Chat with Marcel Frehner

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Hey Marcel, I heard you prepared a poster for GeoMod with the title:

Fold axis rotation during transpressional folding:

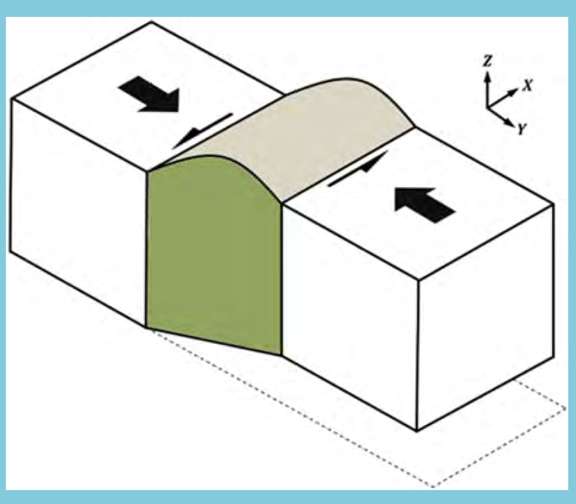
Insights from numerical modeling and application to the Zagros Simply Folded Belt

That's right! Wanna see it?

Yeah sure. But maybe explain first what transpression is, plz.

Well, transpression (or oblique convergence) is a common tectonic setting at plate boundaries characterized by two components of relative plate velocity:

- one component is perpendicular to the plate boundary (shortening component)
- one component is parallel to the plate boundary (strike-slip component)



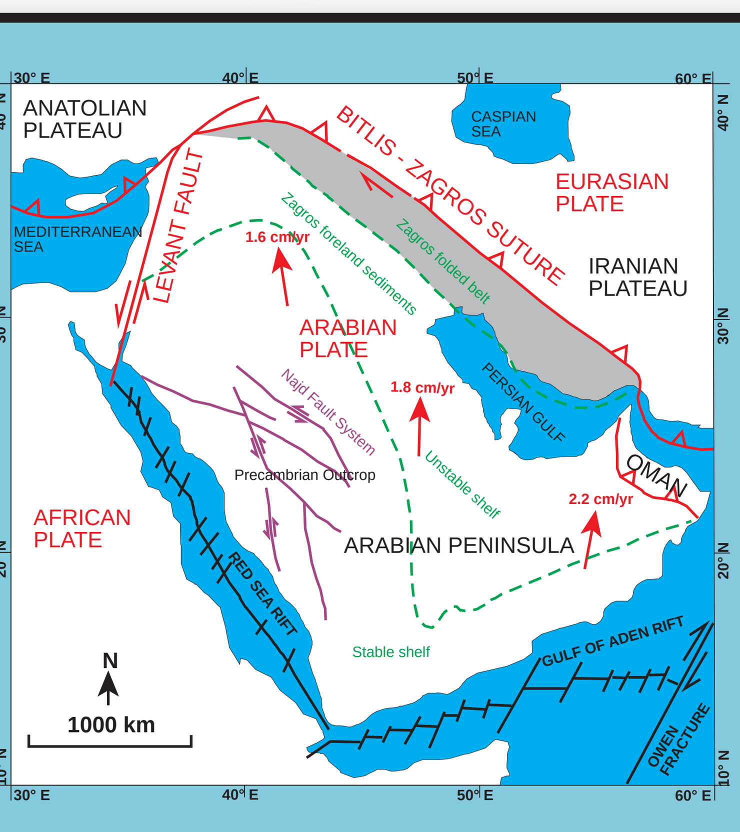
Schematic sketch of transpression after Nabavi et al. (in press).

A good example for oblique conversion is found in the Middle East, where the Arabian plate converges obliquely towards the Eurasian plate with an angle of about 35° with respect to the plate boundary in the Zagros Mountains.

Oblique convergent plate boundaries may be characterized by ...

- homogeneously distributed strain (i.e., true transpression).
- full strain partitioning resulting in areas exhibiting shortening structures (thrust, folds) bounded by areas exhibiting simple-shear structures (strike-slip faults).
- any mixture between the two end-member cases above.

