Effective rheology of a two-phase subduction shear zone: insights from numerical simple shear experiments and implications for subduction zone interfaces

P.I. Ioannidi[1], L. Le Pourhiet[2], P. Agard[2], S. Angiboust[3], O. Oncken[1]

1: GFZ German Research Centre for Geosciences, Potsdam, Germany
2: ISTeP - UMR 7193, Sorbonne Université, Paris, France
3: Institut de Physique du Globe de Paris, Sorbonne Paris Cité Univ. Paris Diderot, CNRS,F-75005 Paris, France

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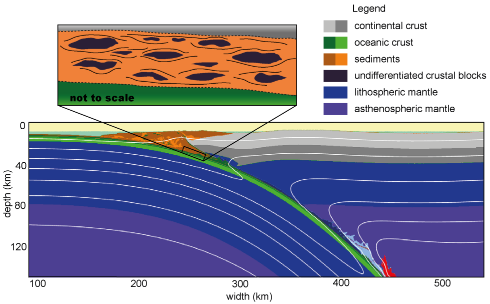
  - Discussion - previous work

Introduction

Motivation

- Large-scale geodynamic subduction models commonly approximate the subduction shear zone by a homogeneous layer.
- Field observations often reveal a mixture of upper and lower plate rocks (mélange).
- Large-scale models cannot resolve such small-scale heterogeneities.
- We investigate how the interface rheology changes when it consists of a block-in-matrix structure (mélange).

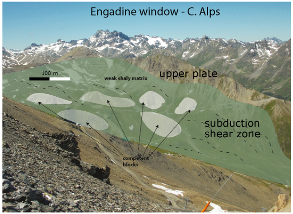


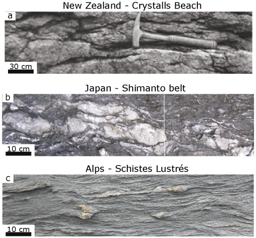
Example of a large-scale geodynamic subduction zone model [Ruh et al., 2015]. Inset shows heterogeneity of the interface in outcrop-scale.

Subduction mélange

What is it and where can it be found?

- A finite zone of mappable thickness, comprising mixed continental and oceanic blocks within a sedimentary and/or serpentinitic matrix.
- Localities: Alps (Arosa, Schistes Lustrés), New Zealand (Chrystalls Beach), SW Japan (Mugi mélange), California (Fanciscan Complex) etc.
- Blocks often undeformed or fractured; matrix strongly deformed mainly by dissolution-precipitation creep.
- Proportions of blocks can vary from 5% to 50% or more.





Left: Engadine Window, C. Alps; Right: picture a from [Fagereng and Sibson, 2010]; picture b from [Kimura et al., 2012].

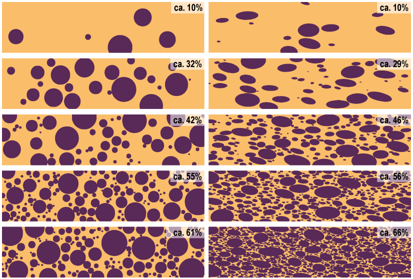
Open questions

- What is the **effective rheology** of a subduction interface, in the special case that it is not a homogeneous medium, but rather characterized by a **block-in-matrix** geometry?
- How does the **concentration of blocks** affect the **bulk deformation** of the mélange?
- Can the **effective rheology** of a mixed material reflect **small-scale complexities**, rendering it thus useful for implementation in large-scale geodynamic models?

Numerical modelling

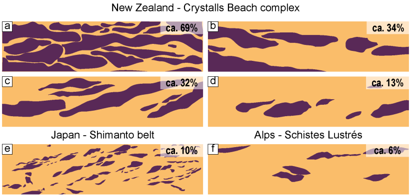
Digitizing mélanges

Synthetic mélange units



Synthetic 2D circular (left) and elliptical (right) models with different concentrations of blocks.

Natural mélange units

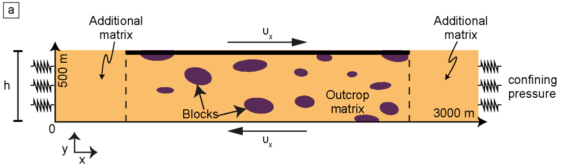


DIgitized field outcrops used as "natural models". (a-d) From the Chrystalls Beach complex, New Zealand [Fagereng and Sibson, 2010]. (e) From Mugi Mélange in the Shimanto Belt, Japan [Kimura et al., 2012]. (f) From the Schistes Lustrés, Western Alps.

Numerical modelling

Setup and boundary conditions [1]

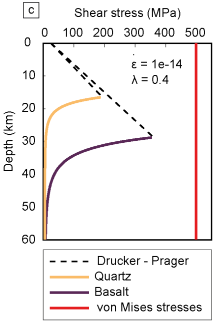
FE code: pTatin2D [May et al., 2014],[May et al., 2015]



b

Dislocation creep parameters used in our models.

