Implication of Flow in the Lower Crust on Strain Localization across Time and Length Scales

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Earth Paradigm: Plate Tectonics
General knowledge of the Earth

- Geodesy
- Geological Data
- Stratigraphy
  - Paleomag

Geophysical Modelling

- Geodynamic Modelling
- Mineral physics
- Thermo-dynamic modelling
- Geochemistry

Geological time

Depth

0 km

4500 km
Geodynamic Modelling

Large scale geodynamics
Says:

To have plate tectonics you need to have weakening mechanisms at plate boundary
Large scale geodynamic modelling says:

To have plate tectonics you need to have weakening mechanisms at plate boundary and some inheritance to produce transform boundary.

Bercovici and Ricard 2014
WELL, WE NEED TO KNOW ABOUT IT BECAUSE IT CONTROLS THE CAPACITY TO HAVE PLATE TECTONIC ON EARTH!

AND ALL THE CONCEPTUAL MODELS OF EARTH RELY ON PLATE TECTONICS

WHY DO WE NEED TO KNOW ABOUT THE STRENGTH OF THE LITHOSPHERE?
WHAT IS THE LITHOSPHERE?
It is not seismically defined like the Moho. It is defined by a mechanical/thermal Boundary Layer.
Yield Strength of Earth materials?

At low pressure and low temperature, it is easy to define a yield strength, since it is the peak deviatoric stress.
At low temperature and low pressure most of the rock have the same yield strength which corresponds to a frictional behaviour.
This corresponds to the brittle behaviour of the lithosphere.
What is Yield Strength at high pressure/high temperature?

rocks become ductile with a lot of different crystal plasticity mechanisms that compete one with each other depending on grain size, strain rate, pressure and temperature.

Figure 5.3 Effects of pressure (left: Carrara marble) and temperature (right: granite) on the stress–strain behaviour of rocks. Numbers on curves give confining pressure (in MPa) and temperature (in °C), respectively (from Jaeger and Cook 1979).
**Ductile flow laws**

\[
\dot{\varepsilon} = A_{DF} a^{-m} C_{H_2O} \tau_{II}^n \exp\left(-\frac{E_{DF} + PV}{RT}\right)
\]

**diffusion creep**

\[
\dot{\varepsilon} = A_{DS} C_{H_2O} \tau_{II}^n \exp\left(-\frac{E_{ds} + PV}{RT}\right)
\]

**dislocation creep**

\[
\dot{\varepsilon} = A_p \exp\left(-\frac{E_p}{RT} \left(1 - \frac{\tau_{II}}{\tau_p}\right)\right)
\]

**Peierls creep**

\[
\dot{\varepsilon} = A_{GBS} a^{-m} C_{H_2O} \tau_{II}^n \exp\left(-\frac{E_{GBS} + PV}{RT}\right)
\]

**GBS creep**

*Popov and Sobolev, 2008*
The lithosphere creeps at all temperature
But yet at small strain, rocks might not be yielding at all!

Figure 5.3 Effects of pressure (left: Carrara marble) and temperature (right: granite) on the stress–strain behaviour of rocks. Numbers on curves give confining pressure (in MPa) and temperature (in °C), respectively (from Jaeger and Cook 1979).
So that part of the lithosphere remains also elastic.
And Elastic mechanical energy can be restored during earthquakes
The simplest rheological model for earth lithosphere looks like

Which is finally quite complex and non linear!
But thinking about it

Elasticity and dry friction do not vary much... and are well constrained

They DO NOT ADD parameters

They only allow for a more accurate description of rheology of the lithosphere

So that in the end, what is really important is the temperature and the petrological nature of rocks
We always split Lithosphere into continental and oceanic lithosphere which distinguish them selves by the nature of the overlying crust.
The oceanic crust is usually thin (7 km) best described using ophiolites like in Oman.

- Basalts
- Gabbros
- Peridotites

Variability is supposed to be smaller, but it might just be that we have less observations! However, whether oceanic crust is typical, or just serpentinized mantle it is always 7 km thick.
The continental crust is highly variable in thickness and composition!
Representing yield strength as a function of depth reaches very different picture for continent and oceans.

