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

John Platt
University of Southern California
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.
Rick Sibson, Mark Handy and others have suggested faults broaden with depth, and the rheology changes. Can we quantify this?
Shear zones in Archean and Proterozoic gneiss terranes can be 20 km or more in width.
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

Velocity distribution across the San Andreas transform system in southern California

from Platt & Becker 2010

\( \chi = 2.047 \)
Cumulative width of a plate boundary shear zone

\[ \text{width} = \frac{\text{Velocity}}{\text{strain} - \text{rate}} \]

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

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*
- 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 (Yardley & Valley 1997).
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.

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 \( p = 1.33 \)
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
Orthopyroxene porphyroclast system in mylonitic peridotite

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

- Dynamic recrystallization in feldspar $\rightarrow$ 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

From Platt, JSG, 2015
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:

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

- $A$ 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 grain size
- 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

- 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.

$V$ is the imposed relative plate velocity.
$w$ is the cumulative width of the shear zones.
Lithospheric strength profile

Stress profiles calculated assuming dislocation creep in two phase aggregates, and bulk strain rate of $10^{-15} \text{ s}^{-1}$
Strain rate vs depth
Upper crust: 50% feldspar, 50% quartz
Lower crust: 70% anorthite, 30% diopside

-33 -32 -31 -30 -29 -28 -27 -26 -25

-40 -30 -20 -10

0 400 800 1200

0 100 200 300

T°C

diff stress [MPa]

depth [km]

Stress

Temperature

strain-rate vs depth: lower crust

-18 -17 -16 -15 -14 -13 -12 -11

strain-rate [sec⁻¹]

depth [km]

cpx diffusion creep

anorthite diffusion creep

anorthite dislocation creep

ultramylonite

cpx-anorthite IWL
Lithospheric mantle: 60% olivine, 40% opx
Strain-rate vs depth

No localization
Width vs depth

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

decoupling above Moho

unlocalized deformation below ~ 70 km
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.