Mechanical restoration of large-scale folded multilayers using the finite element method: Application to the Zagros Simply Folded Belt, N-Iraq

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[I] ABSTRACT

There is a large number of numerical studies concerned with the evolution of geological folds. Common to all of these studies is the fact that they consider a forward directed time evolution, as in nature. On the other hand, very few reverse-time simulation studies exist. In such studies, folded geological layers are taken as initial conditions for the numerical simulation and the folding process is reversed by changing the signs of the boundary conditions. The goal is to find the geometry before the folding process and the amount of shortening necessary for the final folded geometry. In contrast to kinematic or geometric fold restoration procedures, the described approach takes the mechanical behavior of the geological layers into account. This approach is therefore called mechanical restoration of folds.

In this study, the concept of mechanical restoration is applied to a two-dimensional 50km long NE-SW-cross-section through the Zagros Simply Folded Belt in Iraqi Kurdistan, NE from the city of Erbil. This area is dominated by gentle to open folds and faults are negligible. The cross section is constructed from field measurements and digital elevation models. Massive carbonate rock units act as the competent layers compared to the incompetent behavior of siltstone, claystone and marl layers. First results indicate that a shortening of at least 50% was necessary to create the present-day folded cross-section. This value is higher than estimates from kinematic or geometric restoration.

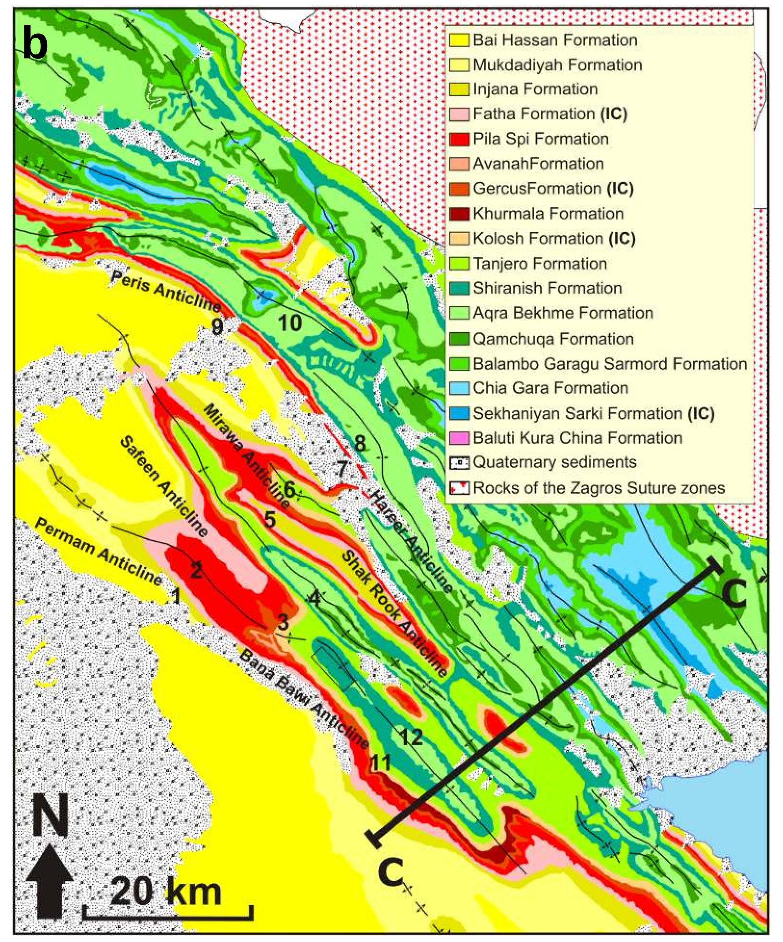
[II] GEOGRAPHICAL AND GEOLOGICAL OVERVIEW

Zagros Suture Zone (overthrusted)

High Folded Zone (simply folded) & Imbricated zones (thrusting)

Foothill Zone (foredeep)