Tectonic overview map of the Middle East (Frehner et al., 2012). Red arrows indicate GPS-velocities relative to stable Eurasia highlighting the oblique convergence within the Zagros Mountains.



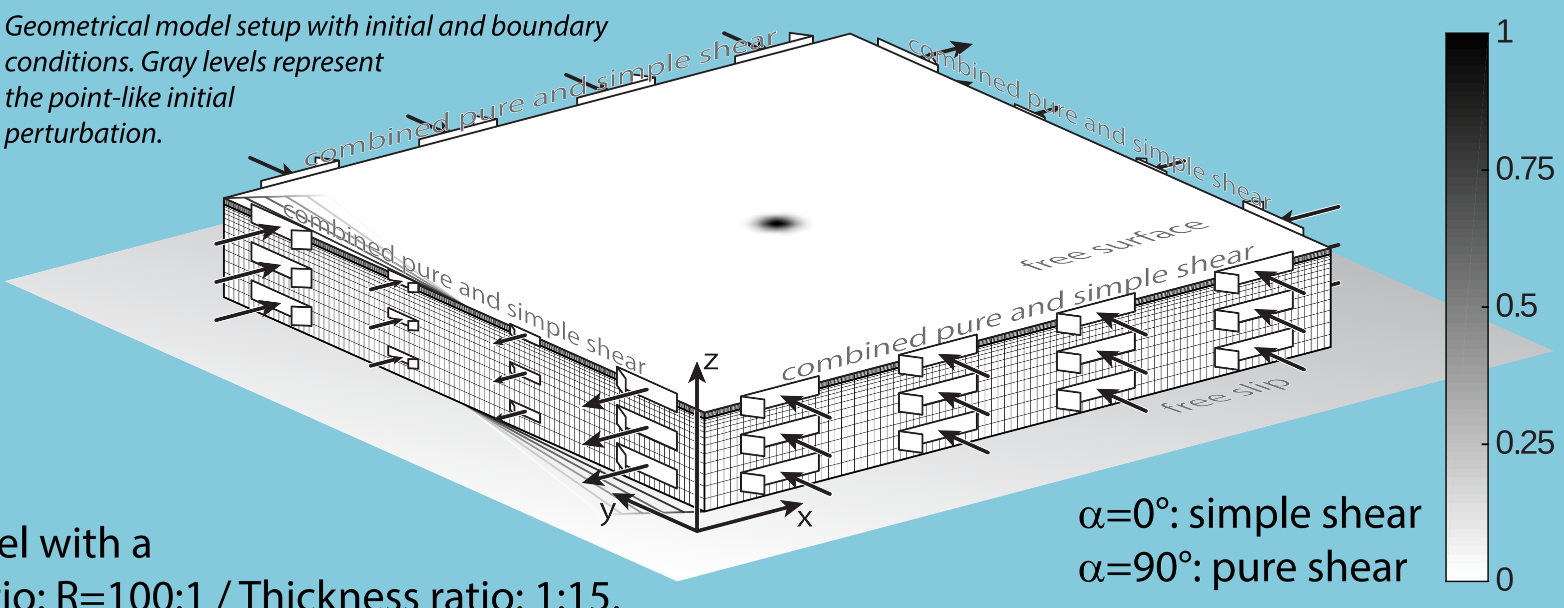
Interesting! Sounds like transpression is really a true 3D problem, right? And you modeled that?

Of course 😎. I developed a fully 3D finite-element model that solves the incompressible Stokes equations with linear viscous (Newtonian) rheology. I give you some details, in case you're interested:

- Mixed velocity-pressure-penalty formulation (Galerkin method)
- Lagrangian grid with cubic isoparametric Q27/4 elements
- Shape functions: Tri-quadratic continuous for velocity; Linear discontinuous for pressure
- Uzawa-type iteration to enforce incompressibility

Btw, I already used and tested this numerical model in 2014.

