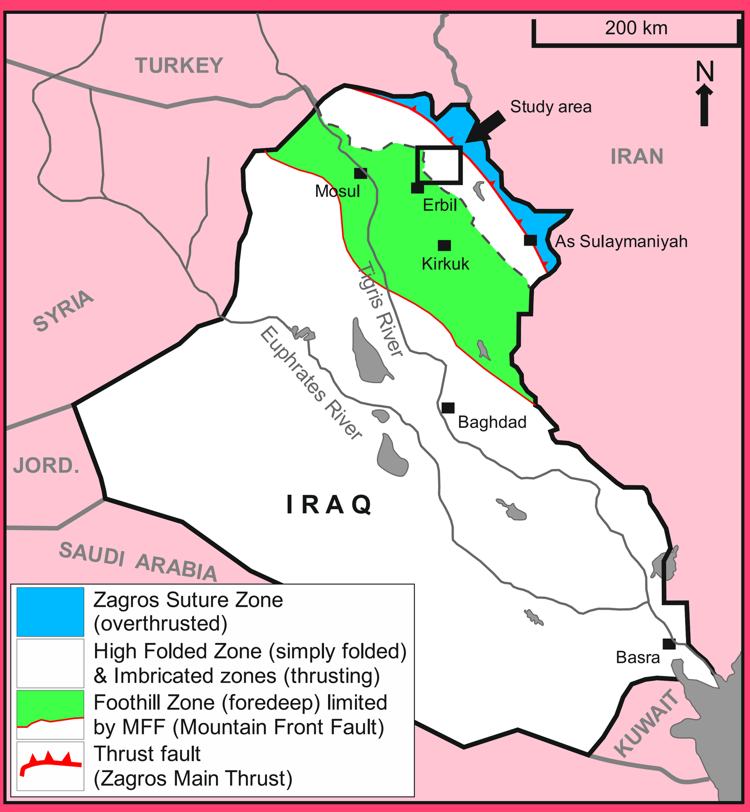
Dynamical unfolding for quality control of geological cross-sections

Marcel Frehner ETH Zurich, Switzerland
Daniel Reif University of Graz, Austria
Bernhard Grasemann University of Vienna, Austria

Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

First author contact:
marcel.frehner@erdw.ethz.ch

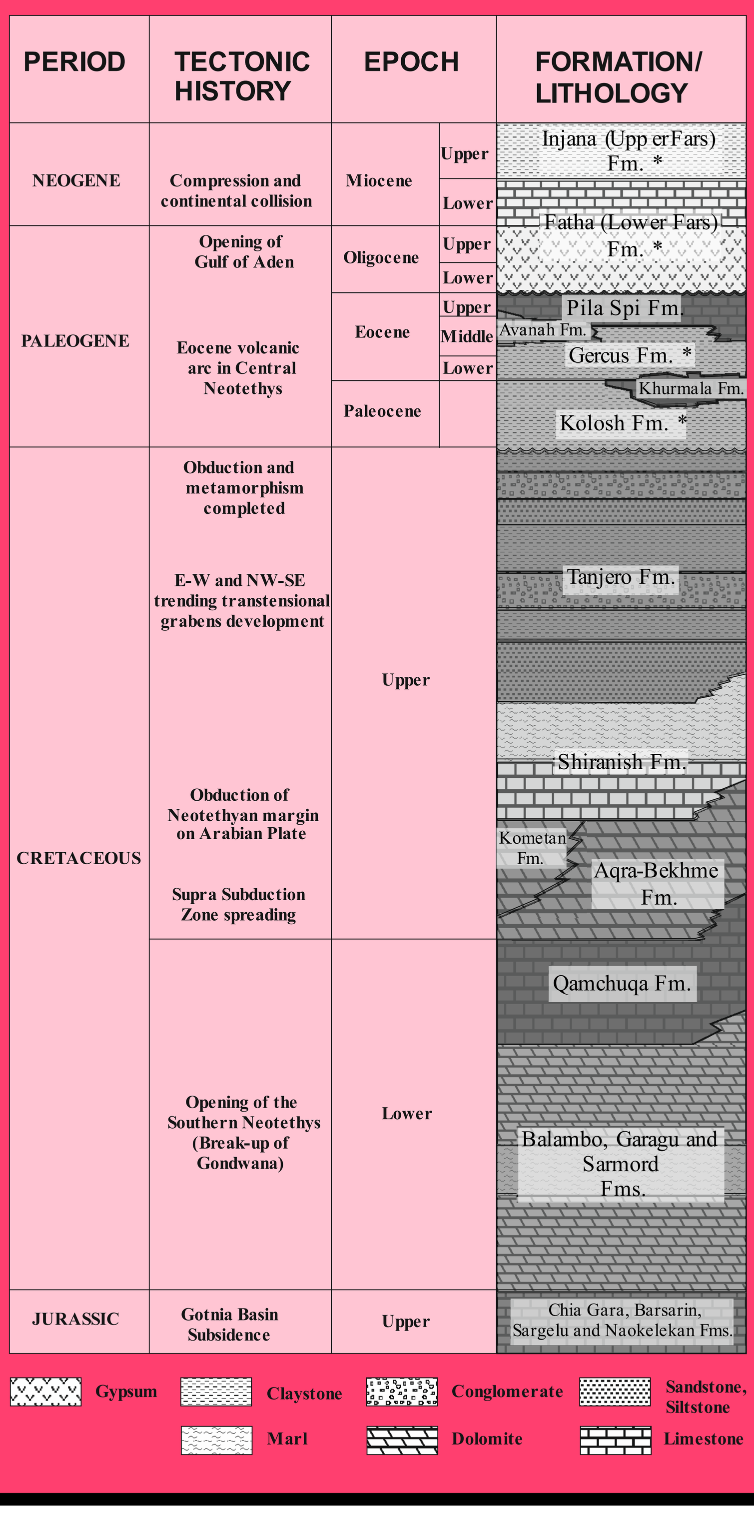
Geological case study



Position of the study area in the High Folded Zone (HFZ) of the Zagros fold-and-thrust belt.

Geological map of the study area after Sissakian et al. (1997) with the positions of the 55.5 km long cross section. The shortening of several short balanced cross-sections is kinematically calculated as (1) 4.5%, (2) 14%, (3) 14%, (4) 15.3%, (5) 16.9%, (6) 14.6%, and (7) 13.5%, which shows an increasing deformation from SW to NE.

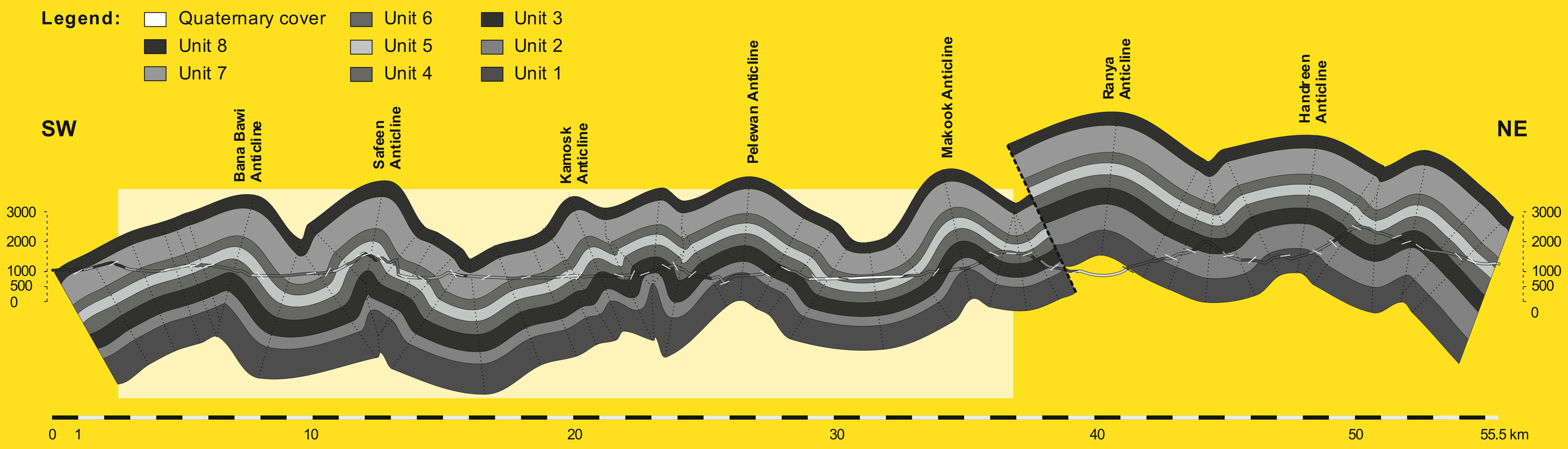
Stratigraphic column of the study area after Sissakian et al. (1997). Formations containing low-shear-strength layers are denoted by asterisks.



