

**Performing forward simulations with a free surface using ASPECT & LaMEM:  
comments on Degen et al. (2025)**

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Degen et al. (2025) submitted a manuscript to GMD in which they use a setup based on data of the Alps to simulate the surface velocity and topography that is expected to develop from a layered lithosphere (Degen et al., 2025). The setup involves several layers with linear viscosity and density below a free surface. The results of forward simulations are used to train reduced basis method surrogate models, and a series of simulations are performed in which 1) the density of the layers was varied, and viscosity of the model was kept constant, 2) the viscosity of the layers was varied while the density was kept constant and 3) both viscosity and density are varied.

Whereas model series 1) and 2) gave forward simulations that appear reasonable to Degen et al. (2025), they report large surface velocities in some simulations of series 3). Without having an exact, or independent solution, Degen et al. (2025) conclude that the large magnitude of velocities is likely caused by “numerical instabilities” of the employed software, LaMEM (Kaus et al., 2016). To further elaborate this, Degen et al. (2025) performed simulations using the software ASPECT (Heister et al., 2017) and report very much smaller vertical velocities from LaMEM, which they interpret to be further evidence that there are instabilities in LaMEM.

The difference of the results from ASPECT and LaMEM could be related to the fact that ASPECT uses a free surface condition that is natural to finite element formulations. In contrast, LaMEM uses a “sticky-air” approach with internal surface to approximate the free surface, as that is more advantageous for structured finite difference methods. Therefore, to quantify the discrepancies of the two methods and evaluate the potential magnitudes of “numerical instabilities” (if any), I reproduce some of the forward modelling results of Degen et al. (2025) and provide more details below. The results clearly show that the discrepancies between ASPECT and LaMEM were caused by the incorrect configuration of the numerical ASPECT models in Degen et al. (2025). Perhaps the most important reason for the discrepancies is that Degen et al. (2025) seem to have placed all the materials upside down in their ASPECT simulations. A second issue is that surface velocity fields extracted from some of the simulations were taken at a stage that the models were not yet in isostatic equilibrium. Since these results were used to train a reduced basis method, this raises significant doubts about the validity of the results of Degen et al. (2025). The inappropriateness of the initial configurations used by Degen et al. (2025) could have been spotted upon inspection and plotting of their results.

Below I proceed with a detailed examination of the various models and with comparing both ASPECT and LaMEM results. The discrepancies are also discussed. Finally, this study shows the importance of detailed code documentation, together with uploads of input files, that allows for reproducibility of scientific results.

## **1. Reproducing the ASPECT & LaMEM results of Degen et al. (2025)**

Since both ASPECT and LaMEM pass the same free surface benchmarks (Crameri et al., 2012; Kaus et al., 2010; Rose et al., 2017) as part of their testing suites, the reported significant differences in results for a simple setup with linear viscosities is rather surprising. It is therefore interesting to reproduce their results using the ASPECT and LaMEM input files provided in (Kumar, 2025). The accompanying README file indicates that ASPECT simulations were performed using ASPECT version 2.5.0. Yet, the provided input file did not work with ASPECT v2.5.0 since the output parameter “surface elevation” was only introduced in version 3.0.0 (see <https://github.com/geodynamics/aspect/pull/5563> ). We have therefore commented this out, after which the free surface ASPECT simulation setup worked with v2.5.0 as provided through a Docker image (see <https://aspect-documentation.readthedocs.io/en/latest/user/install/docker-container/installing-docker.html> ). In the sticky air layer setup, we additionally had to comment out the line “set Mesh deformation boundary indicators = top: free surface” since a free slip upper boundary was used.

An additional issue with the manuscript and data files is that it is unclear how the model parameters of the input script “alps\_HR\_84.prm” are linked to the density /viscosity values listed in the file “TrainingParameterAlps\_LHS\_100\_vary\_viscosity\_density.txt”. The parameters used in “alps\_HR\_84.prm” correspond to those listed on line 84 of “TrainingParameterAlps\_LHS\_100\_vary\_viscosity\_density.txt”, but since the first line is a comment, it appears to actually be model 83 of that series. As will be discussed below, the same confusion remains for other simulations. We can thus not state with certainty which parameters were employed in the various figures shown in the manuscript (a clear numbering in the data tables would have been very helpful).