Material	Density (kg/m³)	A (MPa⁻ⁿs⁻¹)	n	Q (kJ/mol)	V (cm³)	Reference	Proxy for
Wet quartz	2650	3.2e-4	2.3	154	0	Ranalli, 1997	Matrix
Basalt	3000	1.0e-4	3.5	250	0	Shelton & Tullis, 1981	Blocks
						Hacker & Christie, 1990	

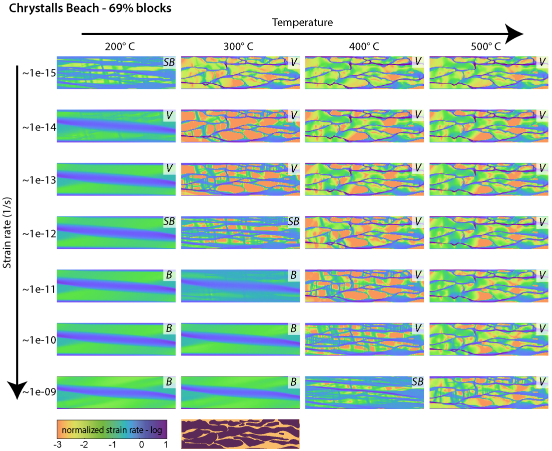


(a) Boundary conditions: purple color represents the blocks, light orange the matrix. Black straight line at the top of the model highlights the interface elements used for computing different rheological parameters. (b) Table with the dislocation creep parameters used. (c) Schematic representation of the rheology used in the models.

[1] A detailed numerical description is given here

Results

Effect of temperature and initial strain rate on bulk deformation



Normalized[2] strain rate (in log) for the Chrystalls Beach model of 69% blocks. Warm colours - low strain localization of strain; cool colours - high strain localization. Each row has the same initial strain rate and each column has the same temperature. At the bottom, the initial geometry of the model is given. SB: Semi-brittle failure, V: viscous failure, B: brittle failure.

[2] Implemented strain rate over the calculated one.

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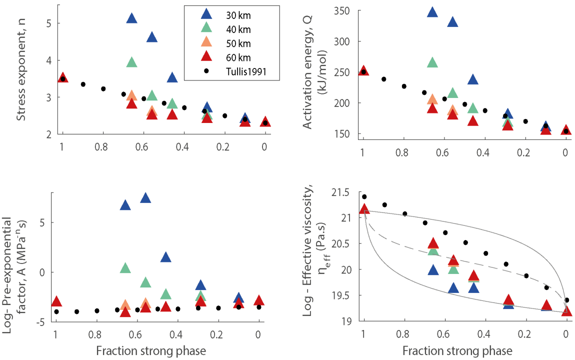
Results

Calculating the effective creep parameters for **elliptical** blocks

- Using stresses and strain rates from **non frictional models**[3] in the dislocation creep equation, the parameters A, n, and Q are estimated.
- The effective viscosity for different block concentrations and temperatures is calculated.

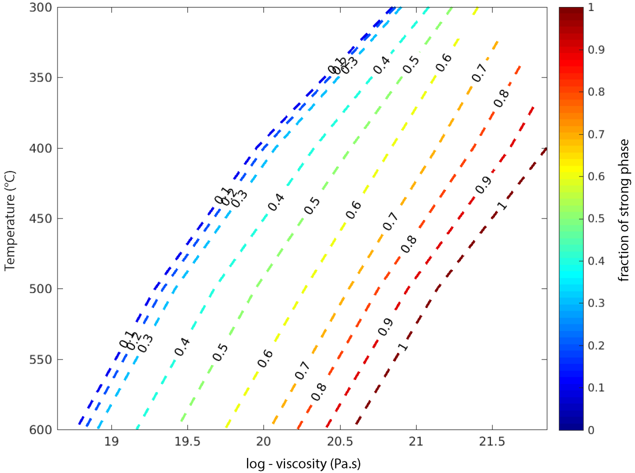


[3] Details on frictional/non-frictional models here

Results

Changes in viscosity with different block concentrations, for **elliptical** blocks

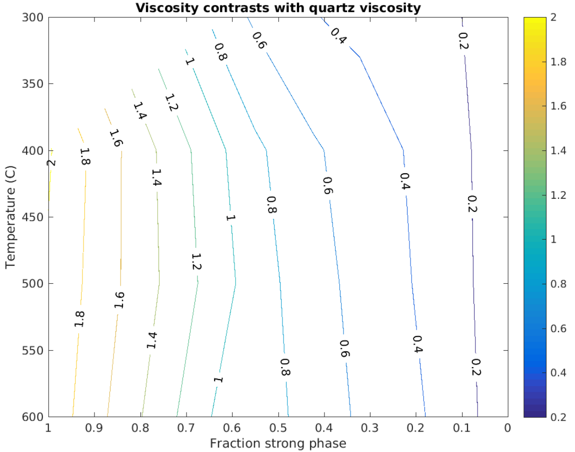
- Effective viscosity is dependent on temperature, strain rate and block concentration.
- With increasing block fractions, the effective viscosity of the mixture also increases.