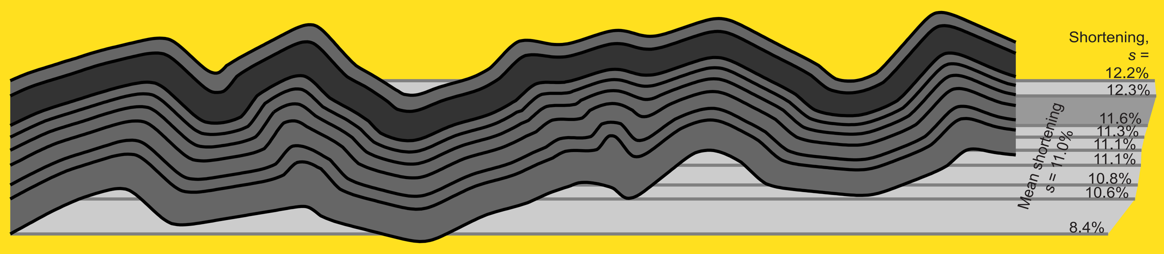
Regional geology
- Precambrian polymetamorphic basement
- 8 im thick sedimentary sequence (starting Late Permian)
- 4 NW-SE striking tectonic zones (Suture Z., Imbricated Z., High Folded Z., Foothill Z.)

Zagros HFZ
- No major detachment
- No evidence of significant faults
- Dominated by harmonic open folds

Balanced cross-sections



Balanced cross-section constructed from field and remote sensing data using the dip domain method. The location of the cross-section is shown in the geological map. The offset of the thrust fault in the NE part of the cross-section is unknown. The part of the cross-section used in the numerical simulations is highlighted in light blue.



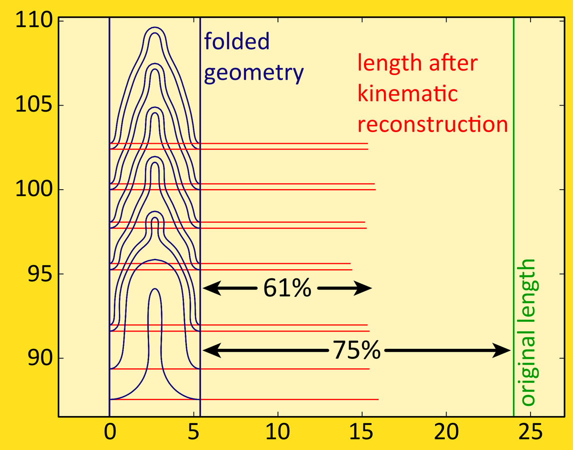
Kinematical unfolding (constant arc length) of the part of the folded profile that is used for the dynamical unfolding simulations.

Kinematical shortening estimates:
- Dip domain method using the whole cross-section: 15%
- Constant arc length method using the part without fault: 11%

Drawback of kinematical reconstruction

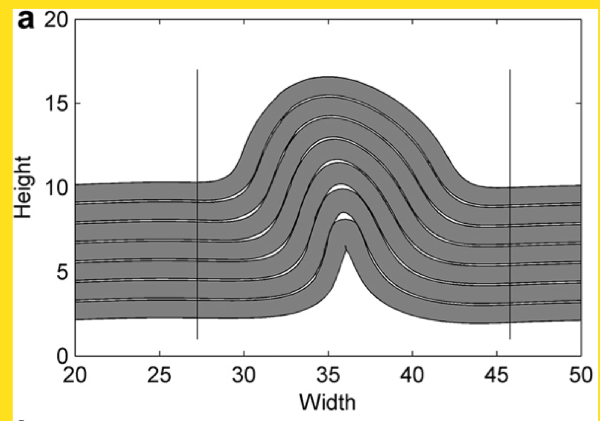
- Purely geometrical (e.g., constant area, constant arc length)
- Many assumptions
- "No physics"
- "No mechanics"
- Pure-shear shortening and thickening prior to buckling initiation is not included in kinematical reconstruction methods