Geometrical model setup with initial and boundary conditions. Gray levels represent the point-like initial perturbation.

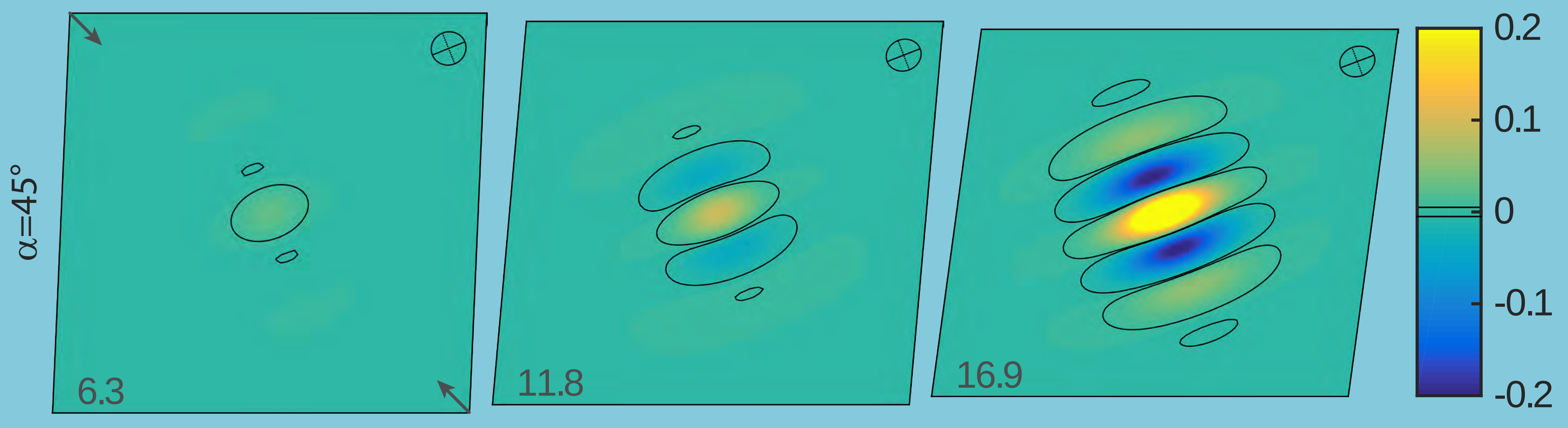


To model folding in transpression, I used a relatively simple 2-layer model with a higher-viscosity layer resting on top of a low-viscosity layer; Viscosity ratio: R=100:1 / Thickness ratio: 1:15. The upper layer exhibits a small initial point-like geometrical perturbation to initiate folding. Folds will grow from this point in all three dimensions.

I then chose the boundary conditions such that transpressional strain is enforced to the model. In other words, I applied a combination of pure- and simple-shear strain to the four lateral boundaries. I call the resulting convergence angle α. The upper boundary I left free, so that folds can develop.

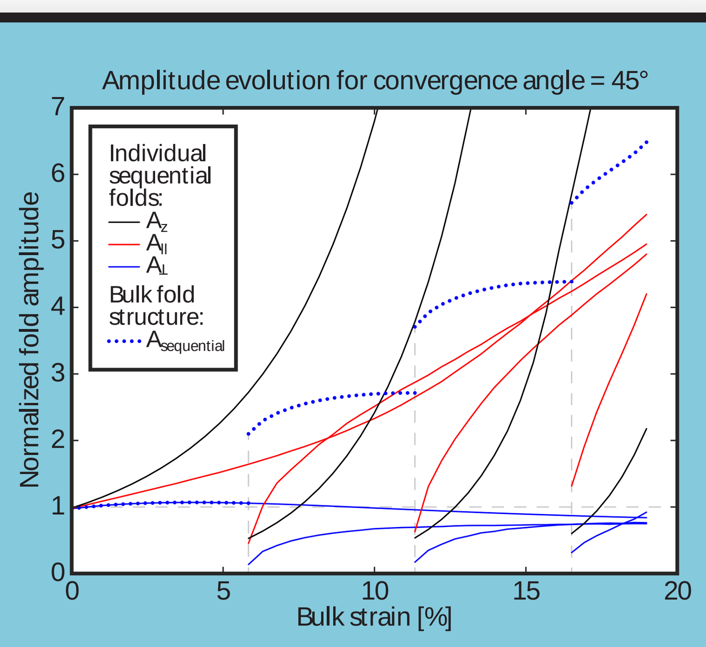
WOW! You're amazing 😍. But now you made me curious. Tell me how these folds grow!