To start, we ran the ASPECT setups as provided. To compare this with LaMEM, we employed the same density and viscosity values for the LaMEM setup. Since only the marker input files were provided for the LaMEM setup (and not the MATLAB or Julia input file to generate them), we can only run this setup on 16 cores with a fixed resolution of 96x96x128 cells. The ASPECT simulation is performed at a much lower resolution of  $16^3$  elements (4096 elements in total). Those are, however, quadratic elements and in the VTK/Paraview visualization,  $32^3$  elements are shown. To run the LaMEM simulations, we employed precompiled binaries of LaMEM and PETSc as provided through the LaMEM.jl package (version 0.4.7). We slightly

modified the options to switch off nonlinear iterations which are not required in this case as the setup consist of linear viscous materials only.

Results are shown in figure 1. Clearly, there is a significant difference between the initial model configurations. Whereas the LaMEM setup has a layered lithosphere directly underneath the free surface, the ASPECT simulations have the initial model setup flipped upside down! The lithosphere is thus lying upside down at 400 km depth, directly above the no-slip upper boundary. This still results in motion of the free surface, but the magnitude is much smaller given the distance of the density anomalies from the free surface and the viscosity of the lithosphere. The fact that the initial setup is upside down is even clearer if we run the simulations forward in time which results in blobs of sticky air rising through the mantle in the ASPECT setup with sticky air (Fig. 1).

To test whether this was simply a mistake with uploading the input setup to Zenodo, or an actual mistake in the manuscript, we made an attempt to reproduce the histogram of Fig. 7 of the manuscript, which shows the vertical velocity in the full model domain for different ASPECT and LaMEM simulation cases. Since the manuscript does not explain *for which timestep* the vertical velocities were extracted, we performed a number of simulations in which we used the input parameters of lines 82,83,84 and 89,90 of the file.

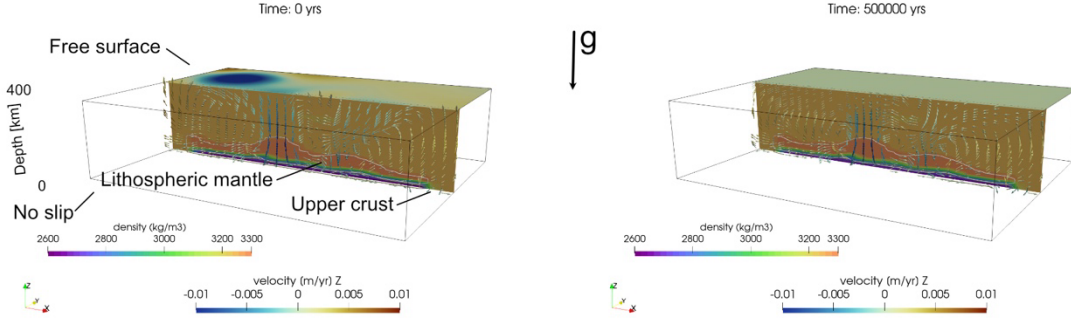
“TrainingParameterAlps\_LHS\_100\_vary\_viscosity\_density.txt” as input parameters. The best match with the histogram on fig. 7 was obtained if we use a very early timestep of the simulation along with the parameters provided in lines 90 and 83 of the input file (which would in that case correspond to realizations 82 and 89 in the manuscript). Timestep 0 of LaMEM simulations is typically the initial guess which employs a constant viscosity throughout the whole model domain and should thus not be used, which is why we show timestep 1.

If we use the results very early on in the simulations (timestep 0 for ASPECT and timestep 1 for LaMEM), the resulting velocities and velocity distributions are similar in magnitude as the ones shown on Fig. 7 of Degen et al. (2025) even though the absolute values of the y-axis of the histogram are different (likely because a different normalization was used). Cross-sections of vertical velocities through the model domain of the different setups confirm that this is consistent with an upside-down model setup (see Figure 2). Velocities at the free surface are much smaller in the ASPECT models because the major density anomalies are located far away from the free surface (and in the vicinity of the no slip lower boundary).

