Viscoplastic Rheological Modelling- A Realistic Approach to Natural Ductile Shear Zones

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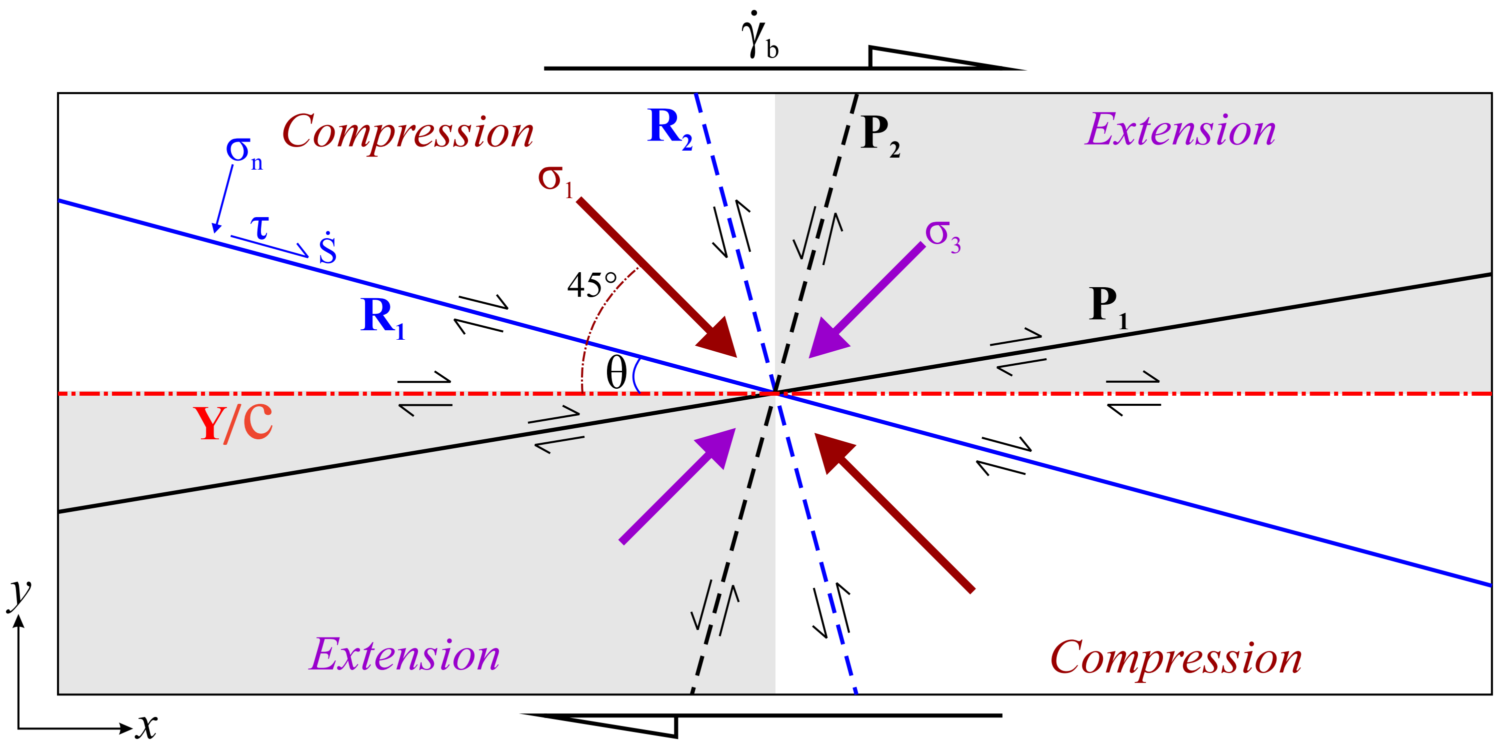
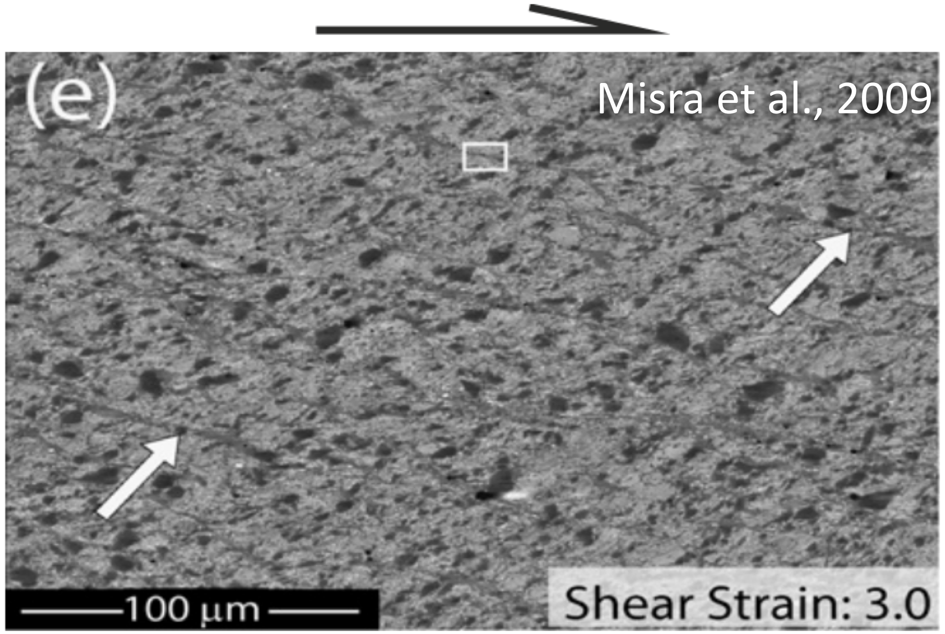
Principle Types of Shear Bands in Shear Deformations



