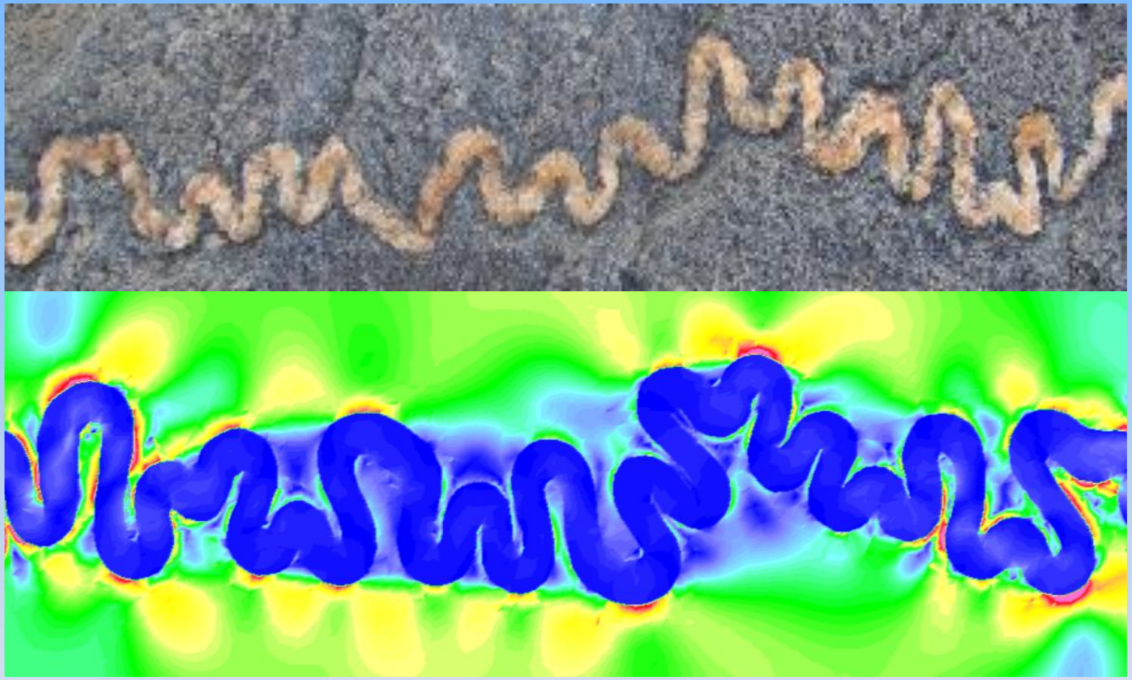
Geometrical softening of a competent layer during folding



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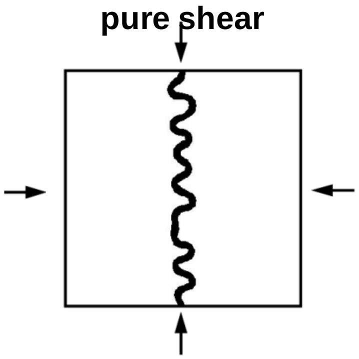
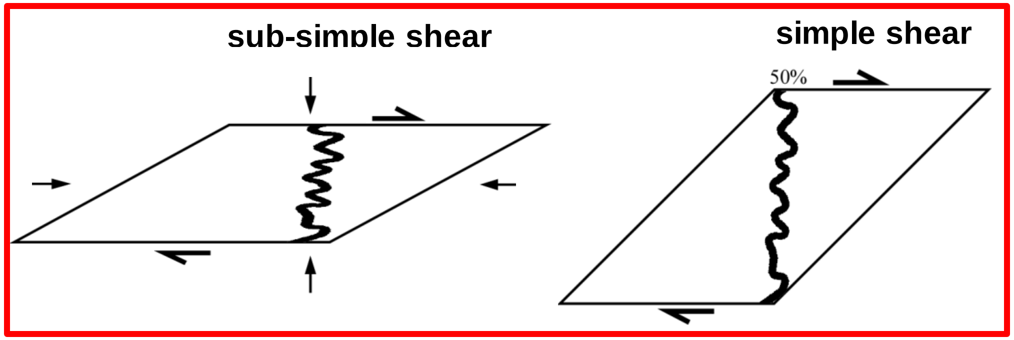
Motivation

- Folds are commonly used to determine the orientation and magnitude of shortening but contain much more information on **kinematics** and **rheology**.
- The use of folds for **strain analysis** requires a first-order quantification of the relationships between parameters that determine folding.

$$\dot{\varepsilon} = \eta\sigma^{n}$$





50 % shortening

Few studies in the literature!

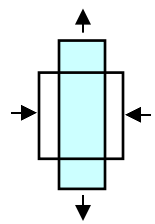
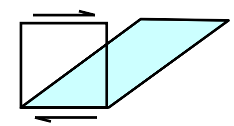
Folding theory is based only on pure shear

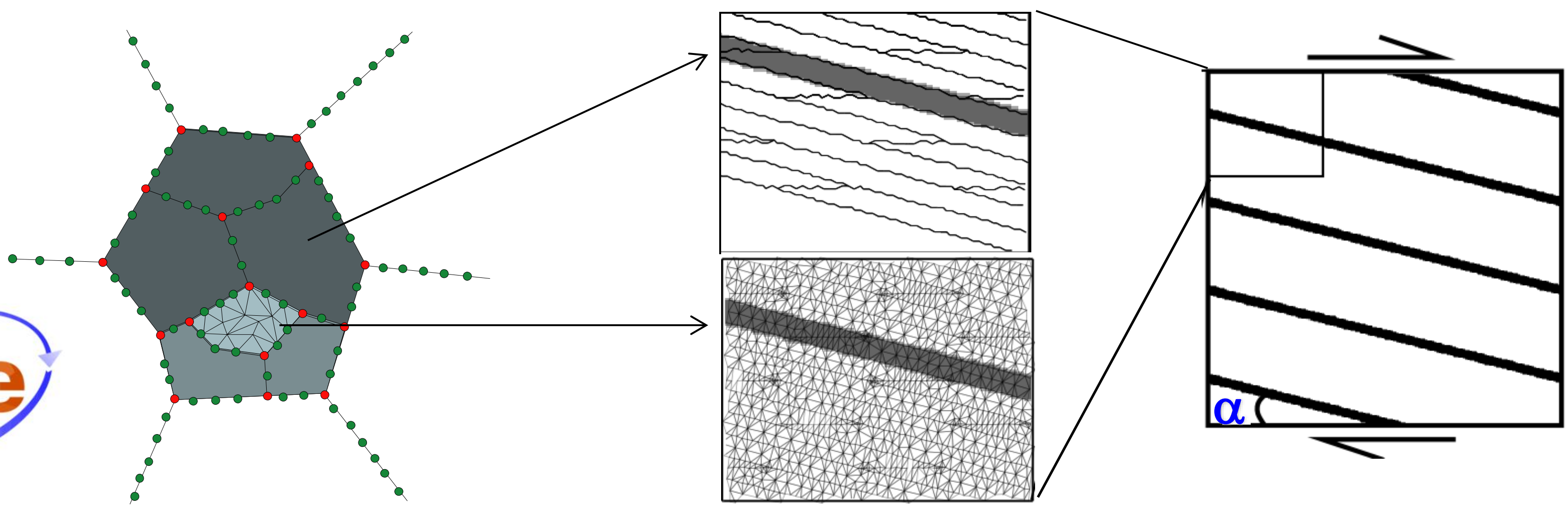
Aims and methods (FEM in ELLE)

Aim → To analyze the mechanical behavior of folding materials depending on:

- Degree of anisotropy (viscosity contrast between competent layer and matrix): $m = \eta_{layer} / \eta_{matrix}$
- The stress exponent (n) of the non-linearity of the viscosity $\dot{\varepsilon} = \eta\sigma^n$
- Initial layer orientation α

Bulk shear strain γ

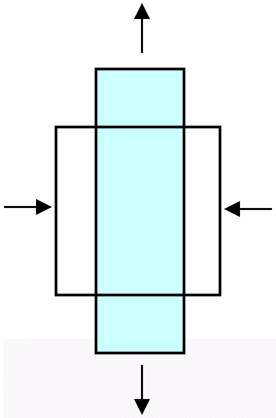
- Boundary conditions: pure shear  or simple shear 
- Initial noise in node position = H / 40 (Validation with Strain Contour Map. Schmalholz & Podladchikov, 2001)