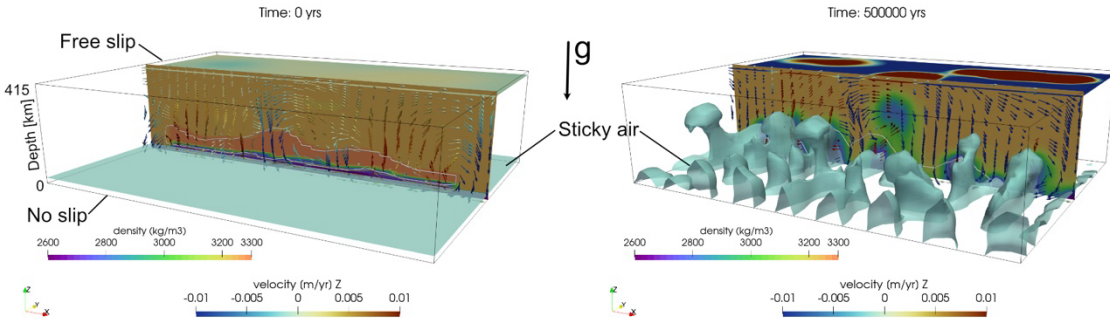
Next, we corrected the input model setup of the ASPECT models and repeated the simulations. In this case, there is a quite good agreement between the ASPECT models with a free surface and the LaMEM models, particularly given the large difference in numerical resolution employed (Fig. 3).