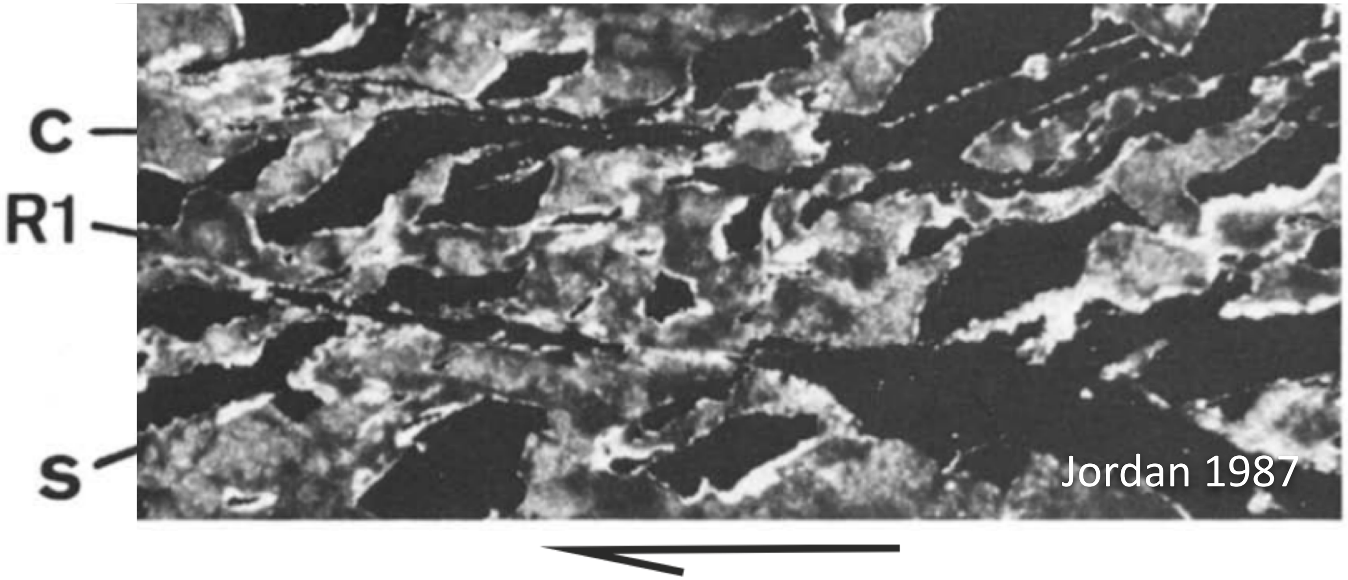
The main types of shear bands are:

- R1: synthetic acute low-angle bands.
- R2: antithetic acute high-angle bands.
- P1: synthetic obtuse low-angle bands.
- P2: antithetic obtuse high-angle bands.
- Y/C: shear parallel bands.

Shear Bands in Shear Zones: Laboratory Experiments

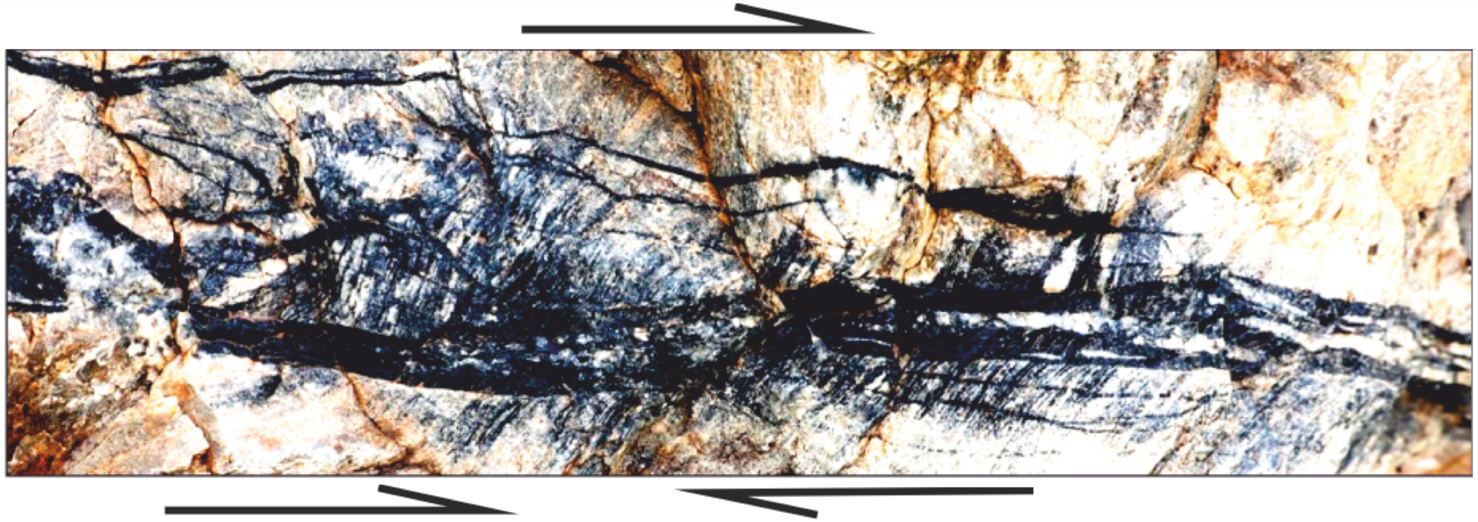


Formation of low-angle R1 bands in quartz aggregates in high temperature shear experiments.



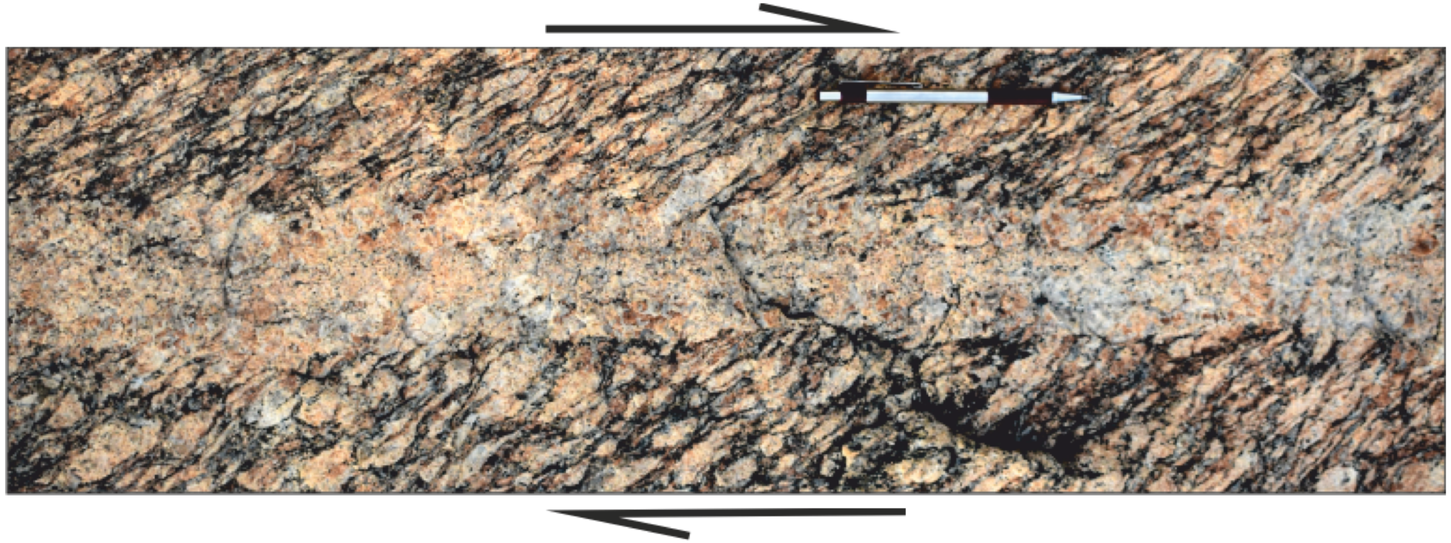
Formation of low-angle R1 bands and shear-parallel C-bands in limestone aggregates in high temperature shear experiments.