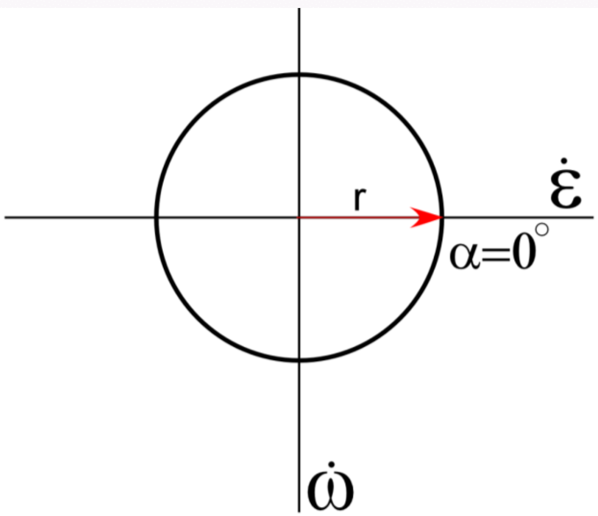
Delaunay triangulation mesh→Used for FEM calculations

Llorens et al., 2013a,b and Llorens, 2019

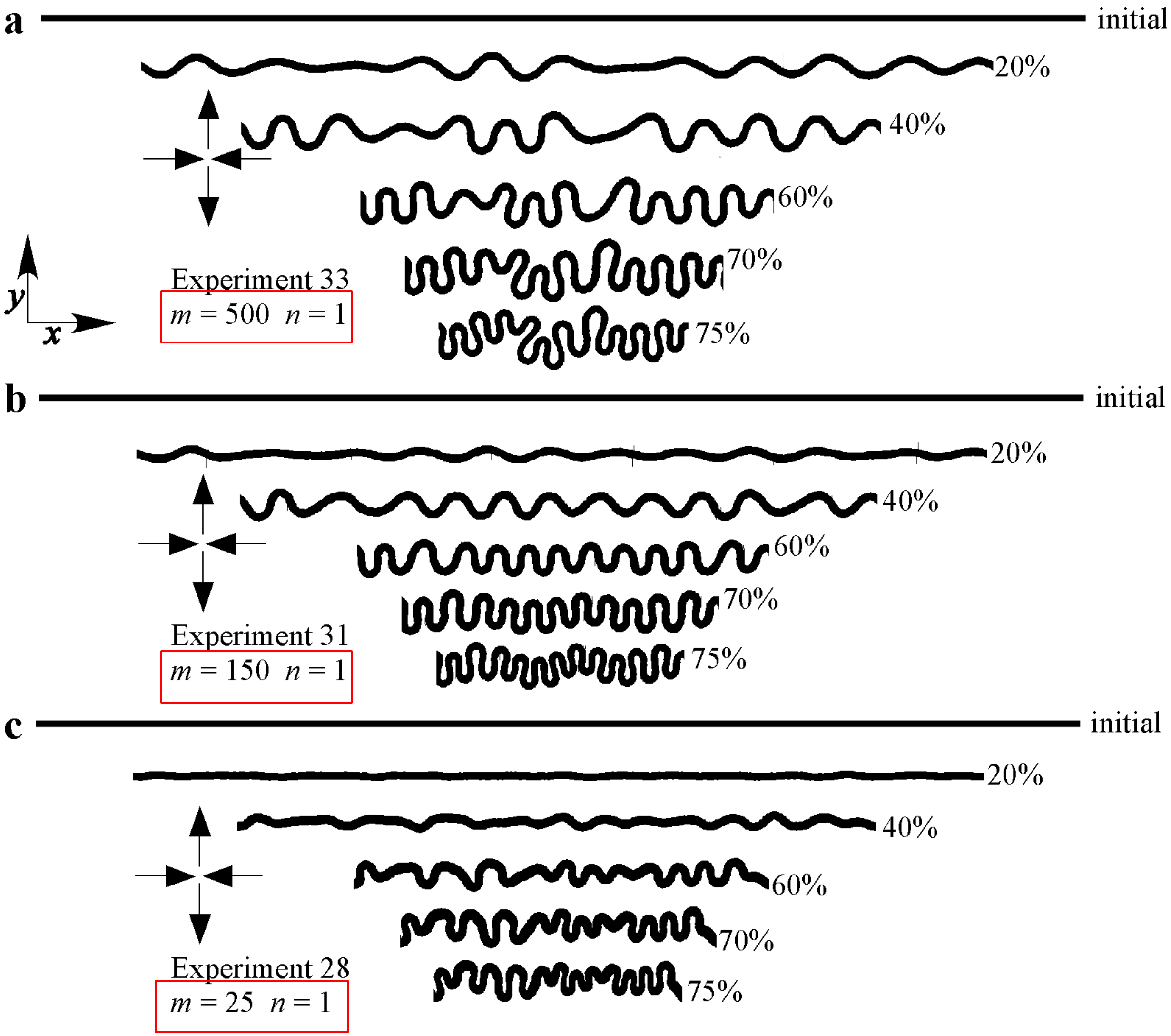
Results: examples of simulation runs



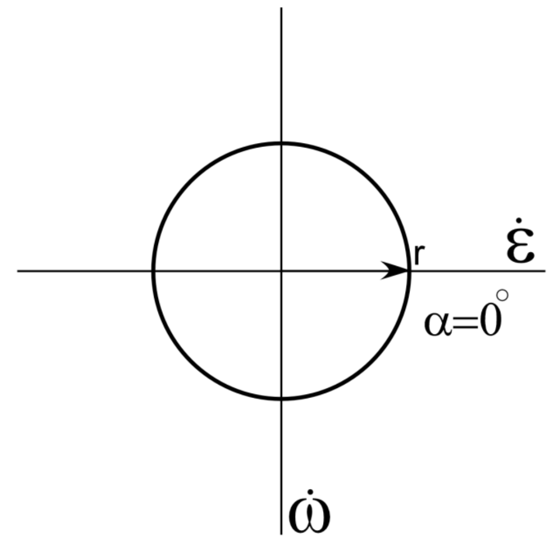
Pure shear: constant strain rate (layer oriented parallel to the shortening direction) $\dot{\varepsilon} = r$



Results: kinematics of deformation, pure shear



Mohr circle for strain rate

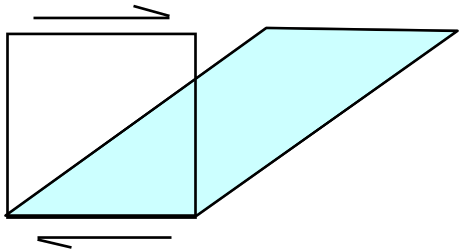


Pure shear → Constant strain rate (layer oriented parallel to the shortening direction)