## Realization 84 using setups by Degen et al. (2025)

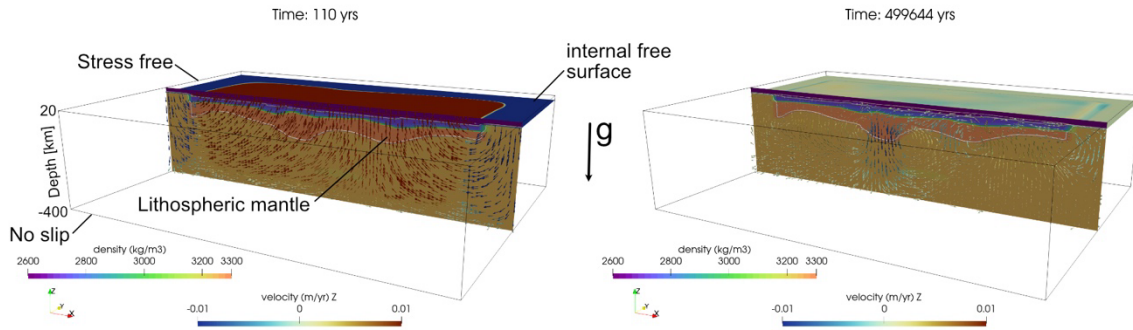
ASPECT & Free Surface



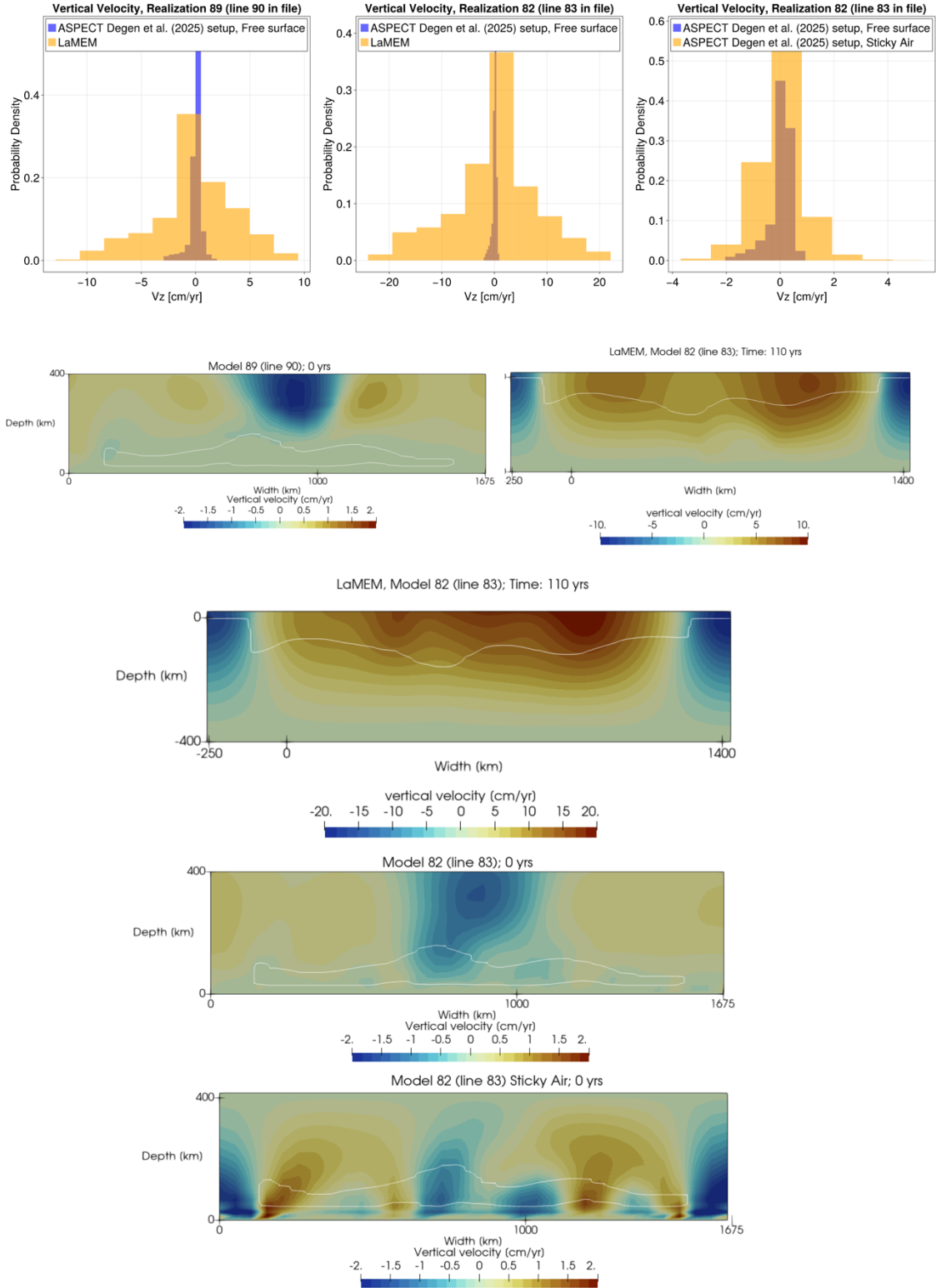
ASPECT & Sticky air



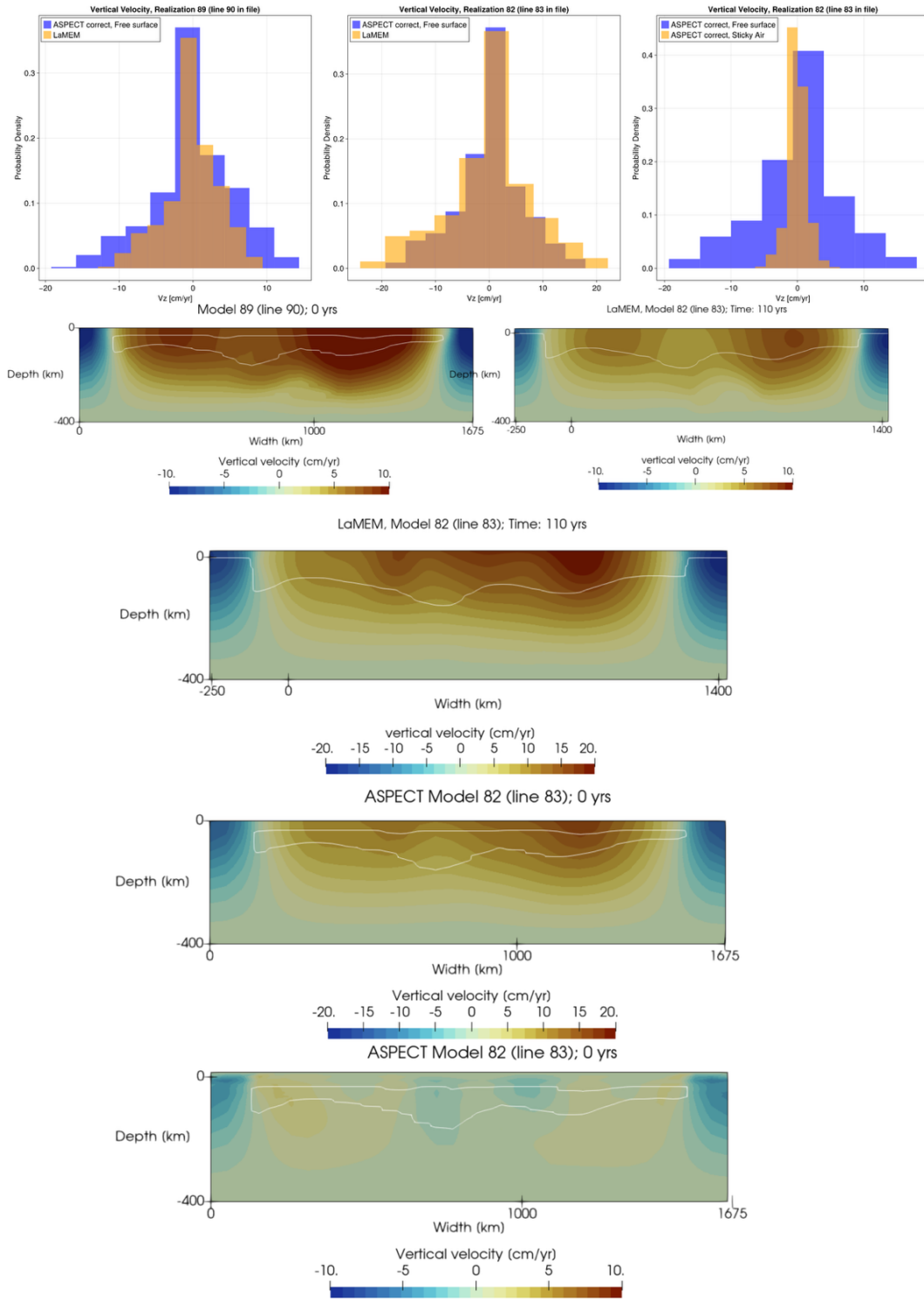
LaMEM & Sticky air



**Figure 1.** Temporal evolution of 3D models of the Alps performed with both ASPECT and LaMEM, as used in the work of Degen et al. (2025). An initial flat topography is employed, with either a true free surface for ASPECT (top row) or with a sticky air layer for ASPECT (middle row) and LaMEM (bottom row). The LaMEM setup shows an initial isostatic balancing stage during which topography builds up, followed by a stage that is dominated by the sinking of the denser mantle lithosphere in the asthenosphere. Clearly, the initial ASPECT model setup is flipped upside down, which results in collapsing of the mantle lithosphere and by the development of plumes (or Rayleigh-Taylor instabilities) of sticky air that rise upwards through the mantle. Note that the ASPECT simulations employ a resolution of  $32^3$  (quadratic) elements whereas the LaMEM simulations employ a resolution of  $96 \times 96 \times 128$  staggered FD cells. See text for further details. The simulations were performed by using the files “alps\_HR\_84.prm” and “alps\_HR\_84\_air.prm” in (Kaus, 2025), taken from (Kumar, 2025) but with correcting typos such that the files are compatible with ASPECT v2.5.0. The LaMEM simulation employs the setup “alps\_lith\_slabs\_400km\_HR\_reg\_HR\_84\_air.dat” provided with the same density and viscosity values as in the ASPECT setup.