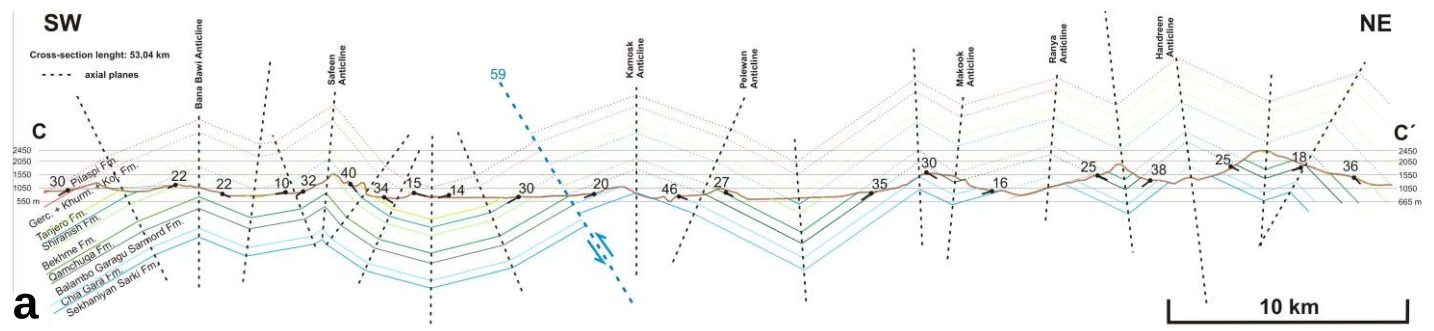
Thrust faulting

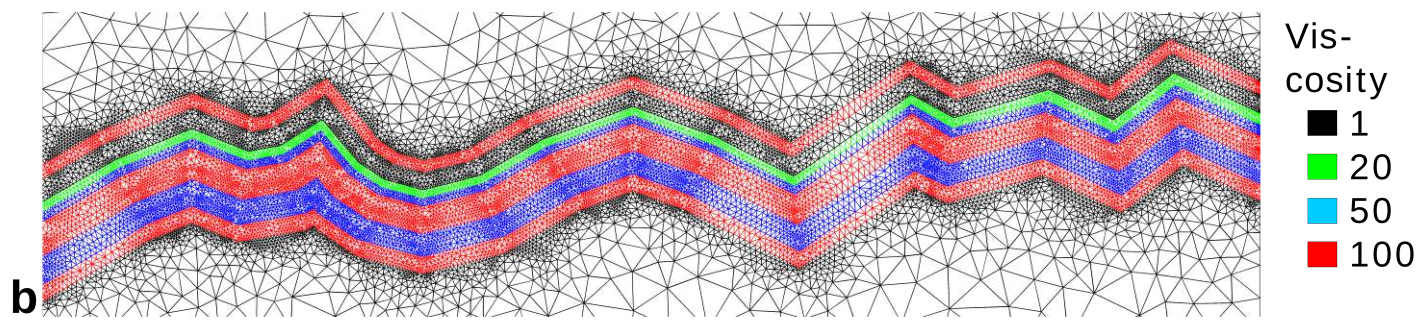


a) Overview of the study area North-East of the city of Erbil, N-Iraq.

b) Geological overview of the Zagros Simply Folded Belt NE of the city of Erbil and the location of profile C-C'. Well visible are the NW-SE-striking fold axes. For further details, visit poster A426 today.

[III] PROFILE C-C'

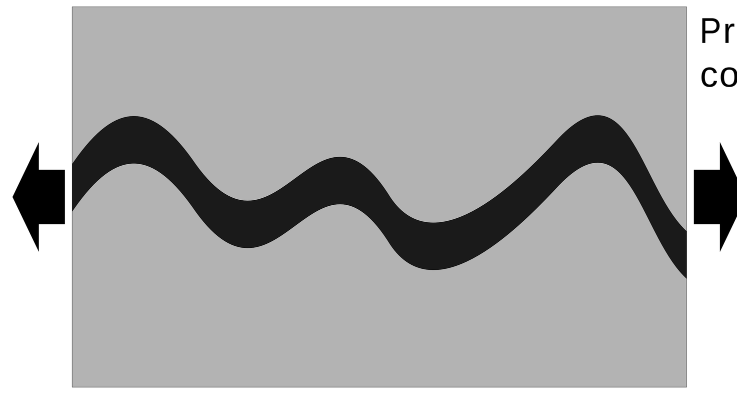




a) Geological profile C-C' constructed using the dip-domain-method. The dip-domain-method leads to sharp corners at fold hinges. These sharp hinges are unnatural and lead to problems during the mechanical restoration (see below). Go to poster poster A426 today for details of the profile construction.

b) Finite element mesh of the profile C-C'. For generating the mesh, the small displacement at the thrust fault (blue in a) is removed from the profile to have continuous layers. Also, the profile is cut at different locations compared to the original profile in a). The profile is cut close to axial planes. This way, modeling results can be improved.