Variability is very high on continents.
Influence of the nature of the continental crust on collision

Yamato et al. EPSL 2008
Influence of the nature of the continental crust on convective stability of the lithosphere.
Influence of the nature of the continental crust on divergent boundaries

Huet et al. GJI 2011
FLOW IN THE LOWER CRUST HAS A MAJOR IMPORTANCE ON THE DYNAMIC OF THE PLATES BOUNDARIES AND STABILITY OF CONTINENTAL PLATES
Now Focusing on strike slip boundaries
Can we actually record long term tectonic record of weak strike slip faults?

Mount and Suppe, 1987
Thatcher and Pollitz approach.

Inferring the viscosity of the crust and the lithosphere from the visco-elastic relaxation model.

We find the lithosphere around strike slip fault is weak.
Rheology of the Lower Crust and Upper Mantle: Evidence from Rock Mechanics, Geodesy, and Field Observations

Roland Bürgmann¹ and Georg Dresen²
How do plate boundaries get weaker?
FABRIC SOFTENING IS EFFICIENT AT WEAKENING INITIALLY STRONG PLATE BOUNDARIES

Increase in **layering content**

Decrease in **grain size**

\[
\sigma = (1-f)\sigma_{\text{protolith}} + f\sigma_{\text{shear zone}}
\]

\[
\dot{\varepsilon} = \dot{\varepsilon}_r + \dot{\varepsilon}_d + \dot{\varepsilon}_g + \dot{\varepsilon}_e
\]

Gueydan et al., 2003, 2004; Montési, 2007

Précigout & Gueydan, 2009
BUT HOW DOES IT WORK IF THE LITHOSPHERE IS ORIGINALLY WEAK?
Kinematic interpretation of the 3D shapes of metamorphic core complexes

**Models**

- **a. Model 1**
- **b. Model 2**
- **c. Model 3**

- **cylindrical extension**
- **extensional step-over**
- **transtensional fault propagator**
Getting now more insights on plate weakening due to flow

\[ v_x = 2 \text{ cm/yr}, \quad v_z = 0 \]

\[ \sigma_{zy} = \sigma_{zy} = 0 \]

\[ \varphi_0 = 30^\circ \]

\[ \varphi_{\text{soft}} = 10^\circ \]

\[ \dot{\varepsilon} = 10^{-15} \text{ s}^{-1} \]

\[ \varepsilon = \frac{10^2}{10^15} \text{ s}^{-1} \]

\[ \sigma_{\parallel} [\text{MPa}] \]

\[ \text{depth} [\text{km}] \]

\[ t \]

mantle inflow
YET in these models, strain localisation is applied from the boundary.

Can we actually localise strain rather than propagating localisation?
Increasing the viscosity increases the brittle ductile coupling.

Increasing the extension rate should also increase it.

YET

Higher extensional rate causes more localised structures.
How does it evolves with time?

With weaker lower crust the strain keep being localised even when structure become badly oriented...
HOW MUCH CAN THESE DOMES STRUCTURE PARTICIPATE TO OBSERVED GPS LOCALISED VELOCITY GRADIENT?
Localised low viscosity lower crust exhumed as notches beneath transtensional step-over permit to impact surface velocity field during the interseismic.

If the notch involves strong mantle lithosphere, most of the interseismic signal can be reproduce.
Can we fit data? YES

GPS data, SB model and viscoelastic notch model

SB model
s=3.4 cm/yr
d=12 km
RMS=0.274 cm/yr

notch model
s=3.4 cm/yr
h1=10 km
L=50 km
RMS=0.105 cm/yr

best fit SB model
s=3.5 cm/yr
d=32 km
RMS=0.101 cm/yr

Traoré et al. 2014
CONCLUSIONS

- The modification of the geometry of the brittle-ductile transition is sufficient to explain the interseismic strain localisation across a strike-slip fault zone.

- Long after an earthquake has occurred, the interseismic geodetic signal is more prone to reflect the rheology of the crust than post-seismic relaxation.
Can long term tectonic flow influence even shorter term deformation?
Flow in the lower crust favours delamination.
Looking at the state of stress in the crust we find that it deforms by buckling and flexure.

Le Pourhiet et Saleeby, 2013
Geology
Meanwhile, the EarthScope array brought a very accurate 3D image of the drip.

Saleeby et al. 2012, Geosphere
Using an effective elastic thickness of 10 km, it is possible to evaluate the flexural response of the crust to the loading of the drip.

