Structural inheritance during multilayer buckle folding: How pre-existing asymmetries result in parasitic folds with wrong vergence

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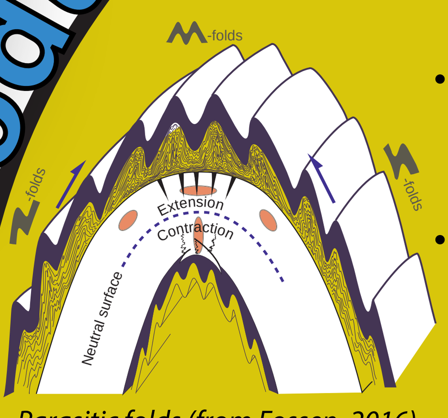
Introduction

What are parasitic folds?

- Develop **simultaneously** with the larger fold.
- Share the fold axis and axial plane orientation with the larger fold.
- Pumpelly et al. (1894) emphasized the "*general parallelism which exists between the minute and general structure*".
- As a result, parasitic folds exhibit a **characteristic asymmetry** (fold vergence):
  - S- and Z-shape on either limb
  - symmetric M-shape close to the hinge



Parasitic folds (from Fossen, 2016).

Pumpelly's rule seems to be axiomatic. van der Pluijm & Marshak (2004) wrote: *"In any case, remember that a pattern of fold vergence opposite to that in Figure 10.16 cannot be produced in a single fold generation (Figure 10.17). In fact, this geometry is diagnostic of the presence of at least two fold generations."*

Figure 10.17 from van der Pluijm & Marshak (2004).

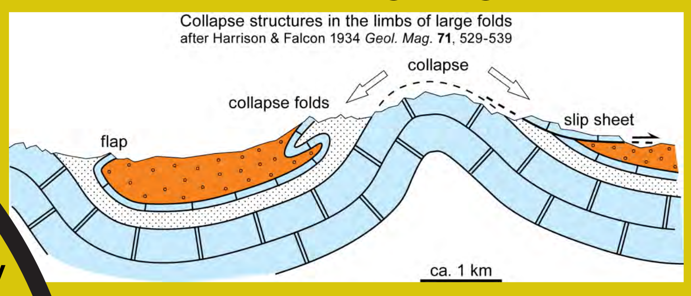
Examples of parasitic folds with wrong vergence

Oblique layers in a ductile shear zone can develop different vergences during simple shear or even unfold completely while other layers remain folded.

Multilayer folds in simple shear with increasing shear strain developing "random" vergences (Llorens et al., 2013).

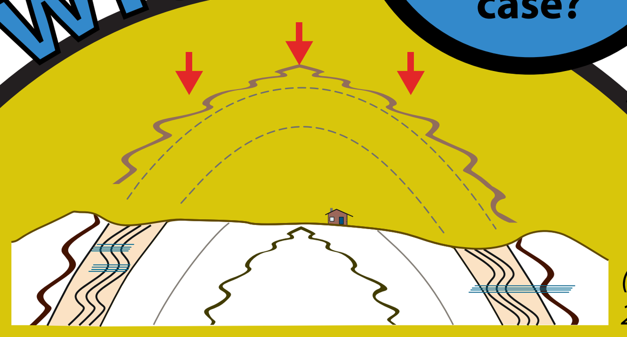
This unpredictable vergence may lead to fold patterns resembling parasitic folds with wrong vergence.

Large-scale collapse structures on the flanks of large surficial antiforms can resemble parasitic folds with wrong vergence.



From lecture notes of Jean-Pierre Burg after Harrison & Falcon (1934).

But does this always have to be the case?



(Fossen, 2016)

Type 3 interference pattern resembling parasitic folds with wrong vergence.