Thx! Here are some example simulation snapshots (in top view) of a simulation with a convergence angle of α=45° and the corresponding plot of the amplitude evolution. You can see how the folds grow in all three dimensions from the initi al perturbation.



Simulation snapshots (top view) of a transpression simulation with convergence angle α=45°. Background strain is increasing from left to right and is given in each snapshot in %. Colors represent topography (i.e., vertical fold amplitude); thin black contour lines mark half the initial value, which defines the individual sequential folds. The upper-right corner of each snapshot shows the horizontal strain ellipse with its major and minor axes.

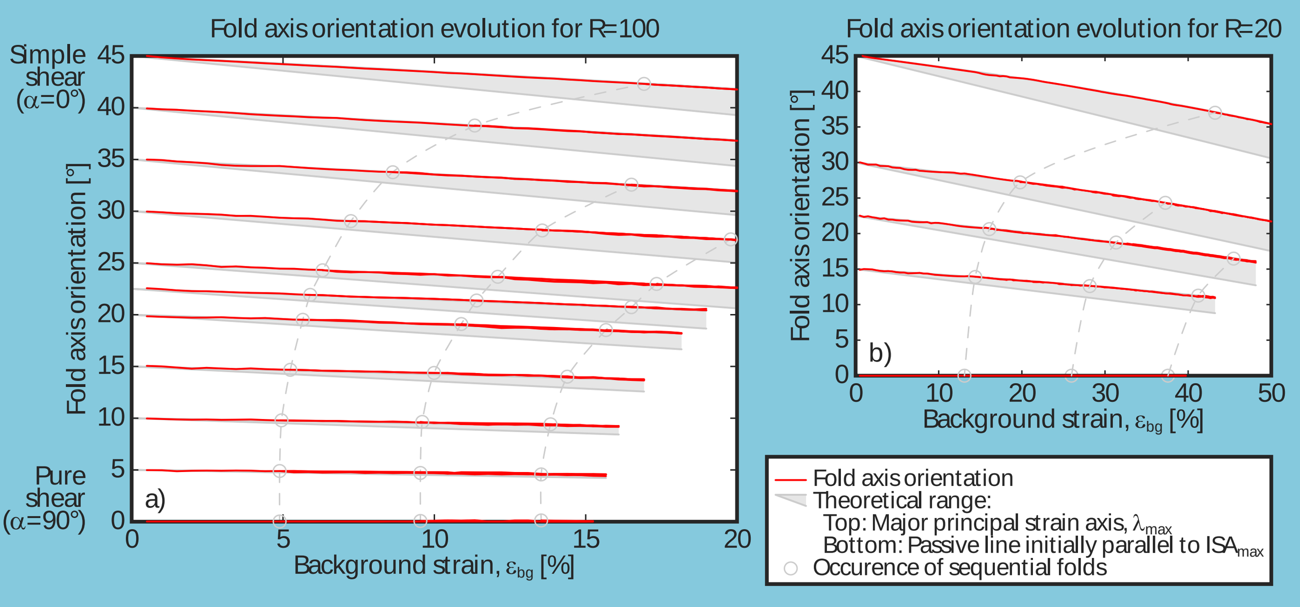
See simulation as a movie.



Amplitude evolution of the simulation on the left (α=45°). A_z is in vertical direction; $A_{//}$ is parallel to the fold axis; $A_\perp$ is perpendicular to the axial plane. $A_\perp$ is the extent of each individual sequential fold while $A_{sequential}$ is the extent of the bulk fold structure perpendicular to the axial plane. Note that the bulk fold structure grows more or less equally in the two lateral directions leading to aspect ratio in map view of about 1:1.