Shear Bands in Shear Zones: Natural Examples



A complex network of shear bands formed by R1 and shear-parallel C bands.

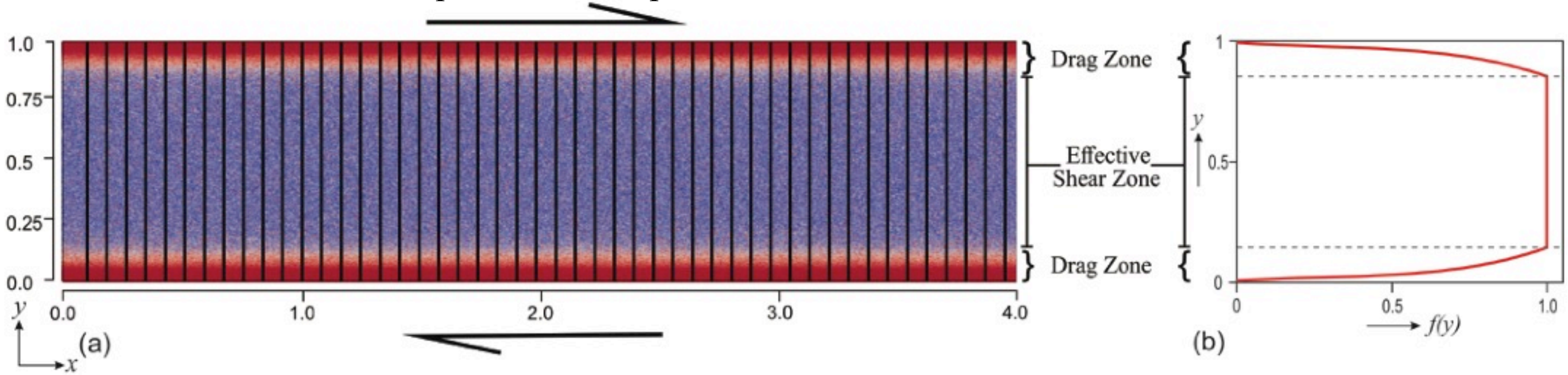
Low-angle shear bands.



An array of shear-parallel C bands.

Numerical Model Design

Initial numerical model set-up with vertical passive markers



Drucker Prager Yield Criterion:

$$\mathcal{F} = \sigma_e - \sqrt{3}\,\sin\varnothing\, P - \sqrt{3}\, C(\gamma_{pl})\cos\varnothing,$$

Viscous Strain Rate: $\dot{\varepsilon}_v = \frac{1}{2}\frac{\sigma^s{}_{ij}}{\eta_v},$

Plastic Strain Rate: $\dot{\varepsilon}_p = \begin{cases} 0, & I_2 < \sigma_e \\ \chi\left(\frac{1}{2}\frac{\sigma^s{}_{ij}}{I_2}\right), & I_2 \geq \sigma_e \end{cases}$

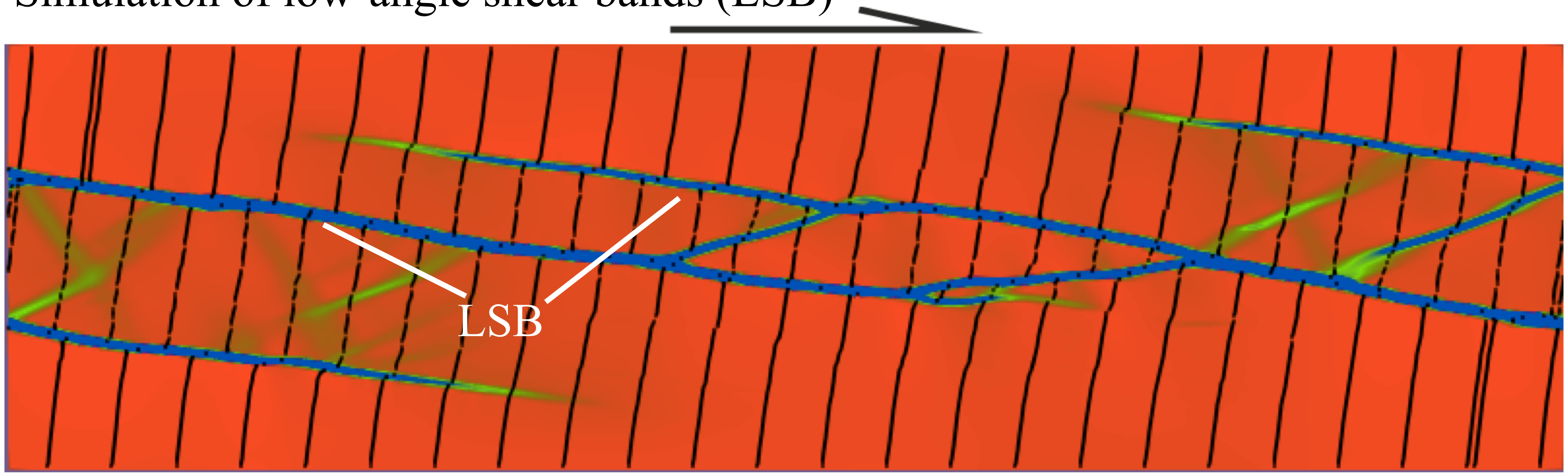
Strain profile function:

$$f(y) = \left[tanh\left((S_w - y)H_F\right) + tanh\left(H_F(y)\right) - tanh\left(H_F\right)\right]^{2p}$$