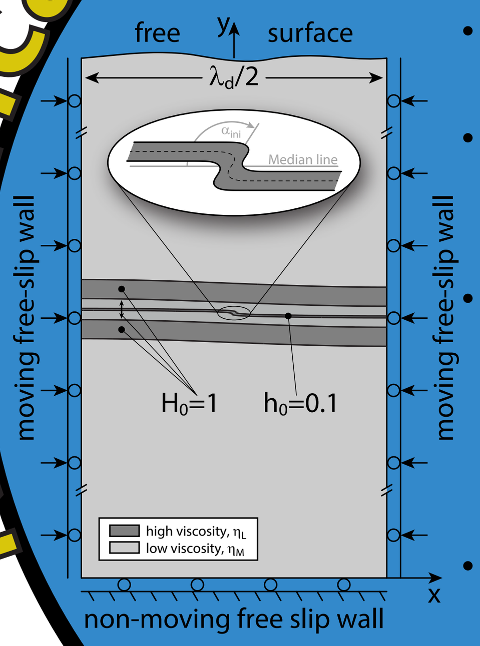
Type 3 fold interference patterns occur when two consecutive folding events share their fold axis, but have an axial plane orientation roughly perpendicular to each other. They resemble parasitic folds with wrong vergence if the second folding event occurs on a much larger scale than the first.

Research question

Is it possible to inherit a pre-existing geometrical asymmetry during buckle folding in layer-parallel pure-shear? And If so, how and under which circumstances.

Numerical model

- 3 high-viscosity layers (viscosity η_L) intercalated with a low-viscosity matrix (η_M).
- Outer layers: thickness: H_0, distance to each other: H_0,
- The dominant wavelength of the 2-layer system is applied as initial perturbation.
- The 10x thinner central layer exhibits an asymmetric initial perturbation leading to a wrong vergence of the developing small-scale fold.
- It also exhibits a small random red noise to allow other small-scale folds to develop independently of the prescribed asymmetry.



Geometrical model setup and boundary conditions.

Rheology: Incompressible linear viscous (Newtonian)

2D finite-element model:

Lagrangian body-fitting mesh
Isoparametric triangular elements with 7 continuous bi-quadratic shape functions for velocity and 3 discontinuous linear ones for pressure
Mixed velocity-pressure-penalty formulation using Galerkin method
Numerical integration on 7 Gauss-Legendre quadrature points
Uzawa-type iteration to enforce incompressibility

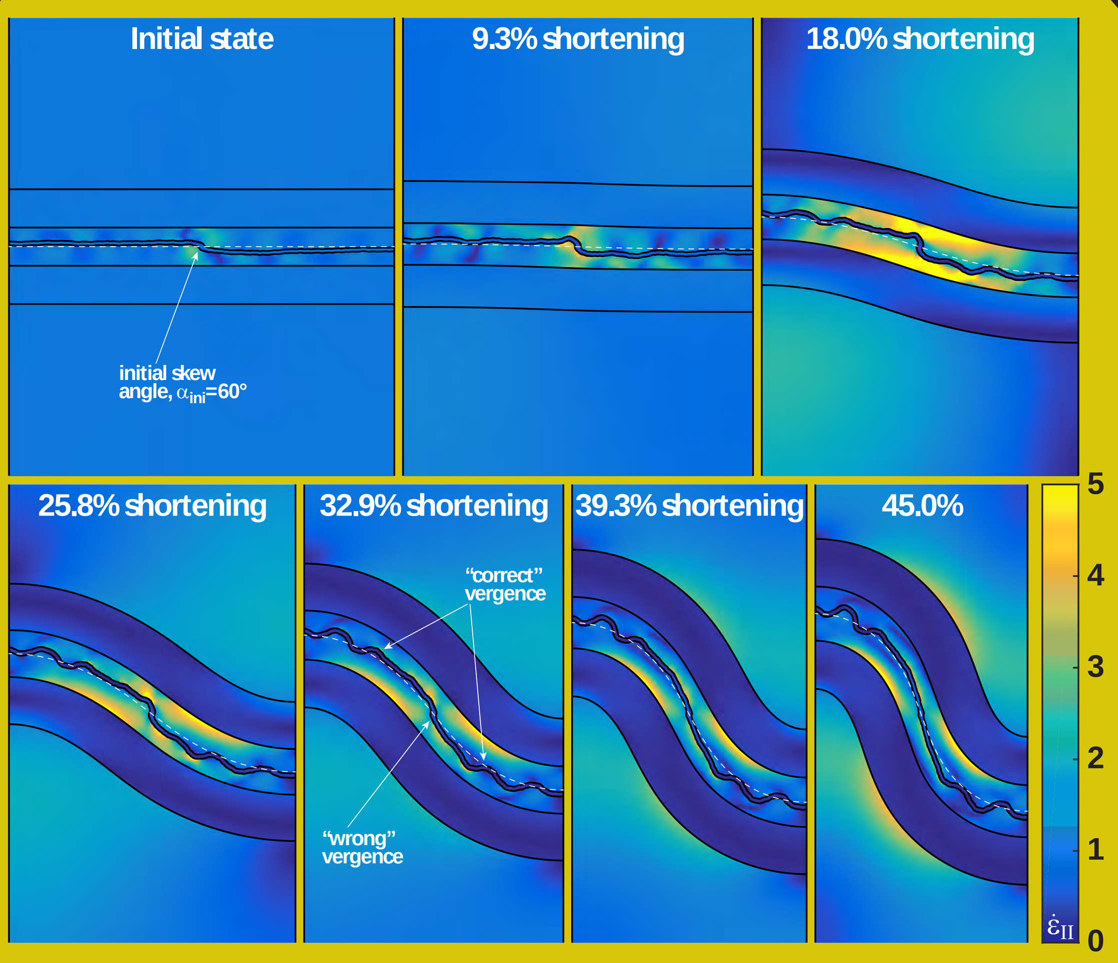
Boundary conditions:

Bottom: free slip
Top: free surface
Left & right: moving free slip
This results in horizontal pure-shear shortening with a constant shortening strain rate.

Results

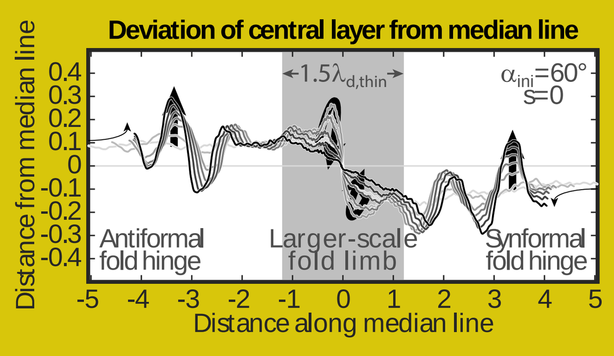
Reference simulation

Scan to see simulation image as a movie



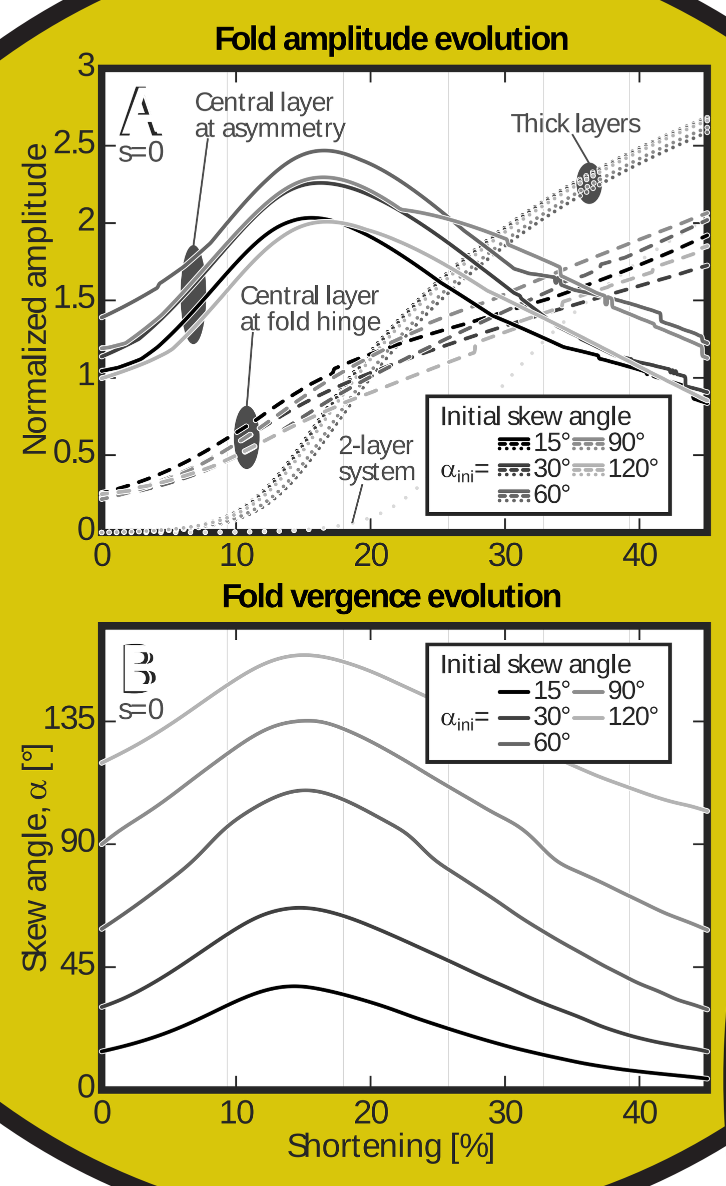
Simulation snapshots of reference simulation: initial skew angle α_{ini}=60° and asymmetry centered on fold limb. Colors: second invariant of strain rate tensor. Dashed white line: larger-scale median line. The initial asymmetry survives the early stages of the buckle folding process, which results in an alleged parasitic fold with wrong vergence, alongside true parasitic folds with correct vergence.