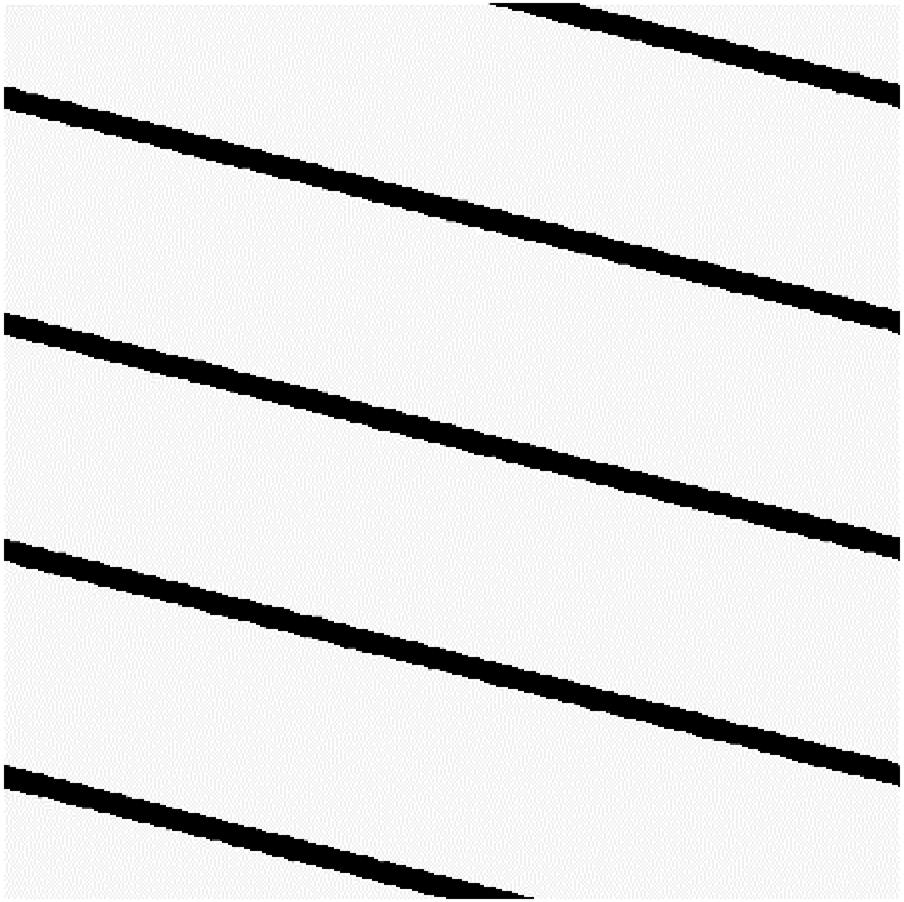
$$\dot{\varepsilon} = r$$

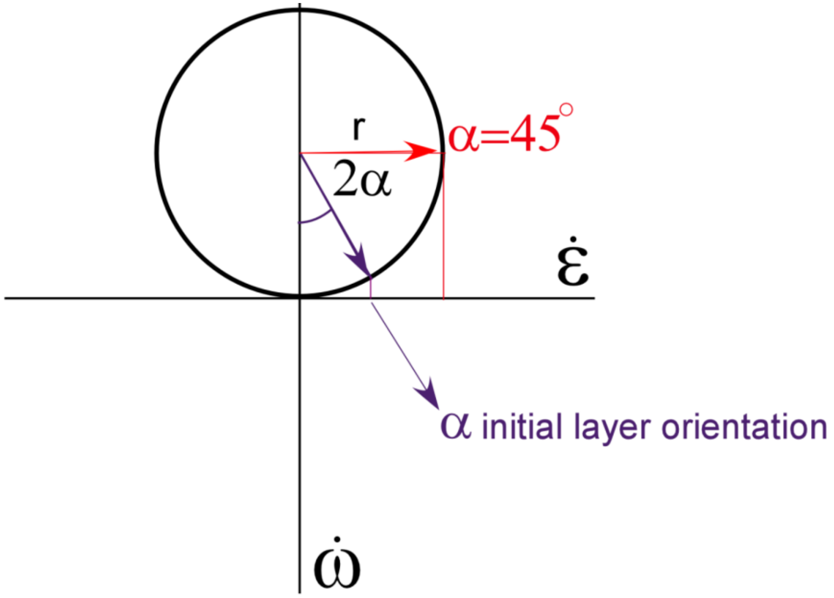
Llorens et al., 2013a and Llorens, 2019

Results: examples of simulation runs

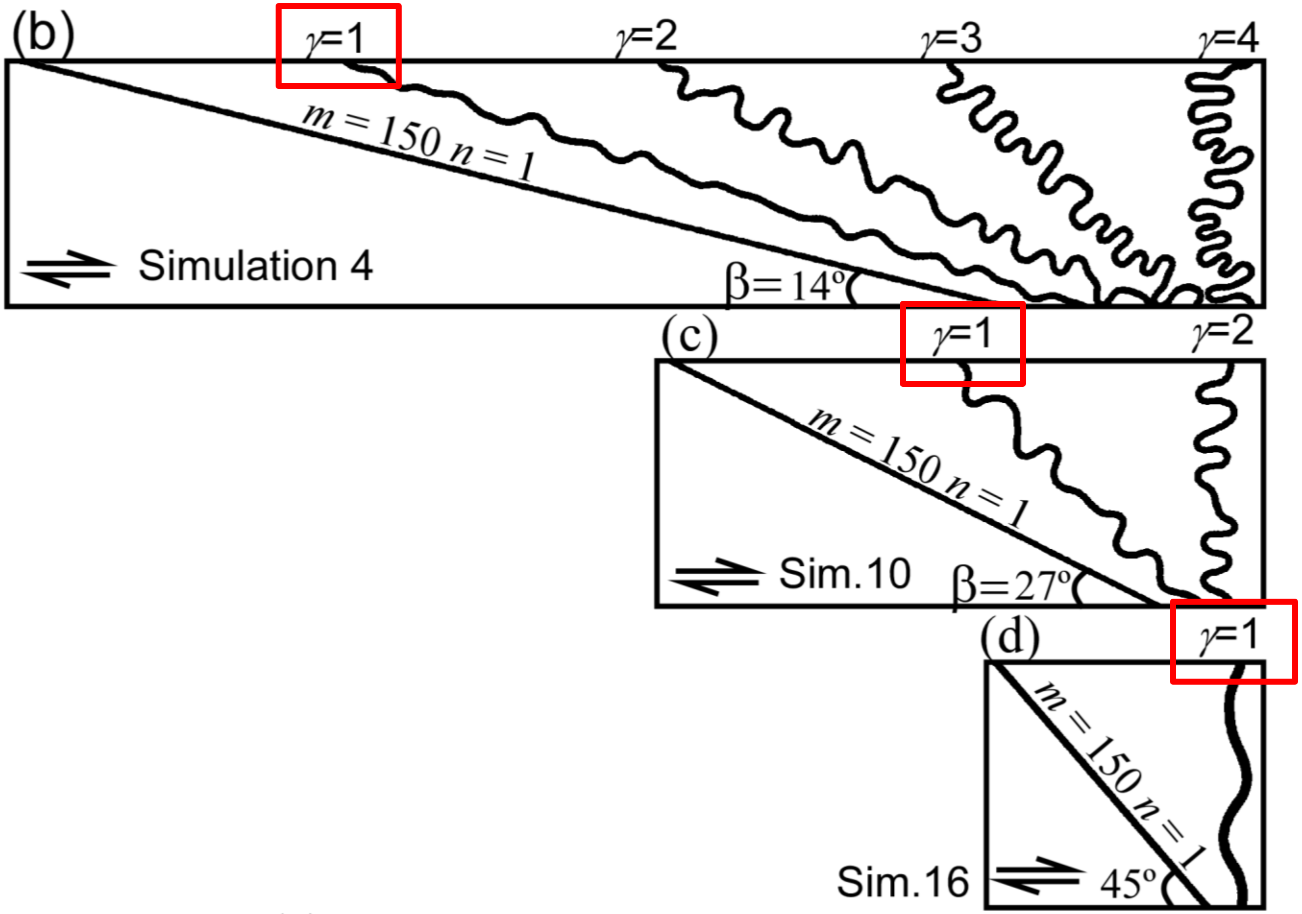


Simple shear: strain rate dependent of the layer orientation respect to the shear plane $\dot{\varepsilon} = r \cdot \sin(2\alpha)$