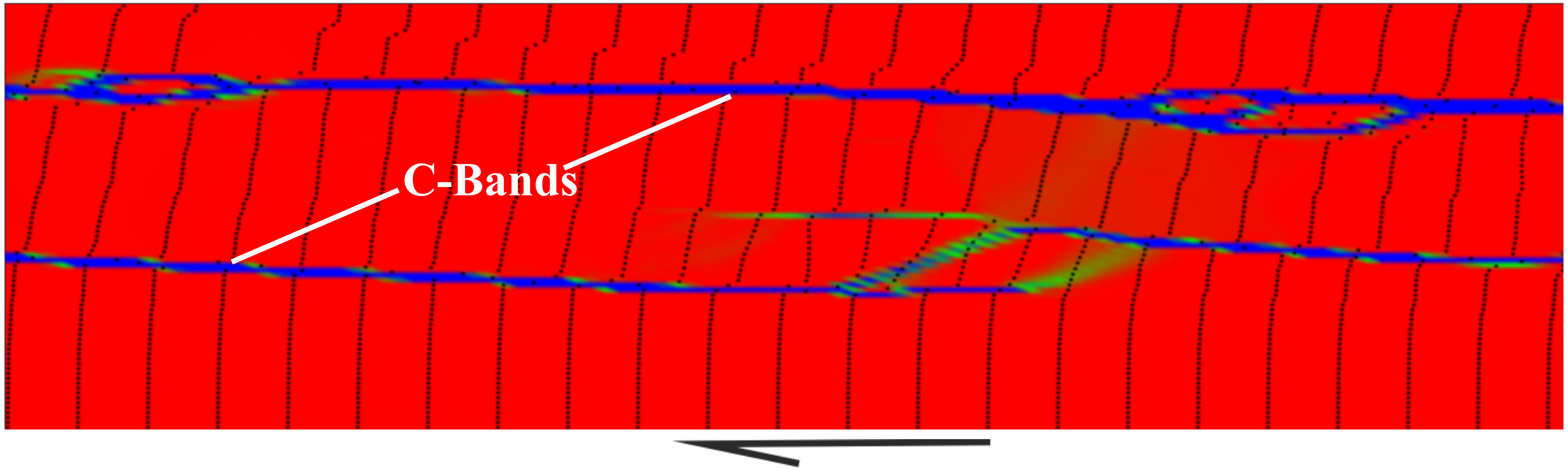
Implementation: A particle-in-cell finite-element code **Underworld 2** (https://www.underworldcode.org/).

Shear Bands in Numerical Models

Simulation of low-angle shear bands (LSB)

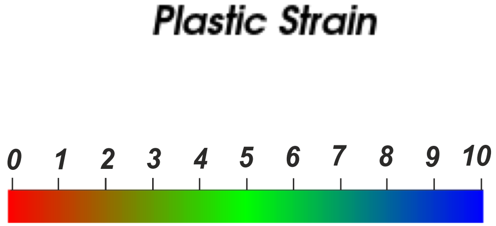


Simulation of shear parallel bands (C-bands)

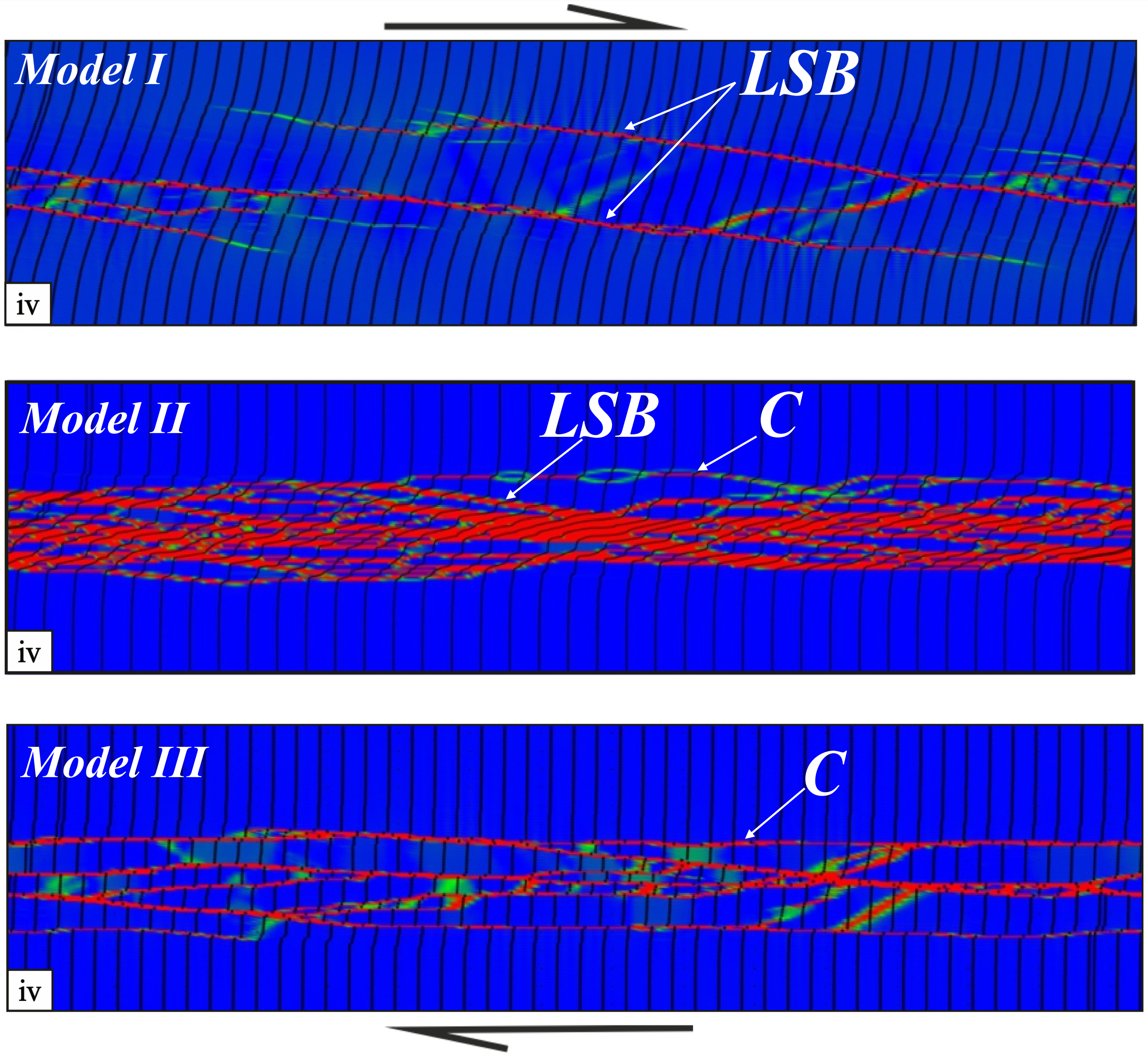


Principle variables chosen in numerical simulations:

- Normalized effective shear zone thickness (δ)
- Bulk viscosity (η_v)
- Bulk shear rates ($\dot{\gamma}_b$)



Bands in Reference Models



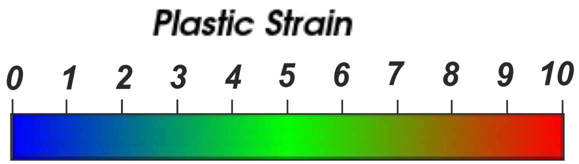
Model Conditions:

Model I: $\delta = 0.7, \eta_v = 1\eta_0, \; \dot{\gamma}_b = 1\dot{\gamma}_0.$

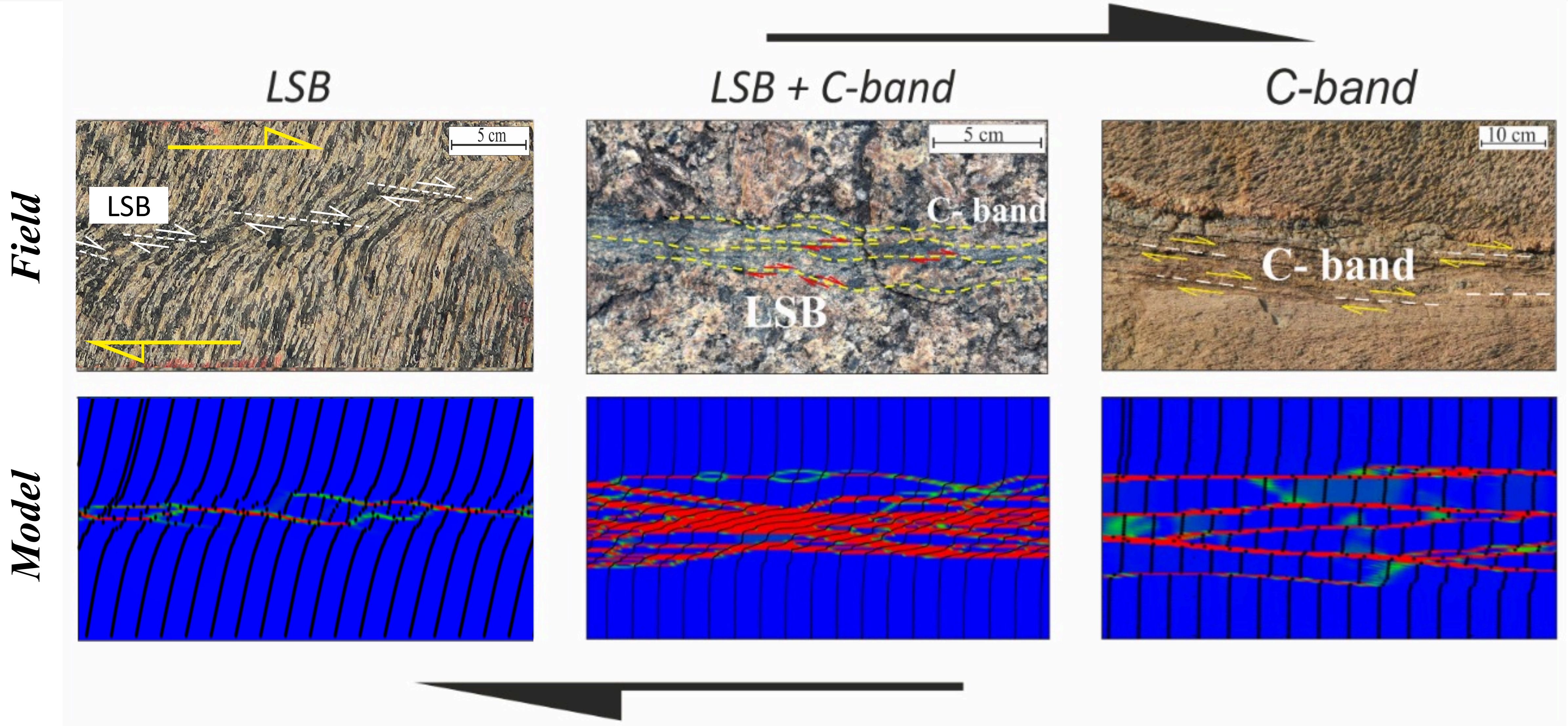
Model II: $\delta = 0.7, \eta_v = 4\eta_0, \; \dot{\gamma}_b = 2.5\dot{\gamma}_0.$

Model III: $\delta = 0.53, \eta_v = 3.5\eta_0, \dot{\gamma}_b = 7\dot{\gamma}_0$

η_0 and $\dot{\gamma}_0$: reference bulk viscosity and bulk shear rate respectively.