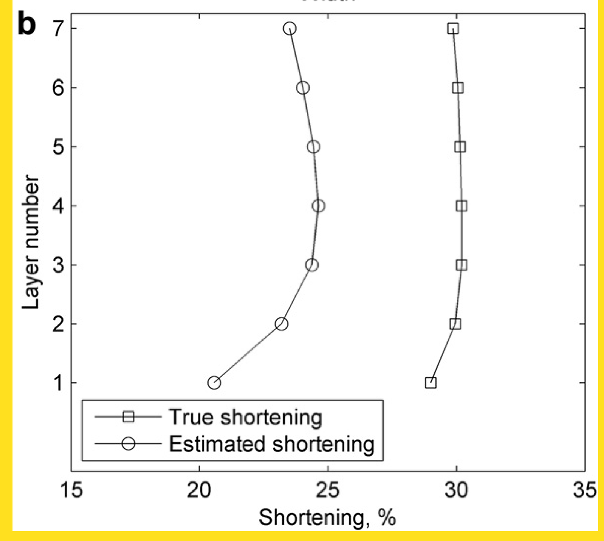
From Lechmann et al. (2010)



Lechmann et al. (2010)
- Numerical forward simulation of Newtonian buckle folding of multilayers (viscosity ratio 1:50) (green to blue in figure)
- Kinematical constant arc length reconstruction (blue to red)
  - Mismatch between the two: 19% average error

Ghassemi et al. (2010)
- Numerical forward simulation of power-law (n=5) viscous buckle folding of multilayers (viscosity ratio 1:100)
- Kinematical constant arc length reconstruction
  - Mismatch between the two: 20% average error

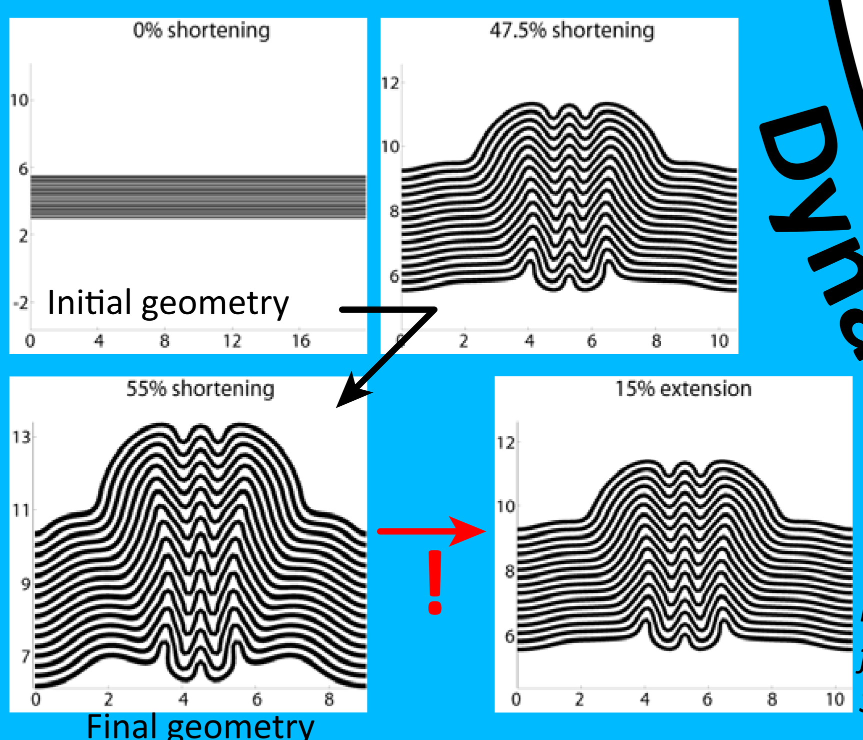




From Ghassemi et al. (2010)