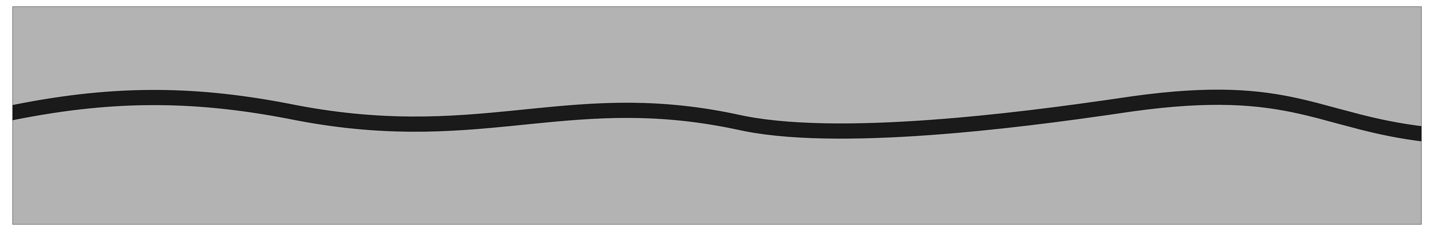
[IV] MECHANICAL RESTORATION



Present-day geometry acts as initial condition of numerical simulation

Applied boundary conditions are opposite to boundary conditions that lead to the folded geometry

A numerical simulation is performed with extensional boundary conditions. In principle, this corresponds to a inverted time simulation.



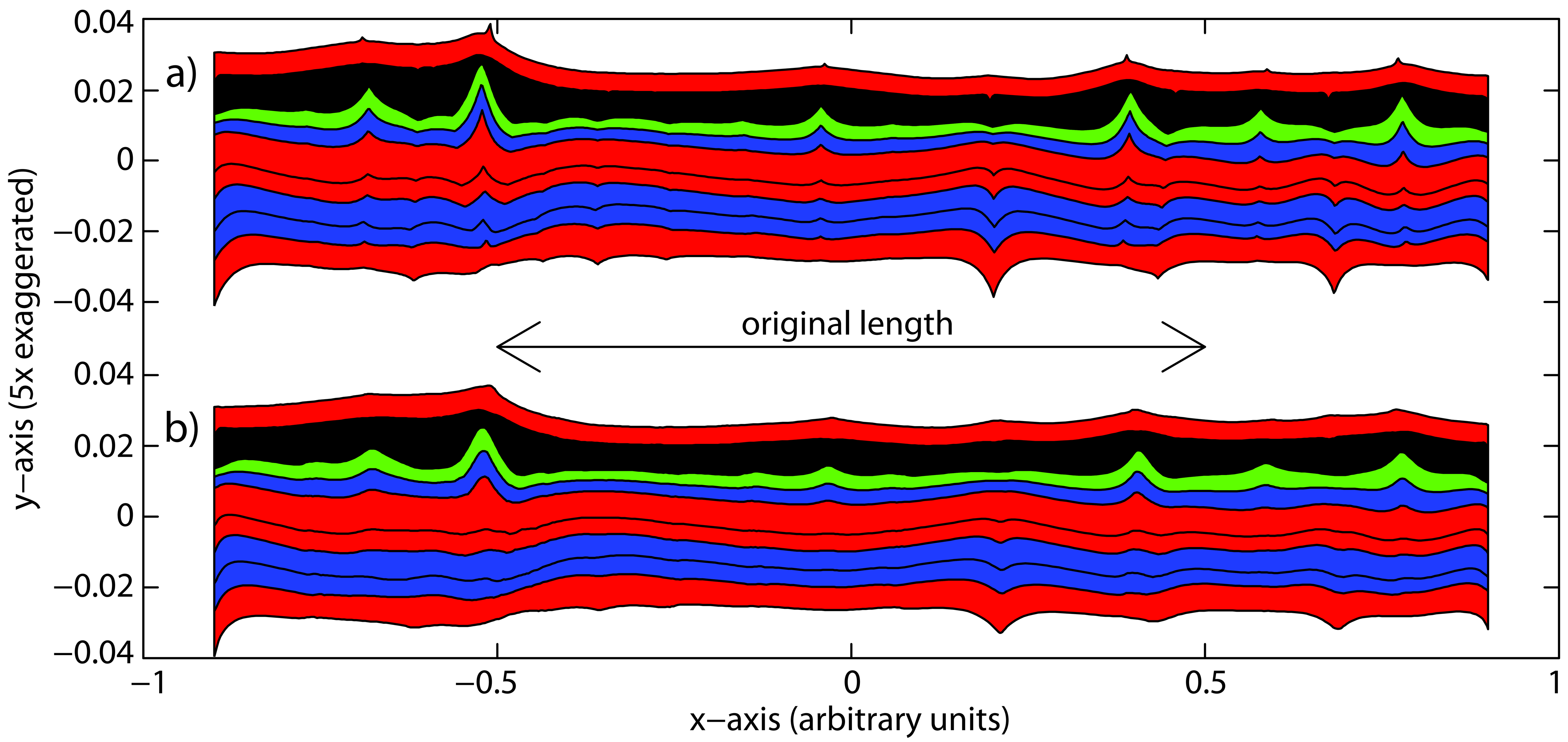
Layers are extended until they are flat. The amount of extension is inverted to get the amount of shortening necessary to deform the flat layers into the original folded geometry.