**Figure 2.** Histograms of vertical velocity throughout the model domain for ASPECT and LaMEM simulations for model parameters provided on line 90/83 of the parameter file. Absolute velocities of the LaMEM and ASPECT are comparable to those shown on Fig. 7 of Degen et al. (2025), confirming that an upside-down setup was used to generate the ASPECT models. Also shown are vertical cross-sections through the center of the domain with vertical velocity, which shows major differences in velocity pattern and magnitude.



**Figure 3.** As figure 2, but for cases in which we flipped the initial model setup of the ASPECT models in the vertical direction to make it consistent with the LaMEM (correct) initial model setup; the ASPECT files “alps\_HR\_83\_correct.prm” and “alps\_HR\_90\_correct.prm” in (Kaus, 2025) are used for this. Now there is a reasonable agreement between ASPECT models with a free surface and LaMEM simulations, even though the ASPECT models are performed at a considerably lower resolution. The largest differences occur for the ASPECT sticky air models (lower row) vs. the ASPECT free surface models (middle row), which might be because the sticky air layer is only resolved in the vertical direction by a single (quadratic) element.

The conclusion of this comparison is that the Degen et al. (2025) indeed used an upside-down initial model setup for the ASPECT simulations to compare it with a correctly oriented LaMEM setup. It is of course not a big surprise that significant differences occur, which disappear if both setups are correctly oriented.

What was made clear in the present analysis is that both ASPECT and LaMEM provide similar results for the same initial configurations. In the results observed by Degen et al. (2025), without visualizing them, they stated that:

*"Considering the randomness of the observed numerical instabilities in terms of the parameter space, the problems are likely associated with internal numerical aspects, including, for example, the type of advection scheme used, the stabilization of the free-surface (sticky-air), or a combination of both." (line 385)*

*"Thus overall, the results obtained with ASPECT were more stable and closer to the expected solutions than those obtained with LaMEM." (line 396)*

*"The **instabilities** are a consequence of the relatively complex geometry and model set-up, showcasing the importance of the development of more realistic benchmarks to further test current software implementations" (line 402)*

Clearly, the discrepancy in the results of Degen et al. (2025) were not the result of lack of realistic benchmarks, but they rather reflect a lack of scientific rigor and self-critical inspection of their own results.

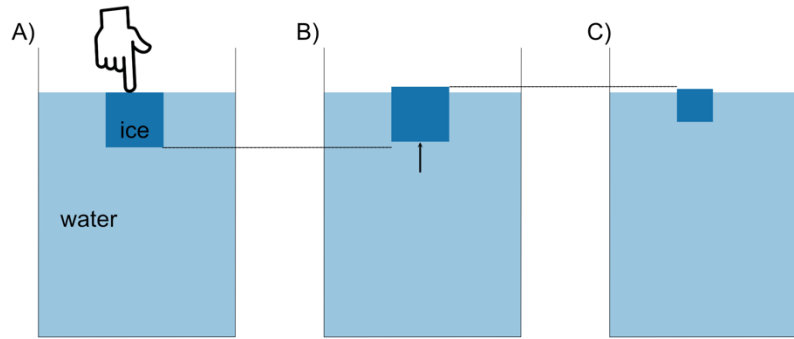
### **Geodynamic simulations involving a free surface**

Degen et al. (2025) report "numerical instabilities" with LaMEM in certain model cases, as discussed in section 4.3, which occurs in cases with variable density and viscosity and not in cases with either variable density or variable viscosity. In those cases, they obtain "unrealistically low heights" and "extreme uplift rates" which are "... in clear contradiction to the low values obtained for the topography for the associated realization...." (line 316-317).

Another important issue at hand is that, based on the reasoning of Degen et al. (2025), the LaMEM simulations are considered correct in some cases but must be wrong in other cases based on some perception on what velocities "should be". In the absence of a true solution (e.g. analytical solution), one cannot trust the result in only half of the cases and ignore the other ones. If the study of Degen et al. (2025) suggest that the code is wrong, then its use on training the reduced order models is not justified and all the training set needs to be re-examined.