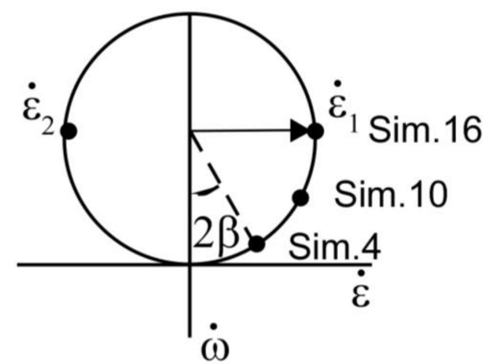




Results: kinematics of deformation, simple shear



Mohr circle for strain rate

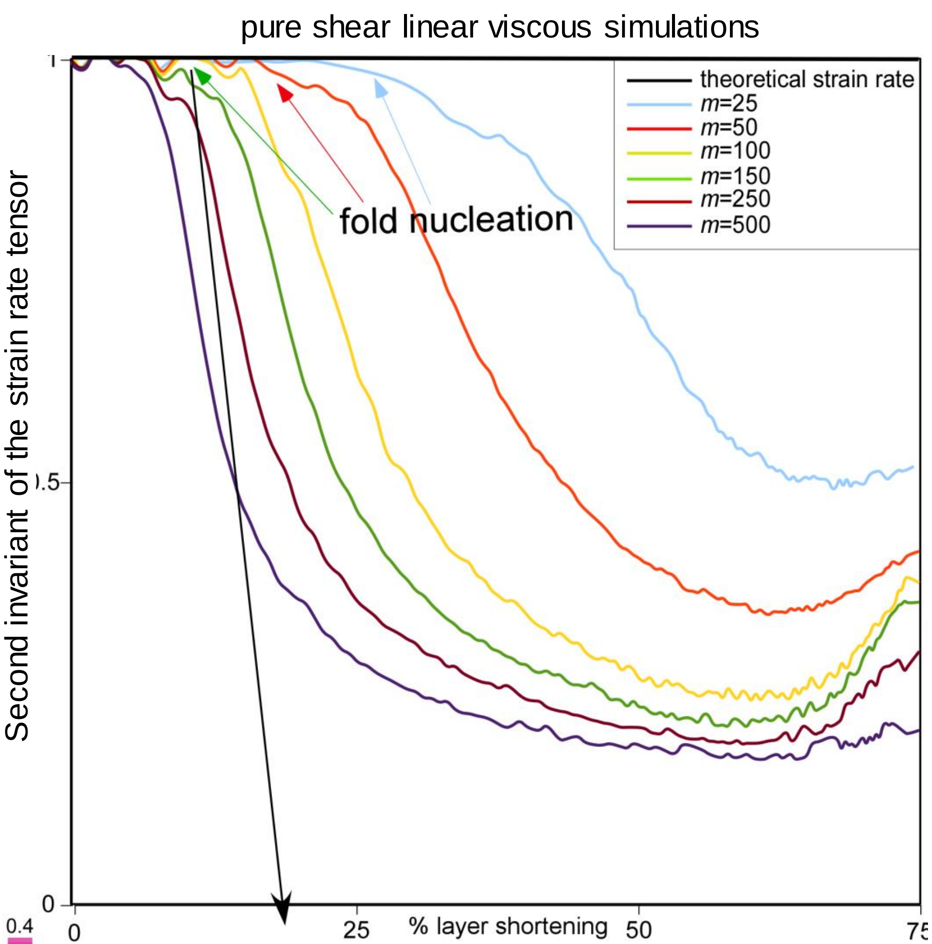


$$\dot{\varepsilon} = r \cdot \sin(2\beta)$$

Strain rate is not constant. It varies with the layer orientation respect to the shear plane

Llorens, 2019

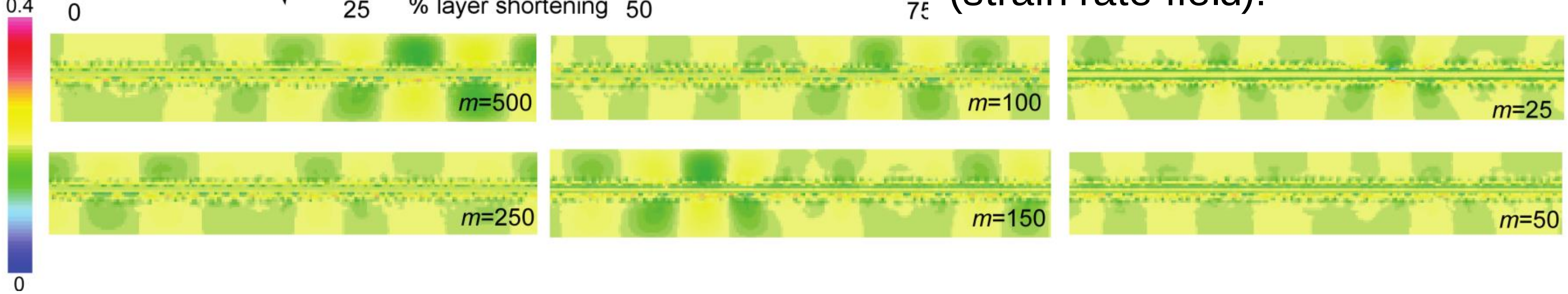
Results: kinematics of deformation, pure shear



Normalised respect to a m=1 simulation (only thickening) → theoretical strain rate

Folding occurs when the second invariant of the strain rate tensor deviates from the theoretical curve. Before that, the layer thickens.

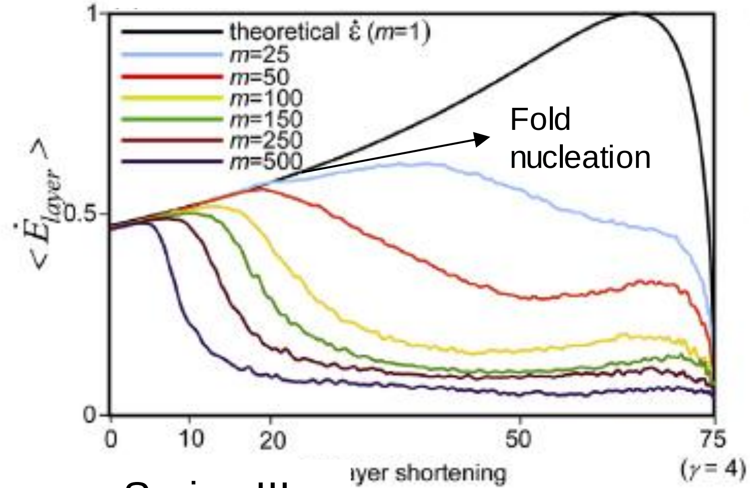
Fold wavelength selection previous folding (strain rate field):