The creeping segment lies on a flexural forebulge.
Using basic principal of yield strength envelopes one can predicts locked elastic patches and location of the maximum strength.
Do we see something in the seismicity?

Hill et al. 1990

Thurber et al. 2006

- 1966
- 1984-2004
- 2004
- 2004-2006
- 150 km is the length scale for flexural bending

- Death Valley, Mount Whitney and the creeping segment are locally aligned.

- Creep Started at 2-3 Ma when the Sierra Nevada rapidly uplifted.
CONCLUSIONS

- Flow in the lower crust of continent participates in long term weakening of strike slip plate boundaries.
- Elastic deformation is small but it is the link between time scales.
- Going across time scale is not possible with one piece of software but coupling approaches with different approximations of the same general rheological model is possible.
Scaling

MUMPS direct solve slope = 1.628 (parallel Matlab "backslash" Style)
GMRES/ILU slope = 1.462 (Petsc out of the box)
FGMRES/Schur/AMG slope=1.008 (Educated Petsc)

Gale 1.6 2011
ptatin3D 2013
Reproducibility of results

Kinematic interpretation of the 3D shapes of metamorphic core complexes

Acknowledgments

[50] GALE is software hosted by the Computational Infrastructure for Geodynamics (CIG) and developed by CIG, Monash University and the Victorian Partnership for Advanced Computing (VPAC). This research was supported by ANR EGEO.
Reproducibility

2.3.2 The models we used utilized different boundary conditions than those provided as standard with the GALE distribution. We provide the StandardConditionFunctions we used as patches which may be applied to the source obtained from the step above. To apply the patches for the StandardConditionFunctions, do the following:

```bash
> cd ${GALE_DIR}/StgFEM/plugins/StandardConditionFunctions
> patch < StgFEM_SCondFunctions_MCC_c.patch
> patch < StgFEM_SCondFunctions_MCC_h.patch
```

2.3.3 The simulations we performed also introduced an upper and lower viscosity cutoff into the Frank Kamenetskii rheology. The cut-off viscosity is not included in the distribution of GALE. To apply the patch which introduces the cutoff viscosity in the Frank Kamenetskii rheology, execute the following commands:

```bash
> cd ${GALE_DIR}/Underworld/Rheology/src
> patch < UW_Rheology_FrankKamenetskii_c.patch
> patch < UW_Rheology_FrankKamenetskii_h.patch
```

2.4 Compilation

As per standard GALE compilation, execute the following commands to compile the source code:

```bash
> cd ${GALE_DIR}
```
2. Configuring Gale
2.1 download the same version of the code

To ensure total reproducibility of our results, we identify the exact version of each of the GALE components we used. One should execute the following set of mercurial commands to obtain the source we used:

```
$ hg clone -r 39d893a884cf http://geodynamics.org/hg/long/3D/gale
$ hg clone -r eb3ff4560d4a http://geodynamics.org/hg/long/3D/gale/PLICellerator
$ hg clone -r 2555fca8fd7f http://geodynamics.org/hg/long/3D/gale/StGermain
```

NOTE: Do not execute "hg pull -u" in each of the component directories which have been cloned.

2.2 Configuration
And...

to define the hinge and load in map
J.C. Savage approach.

High velocity gradient observed with GPS during the interseismic period are reproduced either by localised displacement at the base of the fault or by applying repeated co-seismic displacement on the fault.
Thatcher and Pollitz approach.

Inferring the viscosity of the crust and the lithosphere from the visco-elastic relaxation model.

MAKE THE ASSUMPTION that the local high velocity gradient in the interseismic signal is the result of the last earthquake.

**Transient visco-elastic**

- transient visco-elastic
- SB73

**Analytical screw dislocation (SB)**

Long term pseudo-static

Numerical screw dislocation

**Transcient after-slip**

Lateral variations in elastic rigidity

Low viscosity zone under the fault

**semi-infinite half space**

**co-seismic**

**interseismic**

**co-seismic slip**

**elastic**

**viscous**

**locked**

**unlocked**

**plastic/frictional**

**dislocation**

**locking depth**

**Thatcher and Pollitz approach.**

Inferring the viscosity of the crust and the lithosphere from the visco-elastic relaxation model.

MAKE THE ASSUMPTION that the local high velocity gradient in the interseismic signal is the result of the last earthquake.