Dynamical unfolding

Basic idea



Figures from S.M. Lechmann

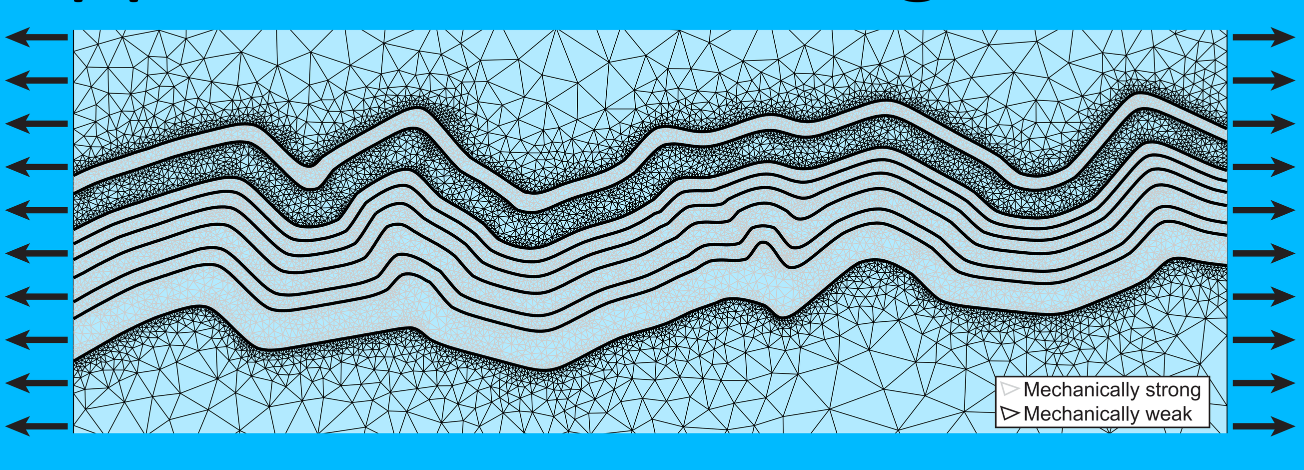
Forward (black arrow):
- Buckle folding from initial geometry to finial fold geometry
- This corresponds to the natural folding.

Unfolding (red arrow):
- Use present-day geometry as initial setup of numerical model.
- Apply horizontal extensional boundary conditions for unfolding.
- Dynamical unfolding simulations correspond to a reverse-time simulation.
- The numerical approach allows including rheological parameters and pure-shear thickening prior to buckling initiation.

