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Solid Earth
Discussions

Interactive comment on "Towards the application of Stokes flow equations to structural restoration simulations" *by* Melchior Schuh-Senlis et al.

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I have read the manuscript of Schuh-Senlis et al. with great interest, in which the authors propose a *"new approach for restoration based on considering geological materials as highly viscous quasi-static fluids"* (line 6-7).

Developing dynamic restoration techniques is an important topic that may indeed guide structural reconstructions and thus improve simple kinematic restorations. As such, this has been a research topic over the past few decades. Whereas many industry-codes rely on assuming a purely elastic overburden rheology, this does not work well in areas governed by viscous flow. Therefore, alternative approaches have discussed doing this by assuming the rheology to be (nonlinear) viscous.

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To my surprise, however, none of the previous literature on this topic is cited or properly discussed here. The impression that you give in the manuscript that you discuss a 'new' method is clearly incorrect; performing restoration by making the timestep negative and the rheology viscous has been proposed earlier and in multiple papers – even in the context of the Rayleigh-Taylor instability.

It might be that 'old' becomes 'new' after 10-15 years, or that you simply overlooked this in your literature search. Therefore, here a summary of some of the previous work that I believe to be relevant in this context. Links are given to the publications.

Kaus Podladchikov (2001) Forward and reverse modelling of the three-dimensional Rayleigh-Taylor instability. Geophysical Research Letters, Vol. 28 (6), p.1095-1098.
https://doi.org/10.1029/2000GL011789
In this paper, we discussed 3D models of the Rayleigh-Taylor instability, and show that an initial 2D perturbation becomes unstable and breaks up into 3D structures. Importantly, in the same paper (Fig. 4) we also show that one can start from these complex-looking 3D structures and model the structure backwards in time by making the timestep negative to retrieve the initial 2D perturbation (something that is certainly not obvious from looking at the 3D patterns). This paper was limited to iso-viscous cases and was applied to a synthetic case rather than to a natural application.

Ismail-Zadeh, Talbot, and Volozh. (2001). Dynamic Restoration of Profiles across Diapiric Salt Structures: Numerical Approach and Its Applications. Tectonophysics 337, p. 23-38.
https://doi.org/10.1016/S0040-1951(01)00111-1
In this paper, the dynamic restoration method is used for viscous materials in the context of salt tectonics, both for synthetic examples with no slip upper boundary conditions and with erosion/deposition/free-surface conditions (hence very similar to the current manuscript). The models were 2D, but took linear (variable) viscosity into account as well as a depth-dependent density structure. In addition to synthetic examples, they also applied the method to a natural case study in the Pricaspian basin.

Ismail-Zadeh, Tsepelev, Talbot and Korotkii (2004). Three-dimensional forward and backward modelling of diapirism: numerical approach and its applicability to the evolution of salt structures in the Pricaspian basin. Tectonophysics 387 p. 81-103.
https://doi.org/10.1016/j.tecto.2004.06.006
Whereas you do cite this paper in your current manuscript, and thus likely read it, you only mention it in the context of 3D forward models and boundary conditions for salt tectonics. Yet, as the 2001 paper of the same group, it discusses a dynamic restoration method using viscous rheologies and negative timesteps, but this time in 3D (for Newtonian, variable, viscosities).

Lechmann, Schmalholz, Burg and Marques (2010). Dynamic unfolding of multilayers: 2D numerical approach and application to turbidites in SW Portugal. Tectonophysics 494 (1-2), p. 64-74.
https://doi.org/10.1016/j.tecto.2010.08.009
In this paper, the authors demonstrate that the dynamic restoration method also works for cases with a nonlinear (power-law) viscosities, by performing forward and reverse simulations of multilayer stack that produces folds. Using synthetic simulations, the authors demonstrate that it is only possible to retrieve flat layers for the correct viscosity pre-factor and power-law exponents. A subsequent application to a natural case study shows that it mostly works, apart from at a specific location within the folded stack where fieldwork determine that there was a significant amount of out-of-plane flow.

Kocher and Mancktelow (2005): Dynamic reverse modelling of flanking structures: a source of quantitative kinematic information. Journal of Structural Geology 27 (2005) 1346–1354
https://doi.org/10.1016/j.jsg.2005.05.007
This paper is on a slightly different scale, but employs the same time-reverse approach to study the bending of layers around a pre-existing weak zone. Here an analytical solution is employed of a thin ellipse and the authors show that such reverse modelling approach combined with field information gives information about both the amount of

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strain as well as about the boundary condition that were active.

Naiara Fernandez (2014). 2D and 3D numerical modelling of multilayer detachment folding and salt tectonics. PhD thesis, Uni Mainz.
https://dspace-dev.ub.uni-mainz.de/handle/20.500.12030/148446
In chapter 5 of her PhD thesis, which can be downloaded from the address listed above, Naiara Fernandez demonstrates that time-reverse structural restoration method works for salt tectonics with a powerlaw overburden (with n=5), in 2D numerical simulations, and for fully 3D cases with sedimentation/erosion. If the correct parameters are employed, a (nearly) flat salt layer can be recovered whereas clear artifacts occur when, for example, a wrong overburden viscosity is employed.

As the (non-exhaustive) list above thus demonstrates, there is a quite rich literature in dynamic restoration of geological structures using essentially the same or very similar methods to what you discuss in your manuscript. In fact, some papers already studied topics that you mention as being important to address in future research (sedimentation, nonlinear rheologies, 3D). What can perhaps be considered a new contribution in your work is that you show that the methodology works in 2D using adaptive mesh refinement methods, and that you apply it to cases where the free surface does not remain flat.

It is in my opinion part of good scientific conduct to properly discuss and acknowledge previous work and I therefore hope that you will modify the revision version of your manuscript accordingly.

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