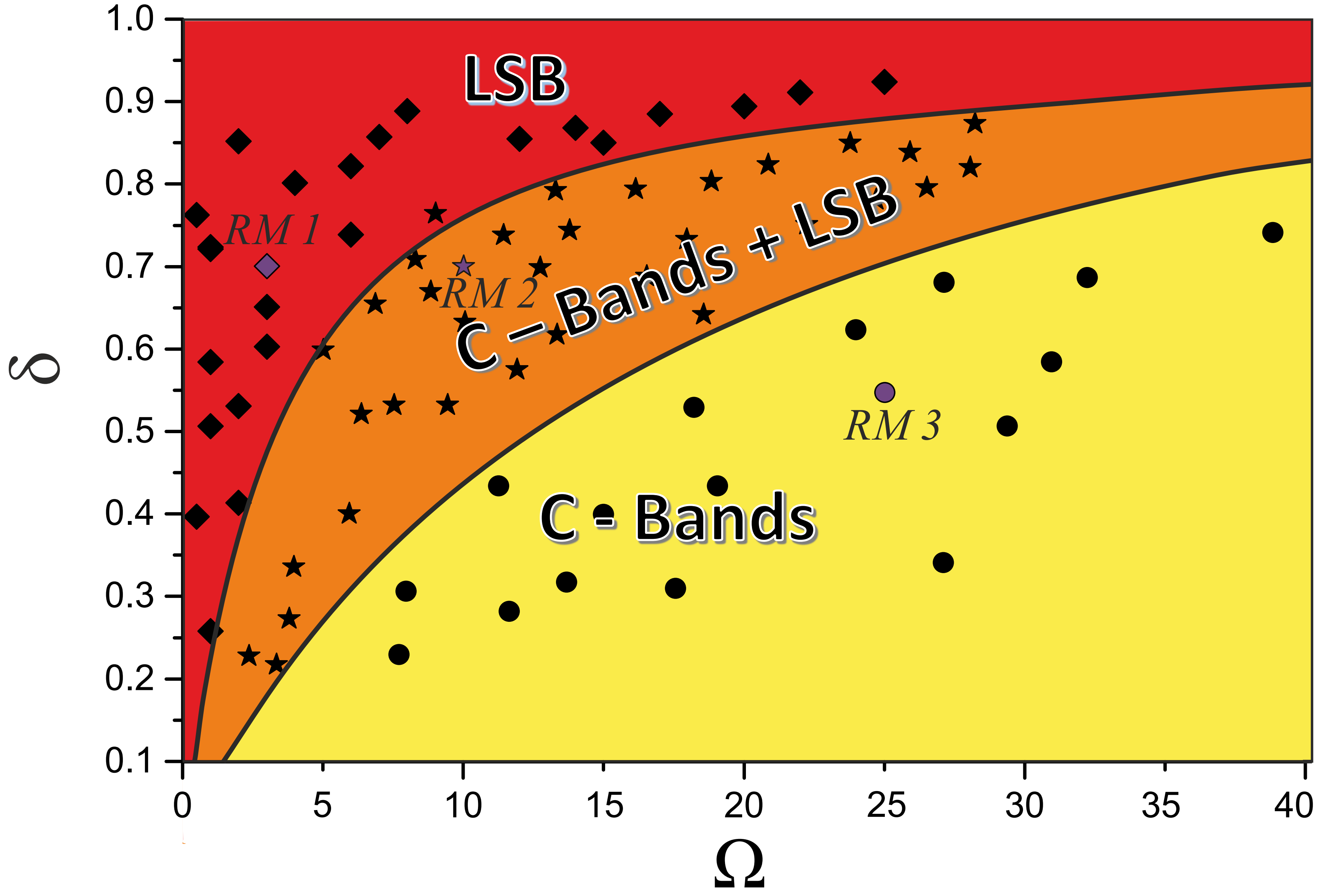


Field vs Model



Numerical models successfully simulate the principle types shear bands observed in field!

Field Diagram



Non-dimensional parameters to control band types:

- Dynamic parameter:

$$\Omega = \frac{\eta_v \dot{\gamma}_b}{C_i}$$

- Geometric Parameter:

$$\delta = \frac{W_C}{W}$$

C_i : initial cohesion.

Analytical Solution

Consider a shear band at an angle θ with the shear direction and undergoing slip at a rate $\dot{S}$ (Fig 1). This slip creates an overall strain in y- direction at a rate,

$$\dot{\epsilon}_{yy} = \frac{\dot{S}\sin\theta}{d}$$

This can be accommodated by viscous deformation perpendicular to the shear zone, given as

$$\sigma_{yy} = 2\,\eta_v\,\dot{\epsilon}_{yy} = \frac{2\,\eta_v\,\dot{S}\sin\theta}{d}$$

This stress will create a resistance to the slip, which can be derived in the following way,

$$\tau_v = -\frac{\sigma_{yy} - \sigma_{xx}}{2}\sin\left\{2\left(\frac{\pi}{2} - \theta\right)\right\}$$

$$\tau_v = -\frac{\sigma_{yy}}{2}\sin 2\theta \qquad [\sigma_{xx} = 0]$$

$$\tau_v = -\frac{\eta_v\,\dot{S}\sin\theta\sin 2\theta}{d}$$

From the modified Mohr- Coulomb criterion, we get

$$|\tau| = C_0 - \mu\sigma - \tau_v$$

$$|\tau| = C_0 - \mu\sigma + \frac{\eta_v\,\dot{S}\sin\theta\sin 2\theta}{d}$$

The viscous resistance term becomes 0 when $\theta = 0$.

General equation for σ and τ:

$$\sigma = \frac{\sigma_{xx} + \sigma_{yy}}{2} + \frac{\sigma_{xx} - \sigma_{yy}}{2}\cos 2\theta + \sigma_{xy}\sin 2\theta$$

$$\sigma = 2\eta_{eff}\,\dot{\gamma}_b\sin 2\theta$$

$$\tau = -\sigma_{xy}\cos 2\theta$$

$$\tau = -2\eta_{eff}\,\dot{\gamma}_b\cos 2\theta$$

$$2\eta_{eff}\,\dot{\gamma}_b\cos 2\theta = C_0 - \mu\,2\eta_{eff}\,\dot{\gamma}_b\sin 2\theta + \frac{\eta_v\,\dot{S}\sin\theta\sin 2\theta}{d}$$

Differentiating with respect to θ , we get:

$$-2\eta_{eff}\,\dot{\gamma}_b\sin 2\theta + 2\,\mu\,\eta_{eff}\,\dot{\gamma}_b\cos 2\theta - \frac{\eta_v\,\dot{S}}{d}(2\sin\theta\cos 2\theta + \sin 2\theta\cos\theta) = 0$$

$$2\eta_{eff}\,\dot{\gamma}_b(\mu\cos 2\theta - \sin 2\theta) - \frac{\eta_v\,\dot{S}}{d}(2\sin\theta\cos 2\theta + \sin 2\theta\cos\theta) = 0$$

$$\frac{(\mu\cos 2\theta - \sin 2\theta)}{(2\sin\theta\cos 2\theta + \sin 2\theta\cos\theta)} = \frac{\eta_v\,\dot{S}}{2\,d\,\eta_{eff}\,\dot{\gamma}_b}$$