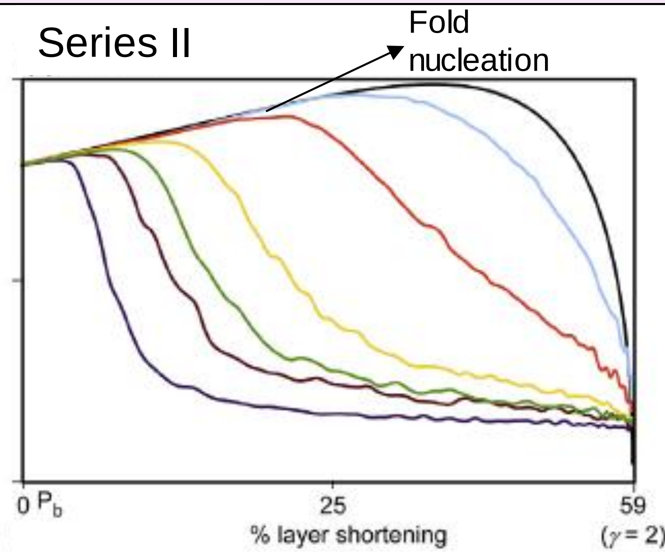
Llorens, 2019

Results: kinematics of deformation, simple shear

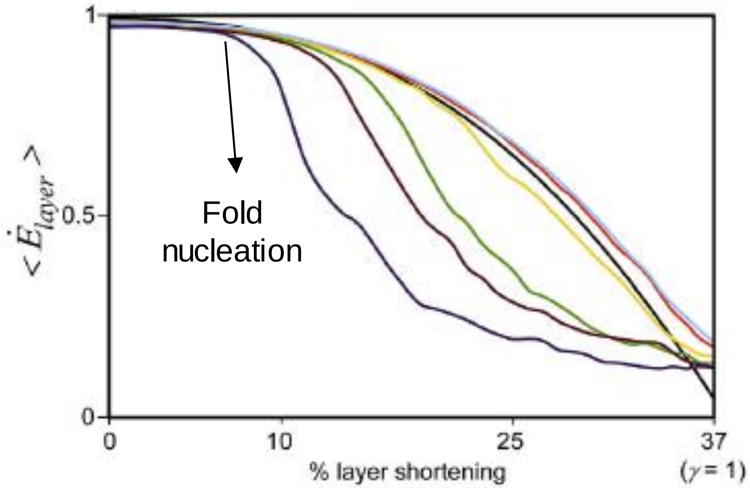
Series I



Series II



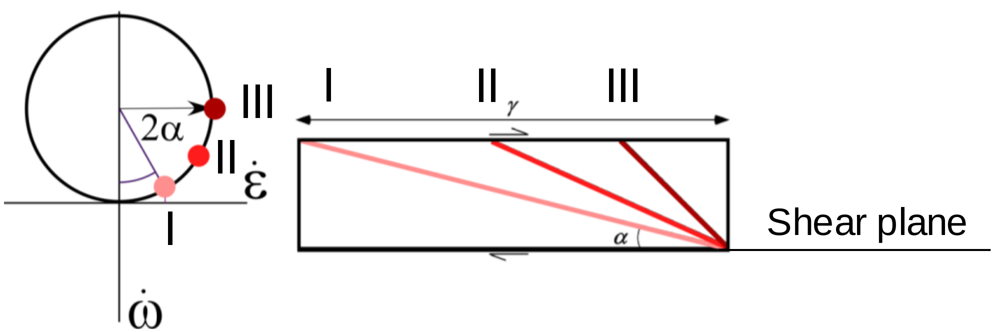
Series III



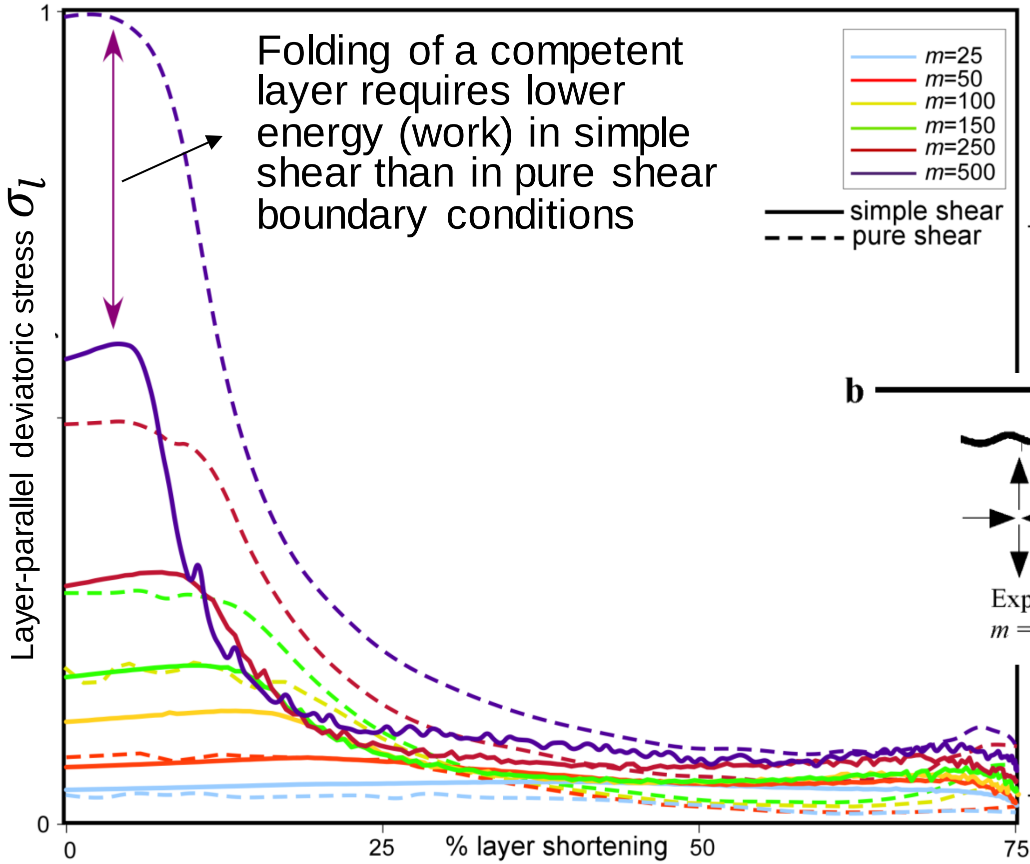
Normalised respect to a m=1 simulation (only thickening) → theoretical strain rate

Folding occurs when the second invariant of the strain rate tensor deviates from the theoretical curve. Before that, the layer thickens

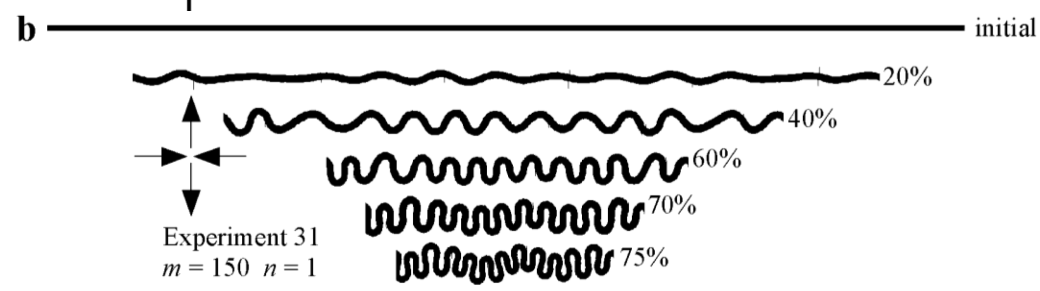
Initial configuration:



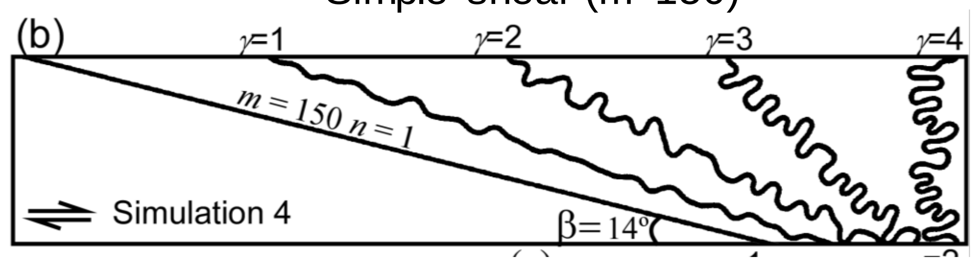
Simple shear vs pure shear



Pure shear (m=150)