Evolution of the larger-scale median line for the reference simulation. Different lines represent the different simulation snapshots.



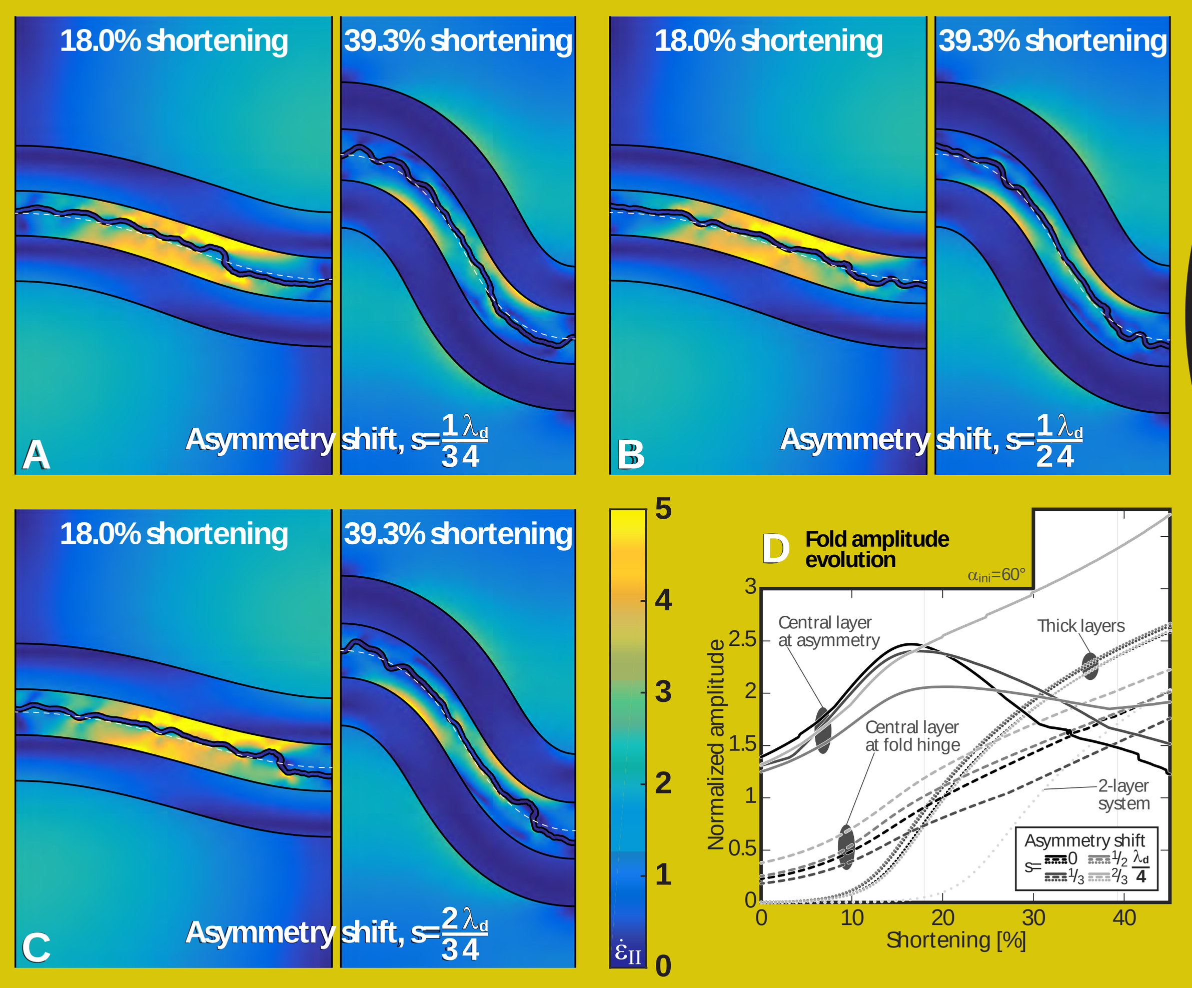
Note that the initial asymmetry first amplifies and later de-amplifies while small-scale folds away from the initial asymmetry amplify continuously.