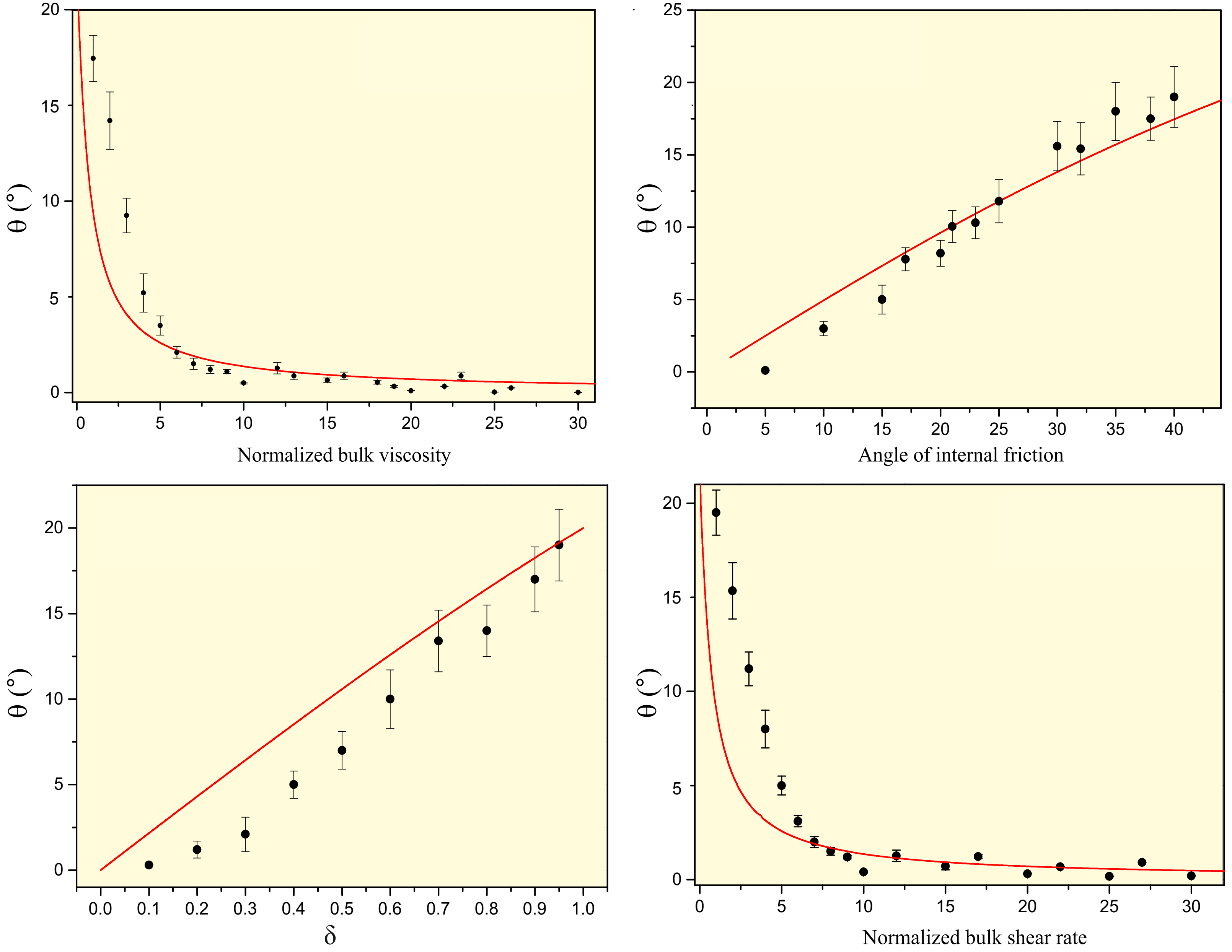
Replacing the slip partitioning factor $\dot{S}$ with A $\times W \times \dot{\gamma}_b$ and $2\,\eta_{eff}\,\dot{\gamma}_b$ with σ_e, we get

$$\frac{(\mu\cos 2\theta - \sin 2\theta)}{(2\sin\theta\cos 2\theta + \sin 2\theta\cos\theta)} = \frac{AW\eta_v\,\dot{\gamma}_b}{d\sigma_e}$$

As $\delta = \frac{W_c}{W}$ and $d = \frac{W_c}{2}$, we can write the above equation as:

$$\frac{(\mu\cos 2\theta - \sin 2\theta)}{(2\sin\theta\cos 2\theta + \sin 2\theta\cos\theta)} = \frac{2A\eta_v\,\dot{\gamma}_b}{\delta\sigma_e}$$