A criteria for "flatness" has to be defined to stop the simulation!

Numerical method

We use the finite element method for simulating slow deformation of incompressible Newtonian (linear) viscous media. The self-developed code comprises a deforming Lagrangian high-order triangular mesh, mixed v-p-formulation, penalty approach and Uzawa-iteration.

[V] MECHANICALLY RESTORED PROFILES

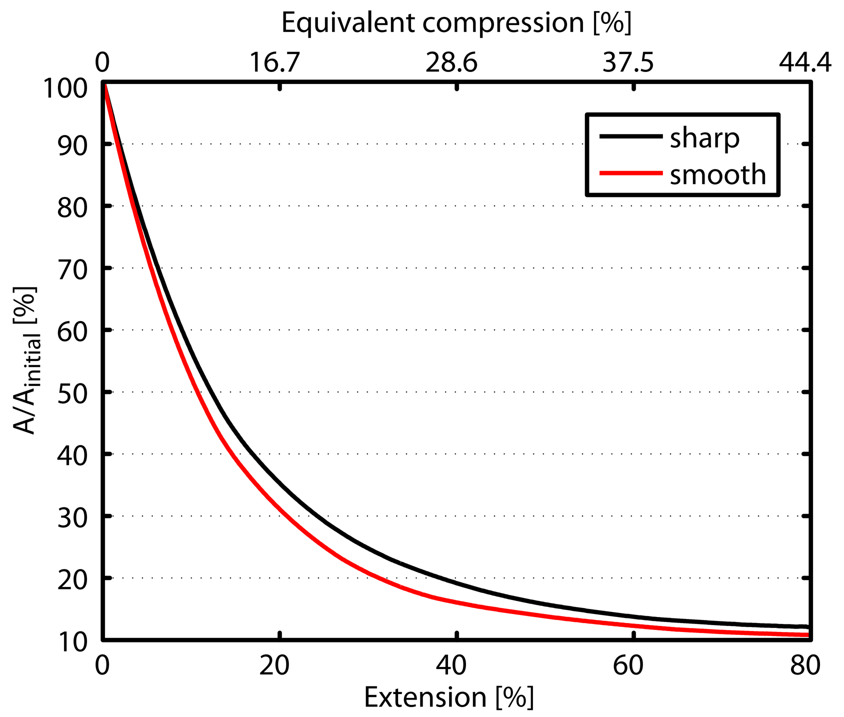


a) & b)
Snapshots of mechanical restoration simulations after 90% extension (corresponds to 47% compression in a forward simulation). Surrounding matrix is not plotted.

a)
Mechanical restoration using the original profile (see above). Initial sharp hinges do not disappear and are still well visible.

b)
A simple corner-smoothing algorithm is applied to the original profile before mechanical restoration. This leads to a smoother result. However, fold hinges still do not disappear.

[VI] FOLD EVOLUTION



Evolution of the mean amplitude of the folded profile during mechanical restoration simulations.

Visualized is the amplitude evolution of the original profile and of the corner-smoothed profile (same as figures to the left).

Both profiles behave almost identical. Also, in both cases, the amplitude evolution curves saturate at around 10%.

[VII] PROBLEMATIC ISSUES

In the presented case study, mechanical fold restoration is unable to fully unfold the folded profile. Possible reasons are:

- Incorrect material parameters (not well known; values had to be assumed)
- Effects in the third dimension that occur in nature but not in the model
- Effects that are not modelled (e.g. solution-precipitation, compaction)

[VIII] CONCLUSIONS

- Mechanical restoration takes the mechanical behavior of individual layers into account.
- Compared to kinematic or geometric fold restoration, mechanical restoration generally predicts larger amounts of compressive strain necessary to generate the folded geometry.
- Mechanical restoration is not yet technically mature enough to be applied as a standard tool. Problematic issues are:
  - Sharp kinks of the folded geometry (e.g. at hinges) never completely disappear when unfolded.
  - Criteria for terminating the unfolding-simulation (i.e. criteria for "flatness") is arbitrary.
- However, mechanical restoration has great potential because it adds information to the analysis of folds compared to kinematic or geometric restoration, and further development of the method is necessary.

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References

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