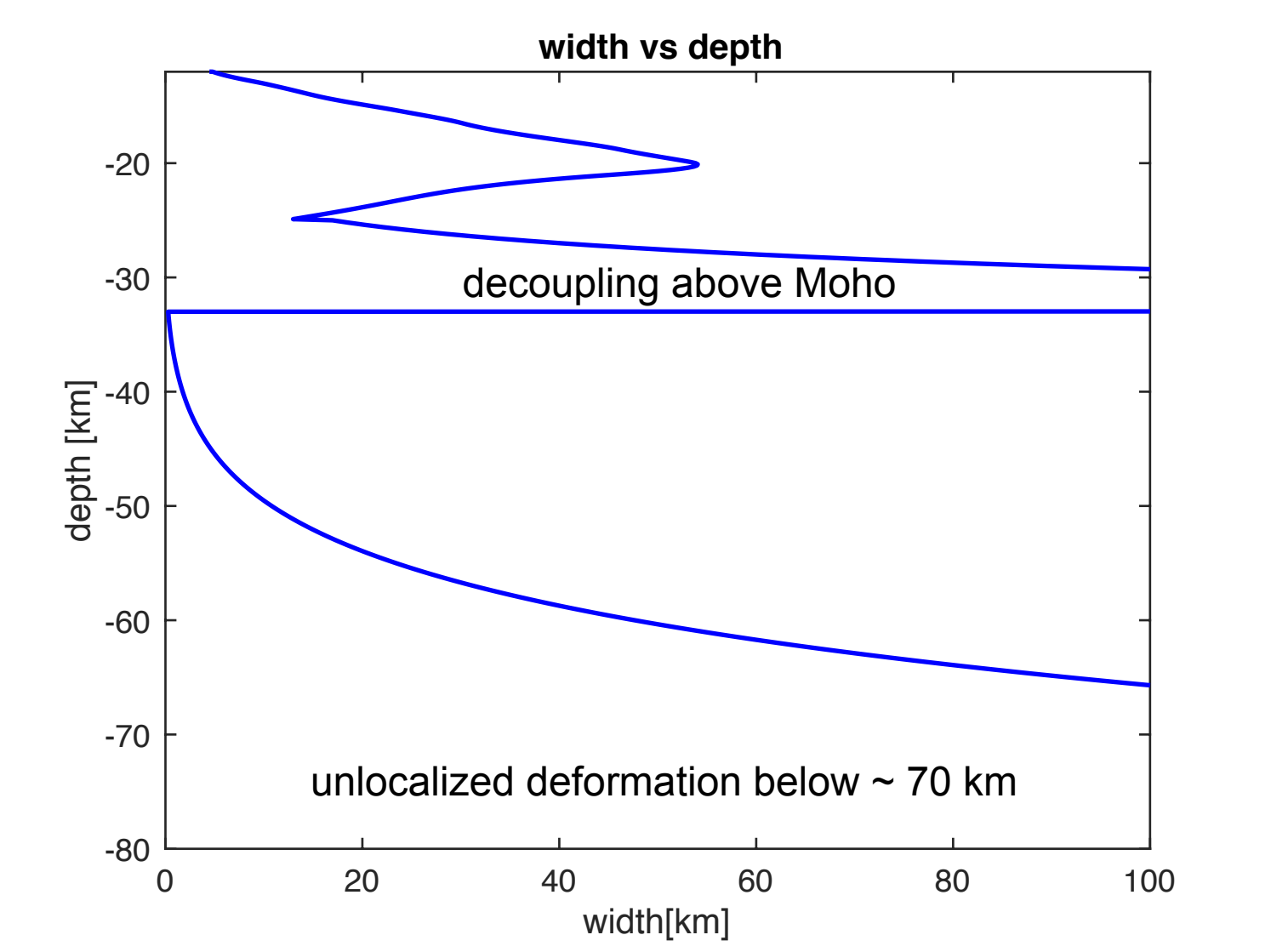
Lithospheric mantle: 60% olivine, 40% opx



Strain-rate vs depth



Width vs depth



Cumulative width of plate boundary shear zone assuming relative plate velocity of 50 mm/yr, and calculated strain rates

Conclusions

Calculated strain rates are strongly dependent on flow laws, water activity, microstructure and stress, among many other variables.

The strain-rates shown here, and the shear zone widths calculated from them, are not necessarily correct, but the method described here offers a way forward.