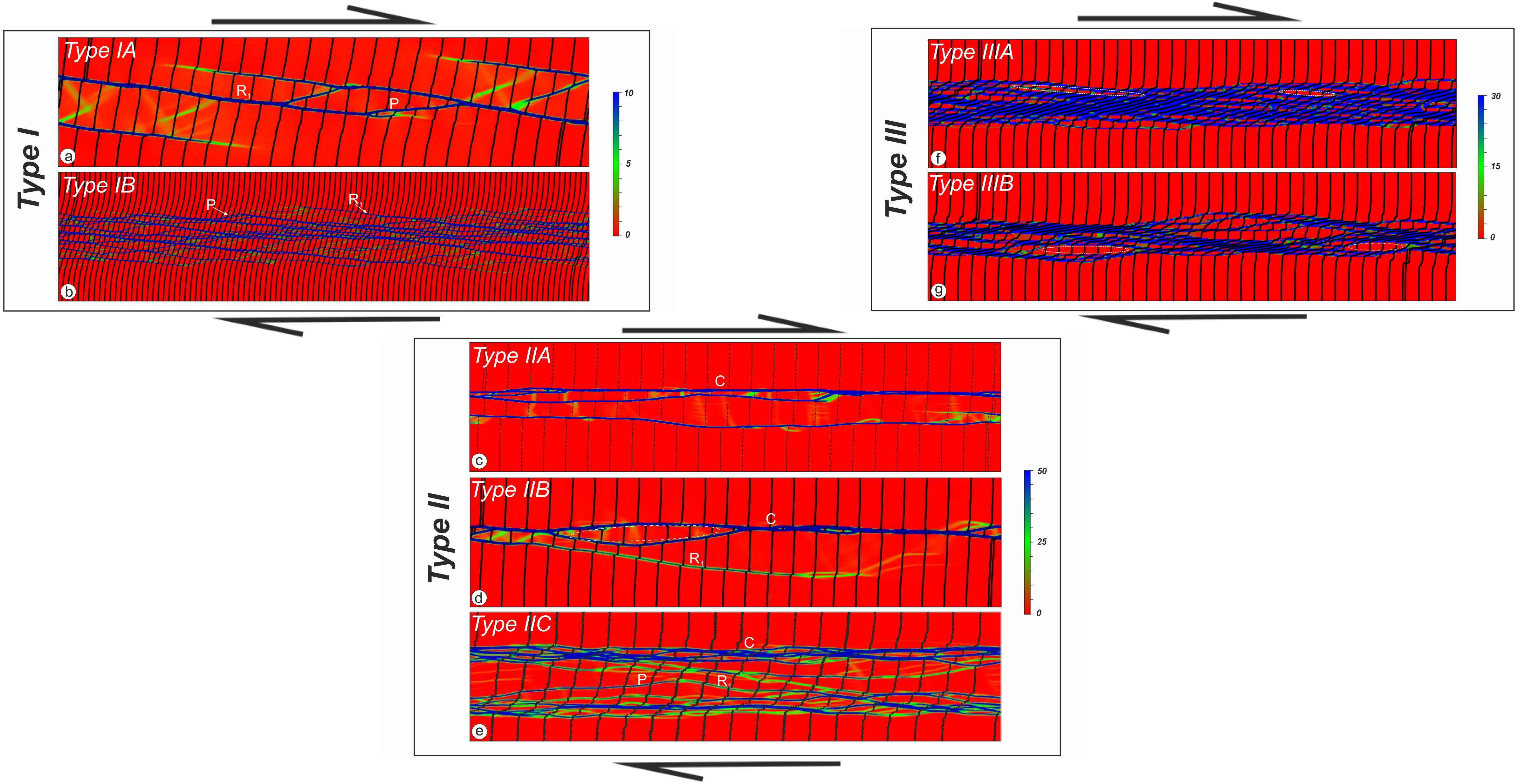
Validation of Analytical Solution



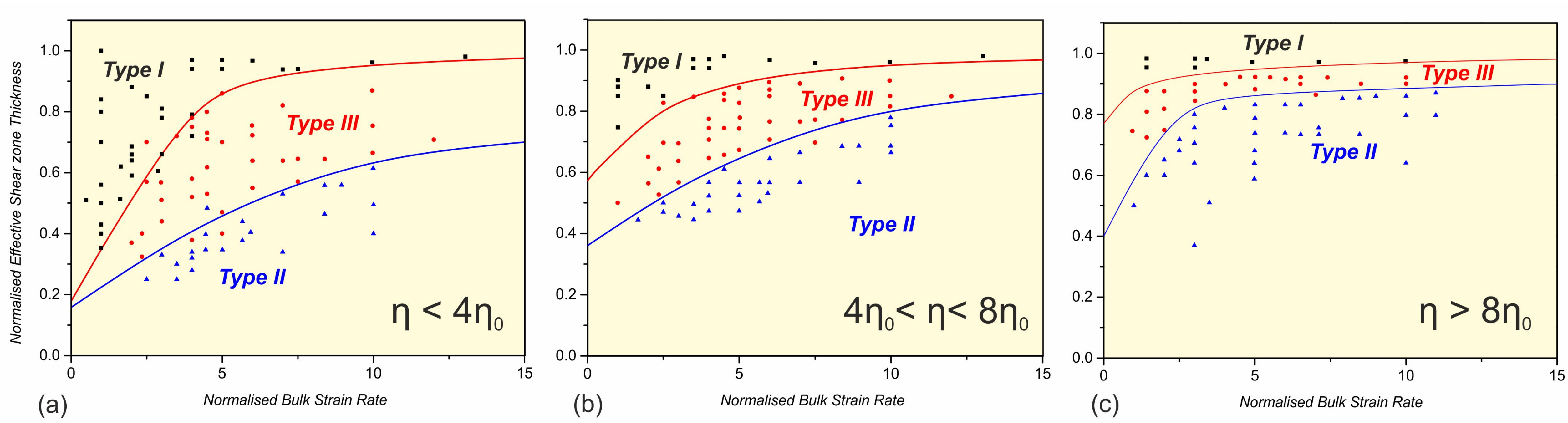
Calculated plots of the shear band angles (θ) using the analytical solution (solid red lines)

Black dots show the data from numerical simulations.

Shear Band Patterns in Ductile Shear Zones



Shear Band Patterns in Ductile Shear Zones



Fields of Type I, Type II and Type III band networking in a space defined by normalized bulk strain rate and normalized effective shear zone thickness

Conclusions

- Shear bands are the evidences that can give several indicators about a shear zone evolution.
- C-band vs LSB growth are two competing mechanisms in ductile shear zones.
- Effective shear zone thickness (W_c), bulk viscosity (η_v) and bulk shear rate ($\dot{\gamma}_b$) play an important role in controlling the shear band orientation.
- Viscoplastic rheology is ideal to experimentally simulate the natural ductile shear zones.

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RESEARCH ARTICLE
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Key Points:

- Ductile shear zones are characterized by two principal types of secondary shear bands: shear-parallel C bands and low-angle shear bands (LSB)
- The origin of C-bands is still unresolved and this study addresses the problem of C versus LSB growth in terms of viscoplastic rheology
- Shear band orientation depends on the normalized effective shear zone thickness and the ratio of global shear stress to cohesive strength

Supporting Information:

Supporting Information may be found in the online version of this article.

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Factors Determining Shear-Parallel Versus Low-Angle Shear Band Localization in Shear Deformations: Laboratory Experiments and Numerical Simulations

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Abstract Understanding the mechanics of shear localization in materials is a key to interpreting a wide range of failure-assisted geophysical processes. This paper addresses a crucial problem of shear band formation in ductile shear zones undergoing simple shear movement. We studied ductile shear zones in two geological terrains of Eastern India and observed extensive micro- to macro-scale shear-parallel deformation bands (C-bands) in them. However, laboratory-scale simple shear experiments on wet sand (Coulomb) and putty (viscoplastic) failed to produce C-bands. They developed shear bands in conjugate sets: low-angle R_1 (10°–15°) and high-angle R_2 (65°–75°) and single sets of low-angle shear bands (LSB), respectively. These contrasting findings between field and experiments motivate us to address the question- under what conditions can shear bands localize parallel to the bulk shear direction? With the help of 2D numerical models, based on viscoplastic rheology, we demonstrate C-band and LSB formation as two competing mechanisms of shear localization, mediated by a combined effect of the shear zone parameters: geometric (shear zone thickness), kinematic (bulk shear rate) and rheological (bulk viscosity). Finally, two non-dimensional factors: (a) dynamic (Ω: global shear stress $\left[\eta_v \dot{\gamma}_b\right]$/cohesive strength $[C_i]$) and (b) geometric (δ: effective thickness $[W_c]$/total shear zone thickness $[W]$) are recognized to show the fields of LSB and C-bands formation. We also provide a theoretical analysis of the shear band orientation as a function of the dynamic and geometric parameters.

Plain Language Summary Ductile materials undergoing shear deformation are characterized by the presence of variedly oriented shear bands, which are narrow zones of significant shear strain localization. Shear band development is an omnipresent geodynamic phenomenon, which influences a wide range of natural processes like earthquakes, landslides, subduction zone dynamics. Studies on shear band formation provide the requisite clues on the failure mechanisms of ductile materials, a topic of great importance for predicting the behavior of earth materials under extreme conditions. This paper is concerned with the factors determining the orientation of shear bands in natural

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Research

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Keywords:

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On the origin of shear-band network patterns in ductile shear zones

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Ductile yielding of rocks and similar solids localize shear zones, which are often internally heterogeneous due to networking of their secondary shear bands. Combining observations from naturally deformed rocks and numerical modeling, this study addresses the crucial question- what dictates the internal shear bands to network during the evolution of a ductile shear zone in homogeneous solids? Natural shear zones, observed in the Chotonagpur Granite Gneiss Complex (CGGC) of the Precambrian craton of Eastern India, show a systematic variation of their internal shear band patterns, classified broadly into three categories: Type I (network of antithetic low-angle Riedel (R) and synthetic P bands), Type II (network of shear-parallel C and P/R bands) and Type III (distributed shear domains containing isolated undeformed masses). Considering strain-softening rheology, our 2D viscoplastic models reproduce these three types, allowing us to predict the condition of shear band growth with a specific network pattern as a function of the following parameters: normalized shear zone thickness, bulk shear rate and bulk viscosity. This study suggests that complex anastomosing shear-band structures can develop even under simple shear kinematics.

About Me

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Ph.D. Ongoing:
Topic: Role of Multiphase Fluid Flows in Geodynamic Processes: A Theoretical and Experimental Study.

Group Head/My Supervisor: Prof. Nibir Mandal

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