Results

Order of magnitude changes in viscosity with different block concentrations, for **elliptical** blocks

- Normalized model viscosity over the viscosity of the weak phase.
- The viscosity of the mixture can increase up to 2 orders of magnitude with increasing concentration of blocks.



Discussion

Limitations

- Field observations on quartz suggest rather viscous deformation by precipitation creep
- The detailed processes of this deformation mechanism are not well constrained yet [Wallace et al., 2012]
- Dislocation creep is active at higher stresses $\rightarrow$ our models represent the minimum depth at which our viscosity estimates are expected
- Dislocation creep is used in most of large-scale geodynamic models $\rightarrow$ direct comparison of our rheology
- For some relevant previous studies, click here

Conclusions

- For **matrix dominated** assemblages, the bulk rheology is similar to that of the purely **weak phase**.
- When **block concentration** $>$ **50%** of the total area, **viscosity increases** due to clast interactions.
- At temperatures where basalt is brittle and quartz is ductile ($300^{\circ} - 400^{\circ}$C): the **bulk rheology** of the model follows a **dislocation creep** law, BUT the bulk type of **deformation** is **semi-brittle**.
- The use of **dislocation creep** suggests that results should be considered as reflecting the **maximum viscous strength** of the bulk model.
- **Scale-independency** of the models renders the effective rheology calculations suitable for use in **larger-scale geodynamic models**.

End

(Additional slides follow)

Selected bibliography I

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Journal of Geophysical Research, 96(90):8081–8096.

Wallace, L. M., Fagereng, Å., and Ellis, S. (2012).
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Additional slides - Governing equations

Return

The visco-plastic 2D version of the Finite Element code pTatin3D is used, which is solving the Stokes equation for incompressible flow [May et al., 2014, May et al., 2015].

We are interested in the steady-state long-term deformation, therefore we neglect elasticity and the code solves for conservation of mass, which is approximated by enforcing incompressibility of the flow, v:

$$\nabla \cdot \mathbf{v} = 0 \tag{1}$$

and conservation of momentum:

$$\frac{\partial \sigma}{\partial x} = 0 \tag{2}$$

Then the full stress tensor is:

$$\sigma = \sigma^d - IP \tag{3}$$

where σ^d is the deviatoric stress tensor, **I** the identity matrix and P the isotropic pressure. Then,

$$\sigma^d = 2\eta_{eff}\dot{\varepsilon} \tag{4}$$

Due to the small size of the models, we neglect gravity. Temperature is constant in each model, and assigned according to a geothermal gradient to mimic different depths.

Effective material viscosity is defined by dislocation creep law as:

$$\eta^{v}_{eff} = \frac{1}{2}(\dot{\varepsilon}_{II}^{\frac{1}{n}-1} A^{\frac{-1}{n}} exp(\frac{Q}{RT})) \quad (5)$$

where A, n and Q are the dislocation creep coefficients.

Pressure dependent Drucker-Prager yield criterion is used as a stress limiter

$$\tau_y = P \sin\phi - Co \cos\phi \quad (6)$$

using the internal friction angle ϕ, and cohesive strength, Co, as input parameters. If the deviatoric stresses predicted by dislocation creep (Eq. 5) exceed the DP yield criterion (Eq. 6), the effective viscosity is re-evaluated as follows:

$$\eta^{p}_{eff} = \frac{\tau_y}{\varepsilon_{II}} \quad (7)$$

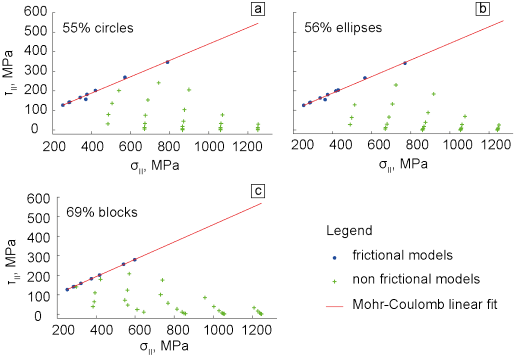
$$\eta_{eff} = min[\eta^{v}_{eff}, \eta^{p}_{eff}]. \quad (8)$$

Additional slides - Results

Frictional vs. non frictional models

Return

- To calculate the effective creep parameters, only models with viscous bulk deformation can be considered.
- In a typical Mohr plot, frictional models (blue dots) plot along the Mohr-Coulomb yield line (red), while all non-frictional models (green crosses) plot scattered below this line.



Additional slides - Discussion

Mixing laws & relevant studies

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Several *mixing laws* have been suggested for estimating the bulk behaviour of polyphase mixtures:

- bound theory (Voigt-Reuss-Hill models) - for elastic parameters
- [Tullis et al., 1991] numerically derived effective creep parameters - did not include brittle mechanisms
- theoretical mixing rule of [Huet et al., 2014] - not including anisotropic blocks and shape preferred orientation

Other relevant studies include:

- [Beall et al., 2019] - numerical study using different boundary conditions, equivalent viscosity estimates
- [Dimanov and Dresen, 2005] - experimental study considering only viscous deformation