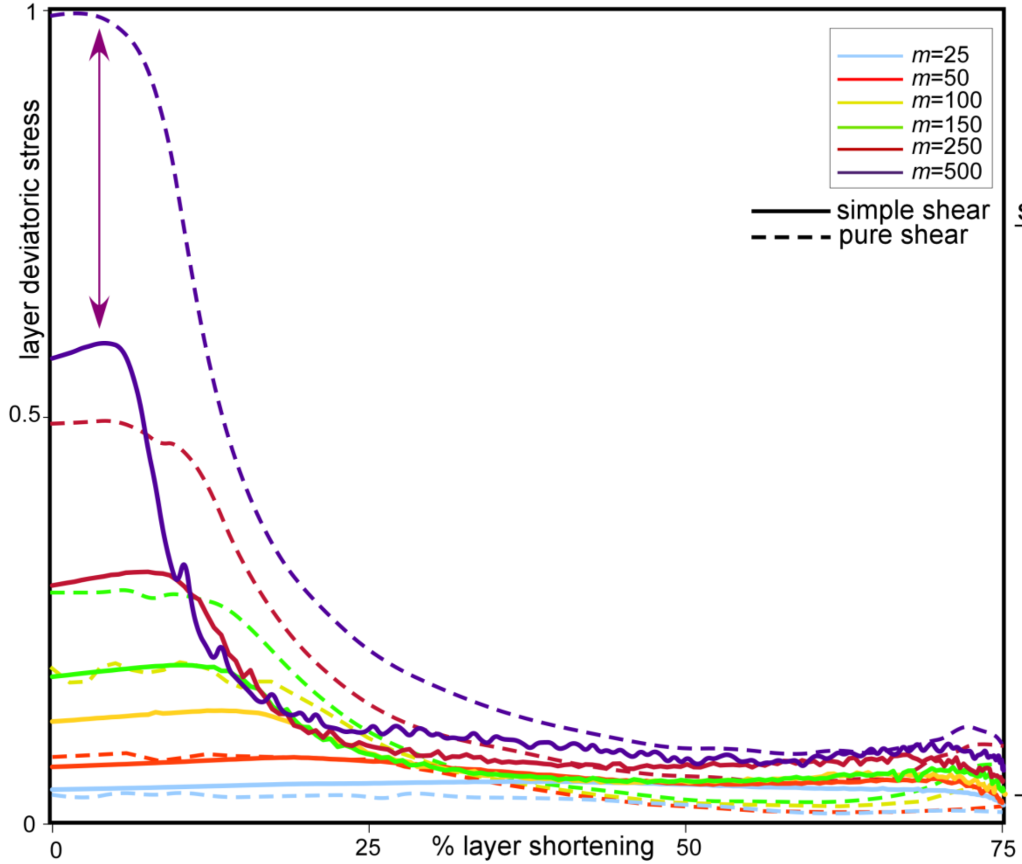


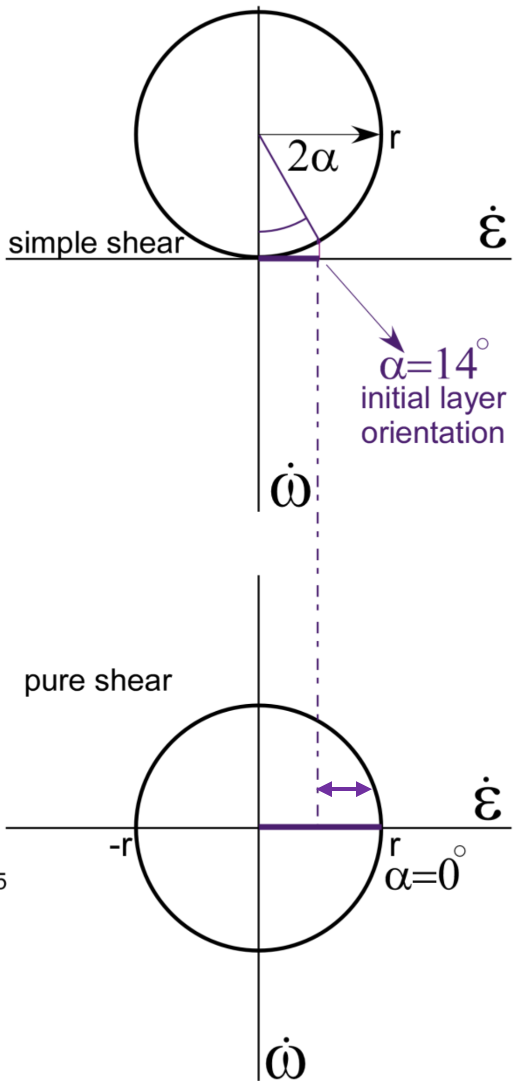
Simple shear (m=150)



Llorens, 2019

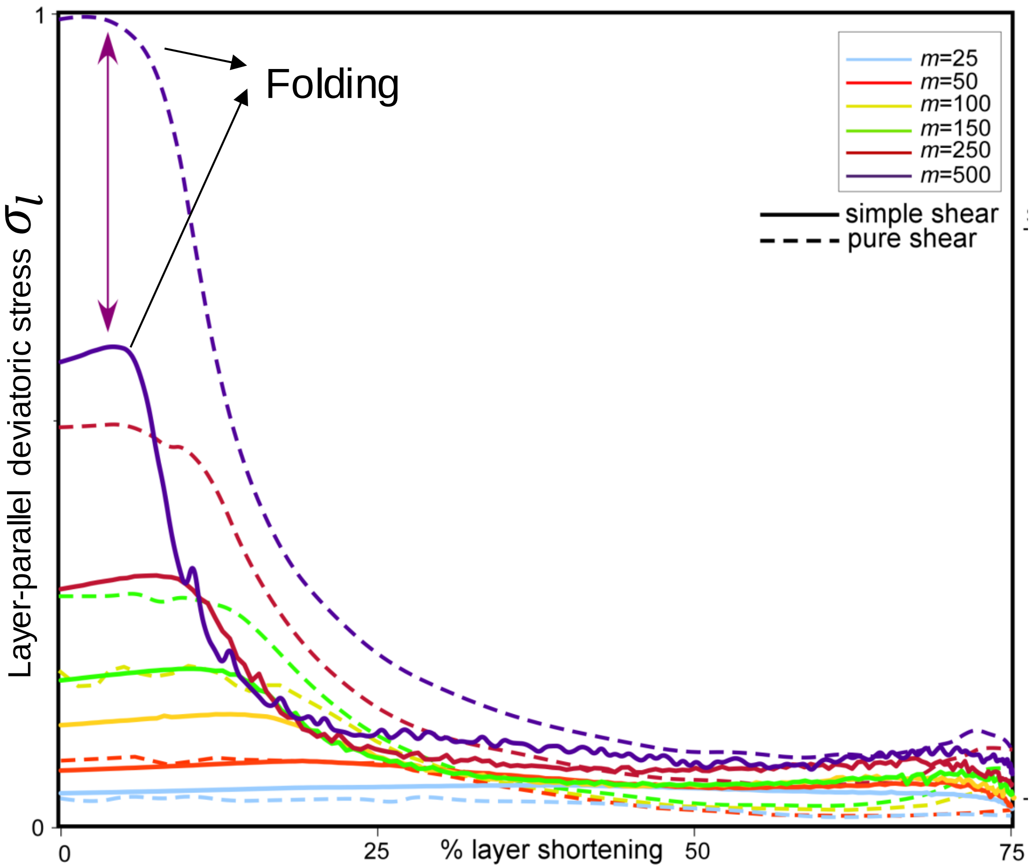
Simple shear vs pure shear





Folding of a competent layer requires lower energy (work) in simple shear than in pure shear boundary conditions

Geometrical softening



The **effective viscosity** is defined as the ratio of the layer-parallel deviatoric stress to twice the background strain rate (which is constant in our simulations):

$$\mu_{ef} = \frac{\sigma_l}{2\dot{\varepsilon}_b}$$

$(\dot{\varepsilon}_b = \text{constant during deformation})$

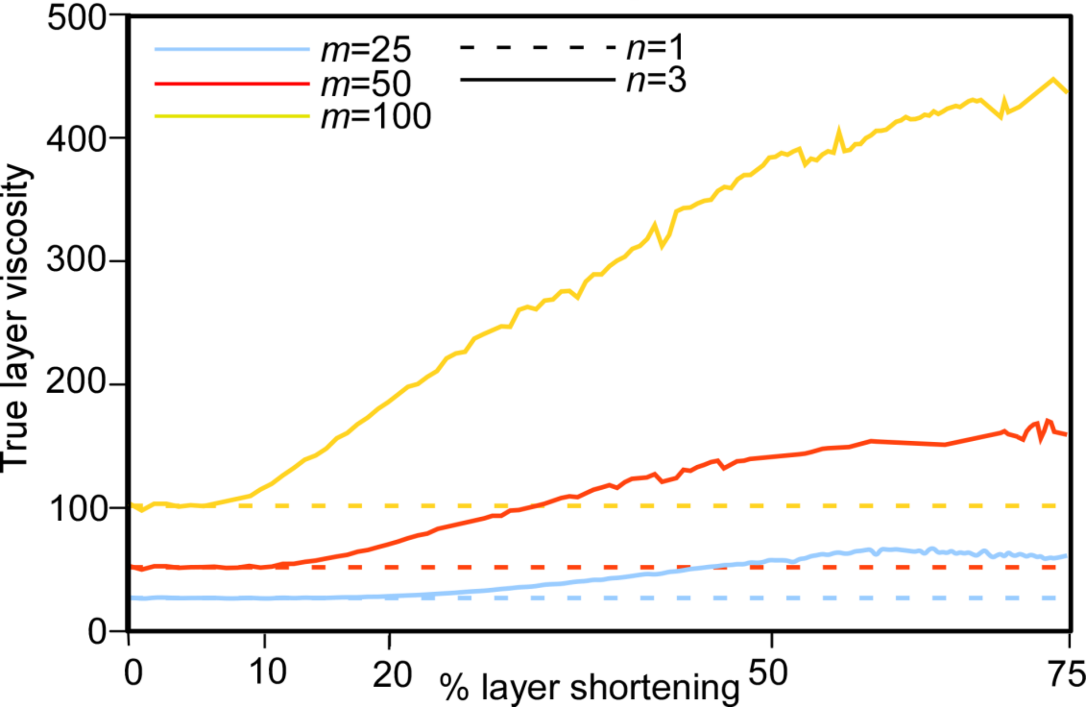
A decrease in layer-parallel deviatoric stress when a competent layer folds, implies a **decrease in the effective viscosity of the layer, representing a geometrical softening.**

Folding produces a softening of the competent layer! (→geometrical softening)

Llorens, 2019

Experimental results: non-linear simulations (*n*=3)

$$\dot{\varepsilon} = \eta\sigma^{n}$$



The true layer viscosity is defined as the ratio of the layer-parallel deviatoric stress to twice the layer-parallel strain rate:

$$\mu_{true} = \frac{\sigma_l}{2\dot{\varepsilon}_l}$$

In linear simulations (n=1), the true layer viscosity is constant. **However, in non-linear simulations (n=3) the true layer viscosity is increased during deformation**.