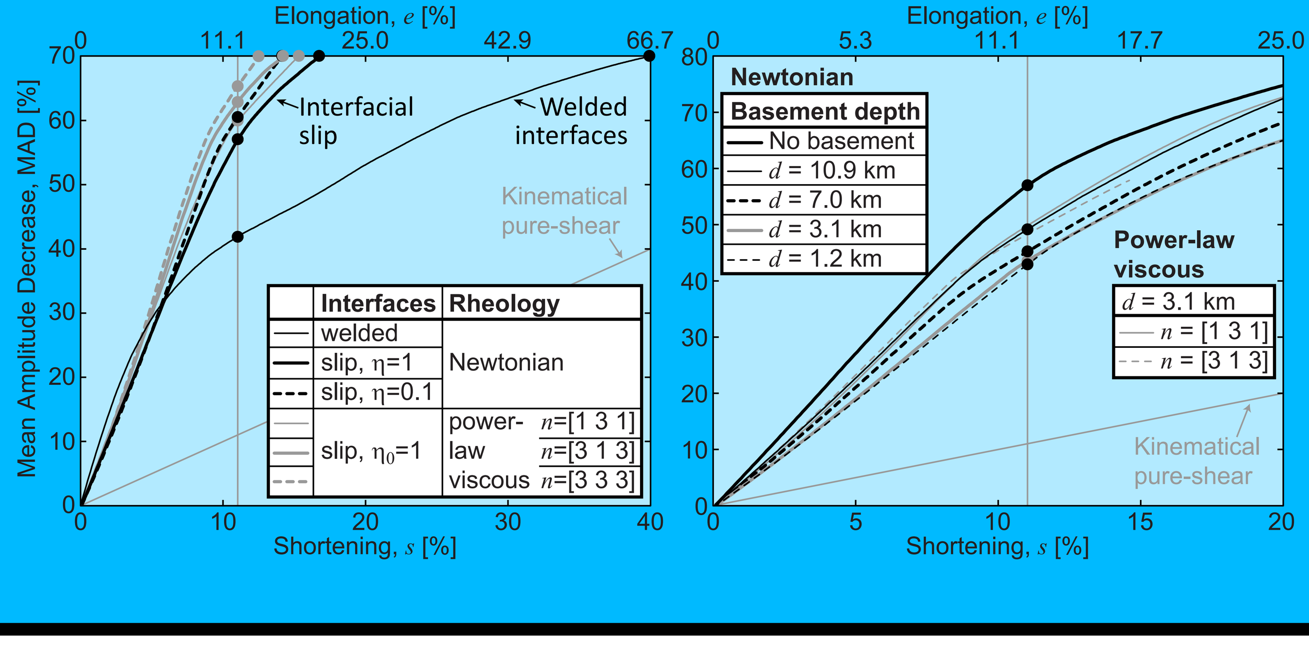
Dynamical unfolding works theoretically in
- 3D for Newtonian media (Schmalholz, 2008) and
- 2D for Newtonian and power-law viscous (n=3) media (Lechmann et al., 2010).

This study is only the second that applies dynamical unfolding to natural folds after Lechmann et al. (2010).

Application to the Zagros HFZ



Geological cross-section discretized with triangular finite-element mesh:
- *Incompressible*
- *Newtonian and/or power-law viscous rheology*
- *Welded interfaces or*
- *Interfacial slip conditions: thin weak layers*
- *Viscosity ratio = 1:100*
- *BC's: base: free slip, top: free surface, left and right: constant horizontal strain rate*



Evolution of fold amplitude during dynamical unfolding simulations without (left) and with basement at depth d (right). Thick black line is the same in both figures.

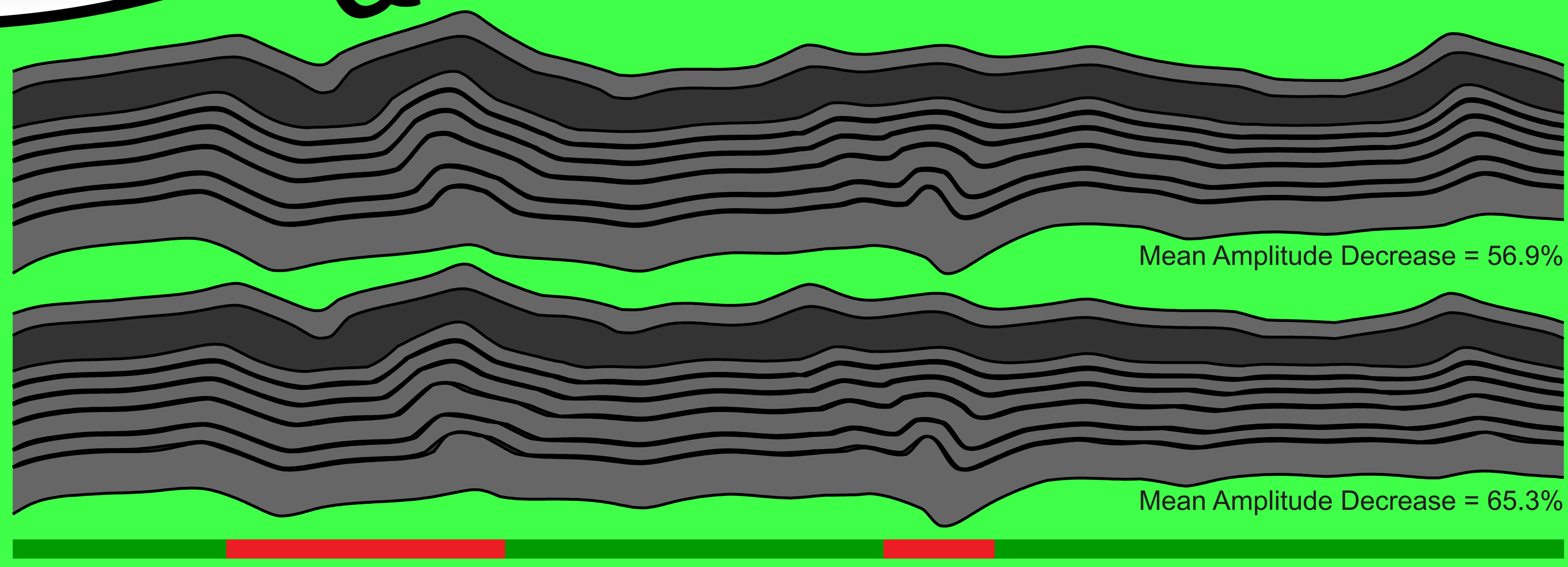
Key Process
- Interfacial slip between lithological units is the key factor for an efficient dynamical unfolding.
- Other processes are of less importance.