But even more interesting is the orientation of the folds!

During all simulations, I tracked the orientation of the fold axes of all sequential folds and it turns out that they are always oriented parallel to the major horizontal principal strain axis (λ_{max}). They initiate in this orientation and then rotate together with λ_{max}. And that's independent of the convergence angle, the applied strain, and most importantly of viscosity ratio between the two layers. Isn't that amazing?

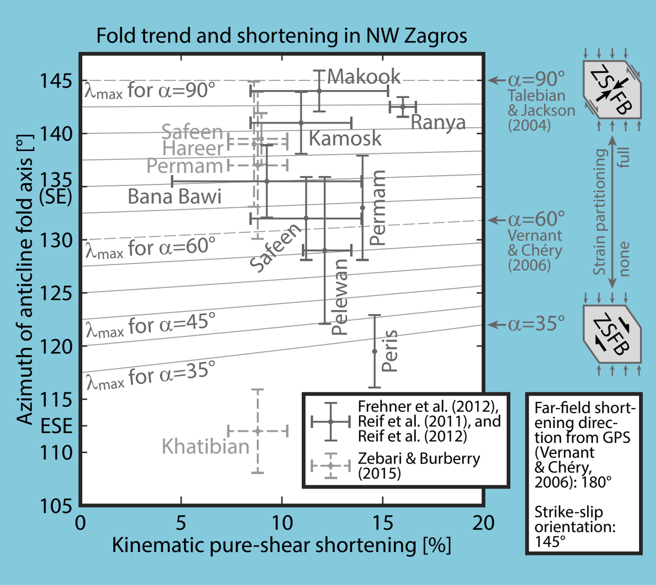


Evolution of fold axis orientation (angle with respect to x-axis) of all individual sequential folds (red lines) for different convergence angles and for two different viscosity ratios, R=100 (a) and R = 20 (b). Gray areas outline the theoretical range of fold axis orientation after Fossen et al. (2013); top edges indicate the orientation of the major horizontal principal strain axis (λ_{max}); bottom edges indicate the orientation of a passive material line initially parallel to the major horizontal instantaneous stretching axis (ISA_{max}).

Indeed! And this also means that the fold axis is NOT a material line, because λ_{max} is not a material line. Instead, hinge migration must take place. So, if I understand correctly, there should be some kind of triangular relationship between the convergence angle, the amount of strain, and the fold axis orientation. If you knew two, you could determine the third. And all of this independent of the viscosity ratio. That's indeed pretty cool!

Exactly! You got it!

And exactly this triangular relationship I applied to the Zagros Simply Folded Belt (ZSFB). Because there, tons of shortening estimates and fold axis orientation measurements exist, but the convergence angle is not really known. Or to be more precise, the far-field convergence anlge is known (see above), but the level of strain partitioning is not well understood. With increasing strain partitioning, the effective convergence anlge within the ZSFB increases because a larger strike-slip component is accommodated by the bordering fault-system. When plotting fold axis orientations vs. shortening estimates, the data lies between a full strain partitioning model (α=90°) and an intermediate model with a convergence angle α=60°. Hence, the fold orientations tell us that there must be some level of strain partitioning.



Fold axis orientations plotted versus kinematic strain estimates of anticlines in the NW Zagros Simply Folded Belt (ZSFB; NE Iraq). In the background, the theoretical fold axis orientation, λ_{max}, is plotted for different convergence angles. End-member convergence angles are sketched on the right based on the far-field shortening direction and strike-slip fault orientation; they are 90° (pure shear) for full strain partitioning and 35° for zero strain partitioning.

This triangular relationship seems really powerful, I didn't expect that. TOP! 👍 Can I see your poster now?

😠 Well, now I don't have the time anymore to prepare one because you asked so many questions. I guess, I will just print this chat feed. But you can download my paper if you like. And I give you some references if you are interested in further details:

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