Varying initial skew angles



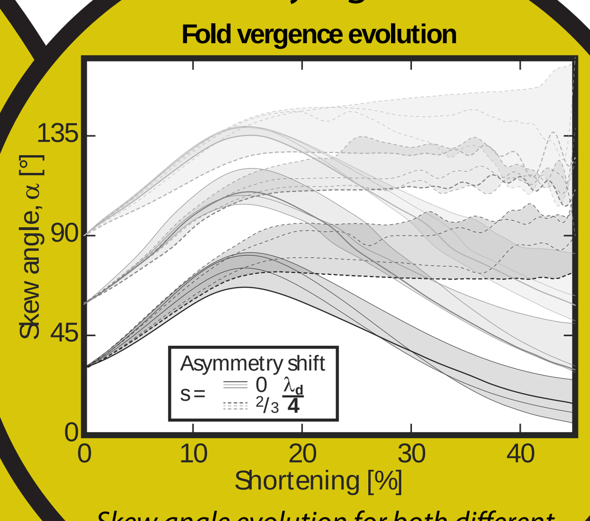
Evolution of fold amplitude and skew angle for different initial skew angles. Amplitudes are normalized with the initial thickness of the corresponding layer. Thin vertical lines correspond to the simulation snapshots. For all initial skew angles the initial asymmetry first amplifies and later de-amplifies.

Varying position of the asymmetry on the larger-scale fold



A-C) Simulation snapshots of simulations with initial asymmetries not centered, but shifted horizontally on the fold limb (expressed as asymmetry shift parameter s). D) Same as to the left (A) but for the simulations shown in A-C. Note that the curves for s=0 are the same as in the figure on the left for α_{ini}=60°. The closer the asymmetry is located to the larger-scale fold hinge, the less pronounced the de-amplification is.

Varying all



Skew angle evolution for both different α_{ini}, different positions on the larger-scale fold and different layer spacings.

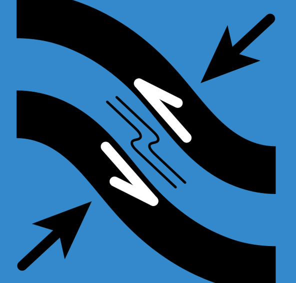
Mechanism of de-amplification

During amplification of the larger-scale fold, two effects take place between the two thick layers (also Frehner & Schmalholz, 2006):

- Layer-perpendicular flattening
- Flexural flow

The resulting deformation field is a complex combination of pure and simple shear:

- Pure shear (layer-perpendicular flattening) squeezes the folds of the thin layer.
- Simple shear (i.e., flexural flow) has a rotational component opposite to the vergence of the asymmetry.



Both effects work against the asymmetry resulting in an efficient de-amplification and unfolding of the asymmetry as soon as the larger-scale fold amplifies.

Both effects diminish closer to the larger-scale fold hinge.

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Conclusions

Potential for structural inheritance of asymmetry:

On the limbs of larger-scale folds, de-amplification and unfolding is very efficient. Potential for structural inheritance is small. Asymmetries may survive only if shortening is small. Otherwise, parasitic folds with correct vergence will overprint the asymmetry.

Closer to the hinge of larger-scale folds, de-amplification and unfolding is less efficient. Potential for structural inheritance is larger. If inherited, the asymmetric fold will develop a type 3 interference pattern.