Quality control

Drawback of dynamical unfolding

Even though it is possible to efficiently reduce the mean amplitude during dynamical unfolding (see yellow panel), a **complete flattening is not possible** (see figures below). This is due to two factors:
- The geological cross-section (i.e., the inital model for the simulation) is in parts not well constrained or not well constructed.
- Physical processes that take place in nature are not included in the numerical model.

- The first point can be due to sparse or inaccurate geological data or due to the cross-section construction method itself.
- The second point includes various deformation processes, such as brittle fracturing, non-volume conserving processes (e.g., solution-precipitation, compaction), or 3D-out-of-plane deformation



Dynamical unfolding simulations after a horizontal shortening of 11.0% (=kinematical shortening estimate).
Upper: *Newtonian rheology, interfacial slip (thick black line in lower figures in the yellow panel)*
Lower: *Power-law viscous rheology with n=3, interfacial slip (grey dashed line in left figure in the yellow panel)*
Colourbar: *Quantitative rating of cross-section where dynamic unfolding works well (green) and less good (red)*

If dynamic unfolding works well in some and less good in other areas, the numerical results can be used for
- **Quality control of cross-section construction:** Problematic areas in dynamic unfolding results may correspond to parts in the cross-section, which are not well constraied by data or badly constructed. Identifying these parts helps improve the cross-section construction.
- **Planning future field campaigns:** Problematic areas in dynamic unfolding results may exhibit complex geological deformation processes. Identifying such areas helps define interesting targets for future field studies.

Conclusions

- Dynamical unfolding identifies interfacial slip as a key process in the Zagros HFZ.
- Problematic areas in the dynamic unfolding can point out
  - Areas with issues with the initial model ➡ Quality control for cross-section constructions
  - Areas with complex geological deformation processes ➡ Identify areas of interest for future field studies

References

Frehner M., Reif D. and Grasemann B., 2012: Mechanical versus kinematical shortening reconstructions of the Zagros High Folded Zone (Kurdistan region of Iraq), Tectonics 31, TC3002.
Ghassemi M.R., Schmalholz S.M. and Ghassemi A.R., 2010: Kinematics of constant arc length folding for different fold shapes, Journal of Structural Geology 32, 755–765.
Lechmann S.M., Schmalholz S.M., Burg J.-P. and Marques F.O., 2010: Dynamic unfolding of multilayers: 2D numerical approach and application to turbidites in SW Portugal, Tectonophysics 494, 64–74.
Schmalholz S.M., 2008: 3D numerical modeling of forward folding and reverse unfolding of a viscous single-layer: Implications for the formation of folds and fold patterns, Tectonophysics 446, 31–41.
Sissakian V.K., Ibrahim E.I. and Al-Waily I.J., 1997: Geological map of Arbeel and Mahabad Quadrangles, sheets NJ-38-14 and NJ-38-15, State Establishment of Geological Survey and Mining, Baghdad, Iraq.

Acknowledgement
OMV Exploration and Production Company