An initial viscosity ratio of *m*=100 can become 400!

Llorens, 2019

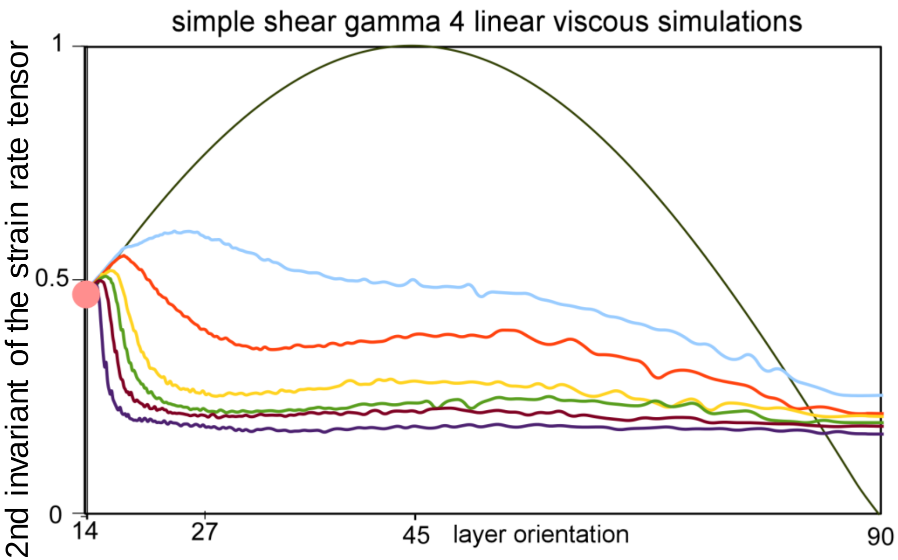
Summary

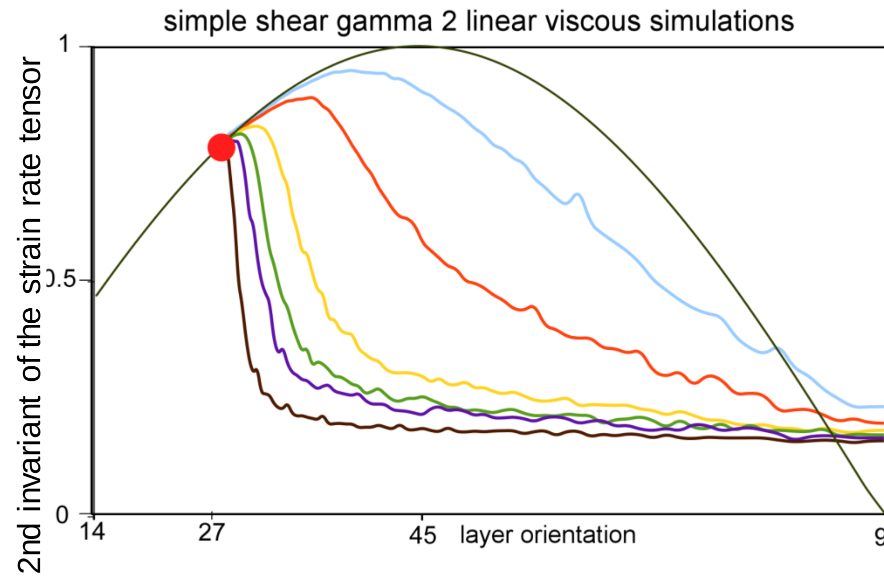
- At the beginning of the deformation the layer thickens ,**following the theoretical evolution for a homogeneous material (*m*=1)**. When the nucleation of folds starts, the second invariant of the strain rate tensor decreases, moving away from the theoretical evolution trend.
- The true layer viscosity can be **greatly increased in non-linear simulations (n=3)**.
- The effective viscosity drops when layer folds, representing a **geometrical softening.**
- Results suggest that the decrease of stress of a competent layer without decreasing the mechanical strength has a direct influence on the behaviour of a lithospheric layer around the crust-mantle boundary, which may **experience geometrical softening depending on the tectonic settings rather than material softening** due metamorphic reactions or grain size reductions.

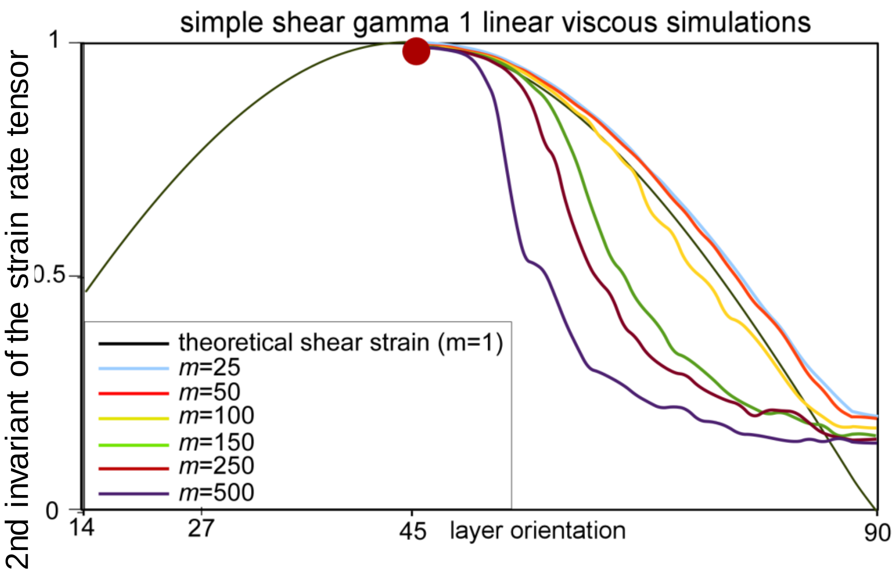
From: Llorens, M.G., 2019**. Stress and strain evolution during single-layer folding under pure and simple shear**. *Journal of Structural Geology*, *126*, pp.245-257.

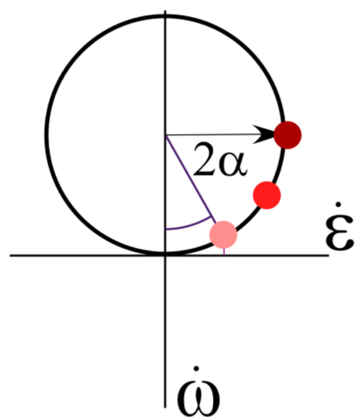
Many thanks!

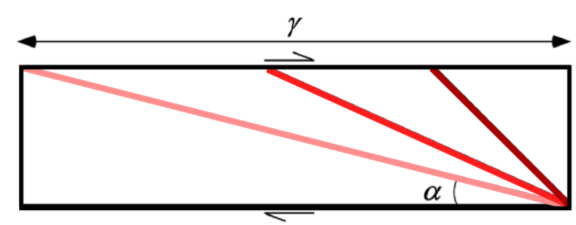
Experimental results: initial layer orientation







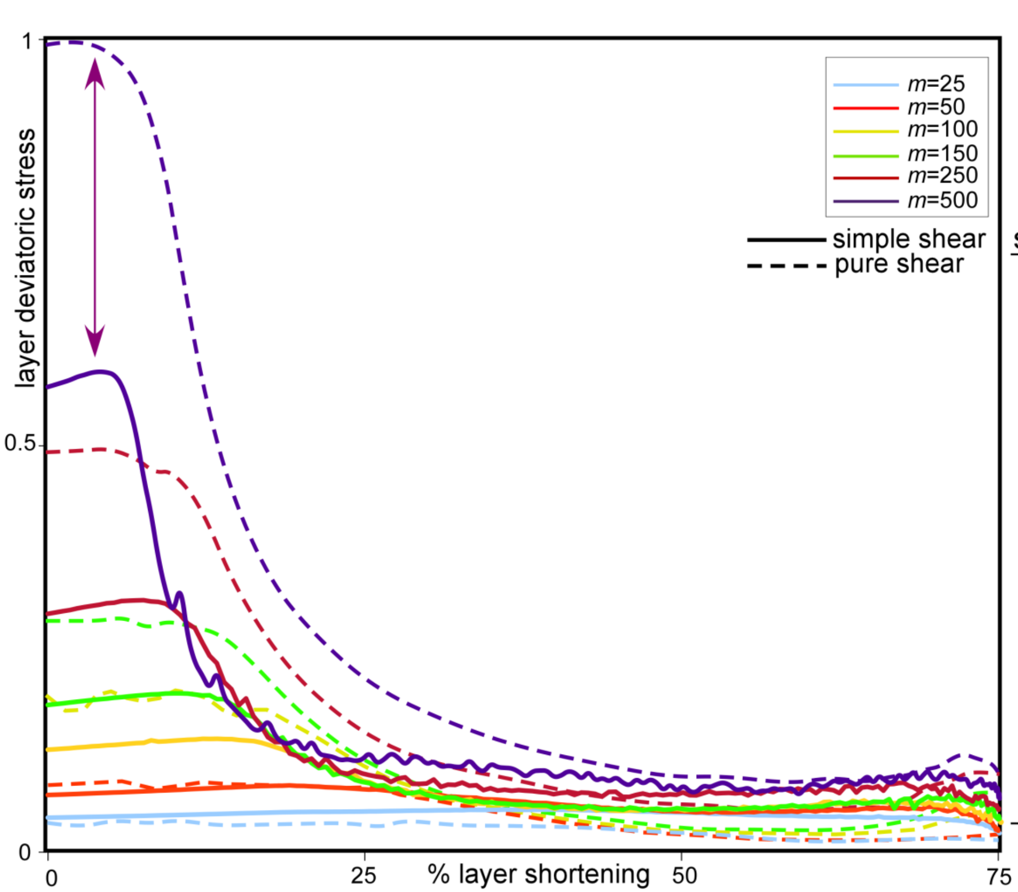


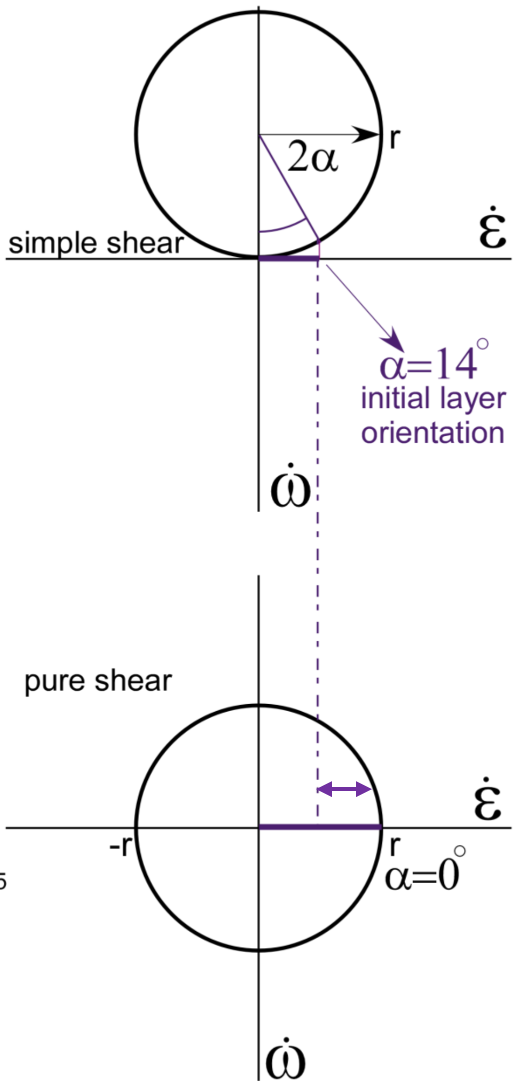


α=14º → γ=4
α=27º → γ=2
α=45º → γ=1

When the layer is oriented at low angle (α=14º) with respect to the shear plane → the incremental strain is lower

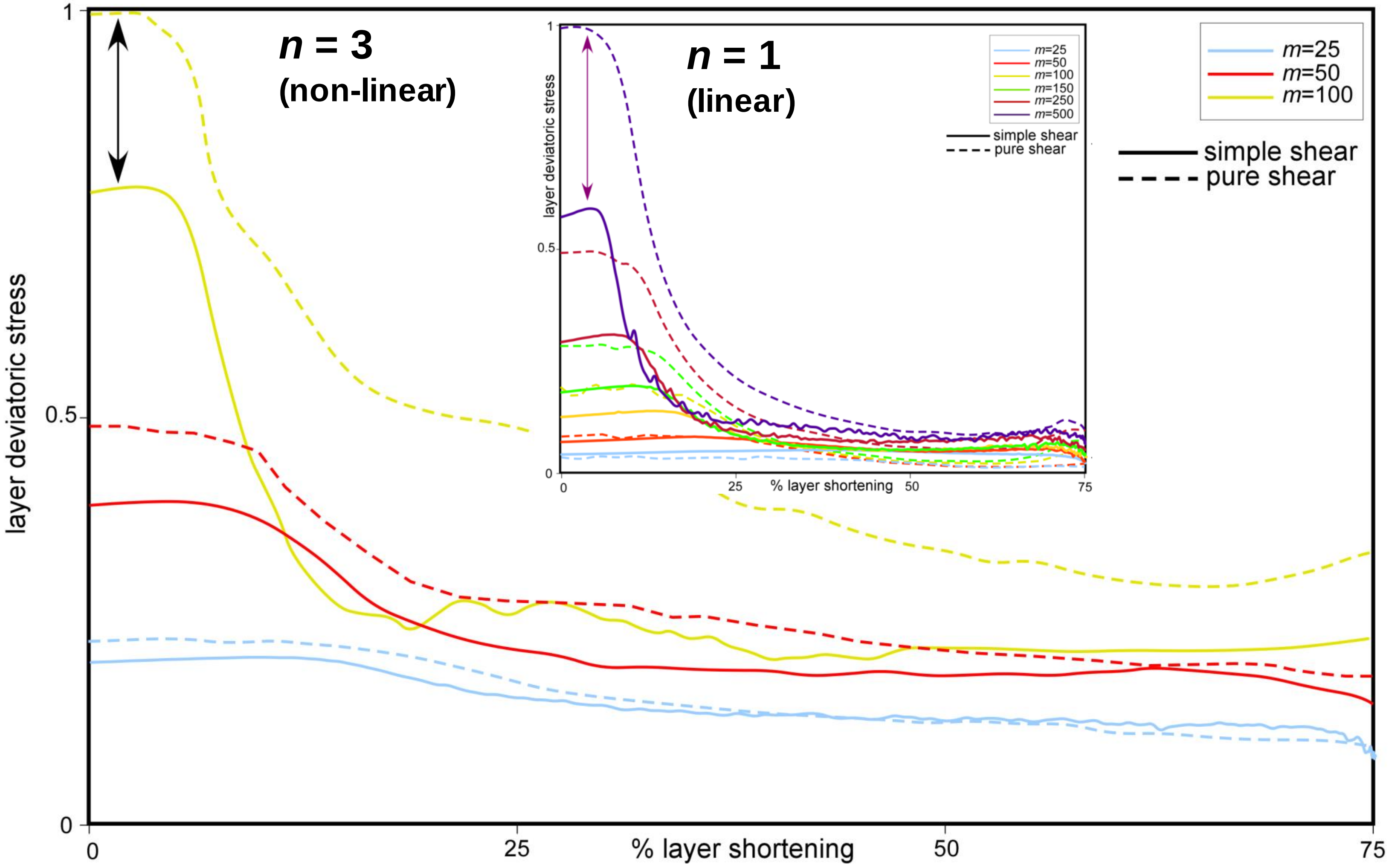
Results: kinematics of deformation, pure shear *vs* simple shear





Folding of a competent layer requires lower energy (work) in simple shear than in pure shear boundary conditions

Experimental results: non-linear simulations (*n*=3)



In non-linear simulations, folding of a competent layer requires lower energy (work) in simple shear than in pure shear, being this difference smaller than in linear cases