Velocities in geodynamic models can certainly be very large if one uses small values of viscosities or large density differences. A simple scaling analysis states that the relevant vertical velocity,  $v_z$ , of a perturbation with amplitude  $A$  and density difference  $\Delta\rho$  scales as  $v_z \sim \Delta\rho g A / \eta$  where  $\eta$  is the viscosity of the material.





**Figure 4.** Illustration of a thought experiment in which an ice-cube is pushed down to the water level (A). If the finger (or load) is removed, it will rapidly rise to reestablish isostasy (B). Melting of the ice will cause its elevation to go down with time which happens on a much longer timescale (C). The initial geodynamic model setup used in Degen et al. (2025), starts with a low-density lithosphere that has an initially zero topography. Likewise, the simulations first have to re-establish isostatic equilibriums before the geodynamic effects become visible.

What seems to be the issue here is another factor, which is that the initial setup has lithospheric density anomalies but an initial zero topography. This model is very far from isostatic equilibrium. To illustrate the importance of such a setup, we will consider a very intuitive analogue (Fig. 4). This analogue setup is the case of loading an ice cube just underneath the surface in a glass of water (see figure above, stage A). If the load is removed, the ice cube will rise rapidly, until it reaches the well-known isostatic formula for ice in water (B). After this initial stage, the ice cube will start melting which will slowly lower the elevation of the top of the ice-cube with time (C). In this case, melting the ice cube is used to emphasize that density redistribution will lead to the relaxation of the topography. The first stage (from A to B) is an artefact of the initial model configuration that does not guarantee isostatic equilibrium at time zero (“pushing the ice-cube down”). The second stage (from B to C) is the one we are interested in, if we wish to understand how dynamic processes affect the surface topography (of either the ice cube or the lithosphere). The initial configuration that Degen et al. (2025) use is of course not identical to that of ice & water. Yet, the features that occur are broadly similar.

The effect of mass redistribution and topography relaxation can be investigated using the setup 82 (line 83 of the parameter file) of figure 3, for both ASPECT and LaMEM simulations. Initially, the simulation is dominated by vertical motion during which the topography builds up (Figure 5). Very typical of this stage are very large vertical velocities which are  $>15$  cm/yr in this case but can be up to meters/year in other initial configurations depending on the employed viscosity values. After a while, the velocity pattern is dominated by the geodynamic processes we are interested in. Only at this stage, results can be interpreted in a geodynamic manner. The ASPECT and LaMEM results are broadly consistent with each other (particularly given the much lower resolution employed in ASPECT).



Indeed, if we consider the vertical surface we see very large velocities during the initial stages, which become smaller at later model stages (Fig. 6), with somewhat similar patterns.

Most computational geodynamicists have observed this effect in simulations with a free surface. For example, in subduction zone simulations with a free surface, the typical subduction velocity patterns develop only after the topography of the continent has risen sufficiently. The isostatic adjustment stage is also discussed in a free surface benchmark study where all codes experience a quite similar trend with rapid initial uplift for case 2 (Cramer et al., 2012).

The duration of the isostatic adjustment stage is not the same in every situation. During a previous study together with T. Baumann, we performed probabilistic inversions for lithospheric rheological parameters to fit to the observed topography and surface velocity of the India-Asia collision zone (Baumann and Kaus, 2015). As in the current manuscript, different viscosity and density structures required a different waiting time until the isostatic balancing stage was over. At the time, we employed a heuristic criteria to distinguish the two stages (Baumann and Kaus, 2015); yet there is certainly room for additional (new) quantitative criteria for this. In absence of such criteria, one can either wait sufficiently long or manually check all simulations. The duration of the initial isostatic balancing stage largely depends on the employed viscosity and density structures, as well as on values employed in the sticky air approach. It is therefore not possible to indicate a generally valid waiting time; yet what helps is to start with an initially small timestep which is slowly ramped up until it reaches a maximum value. This is the recommended approach for LaMEM and used in the [subduction examples](#) for example, and is also suggested in the ASPECT documentation when they discuss [free surface setups](#).

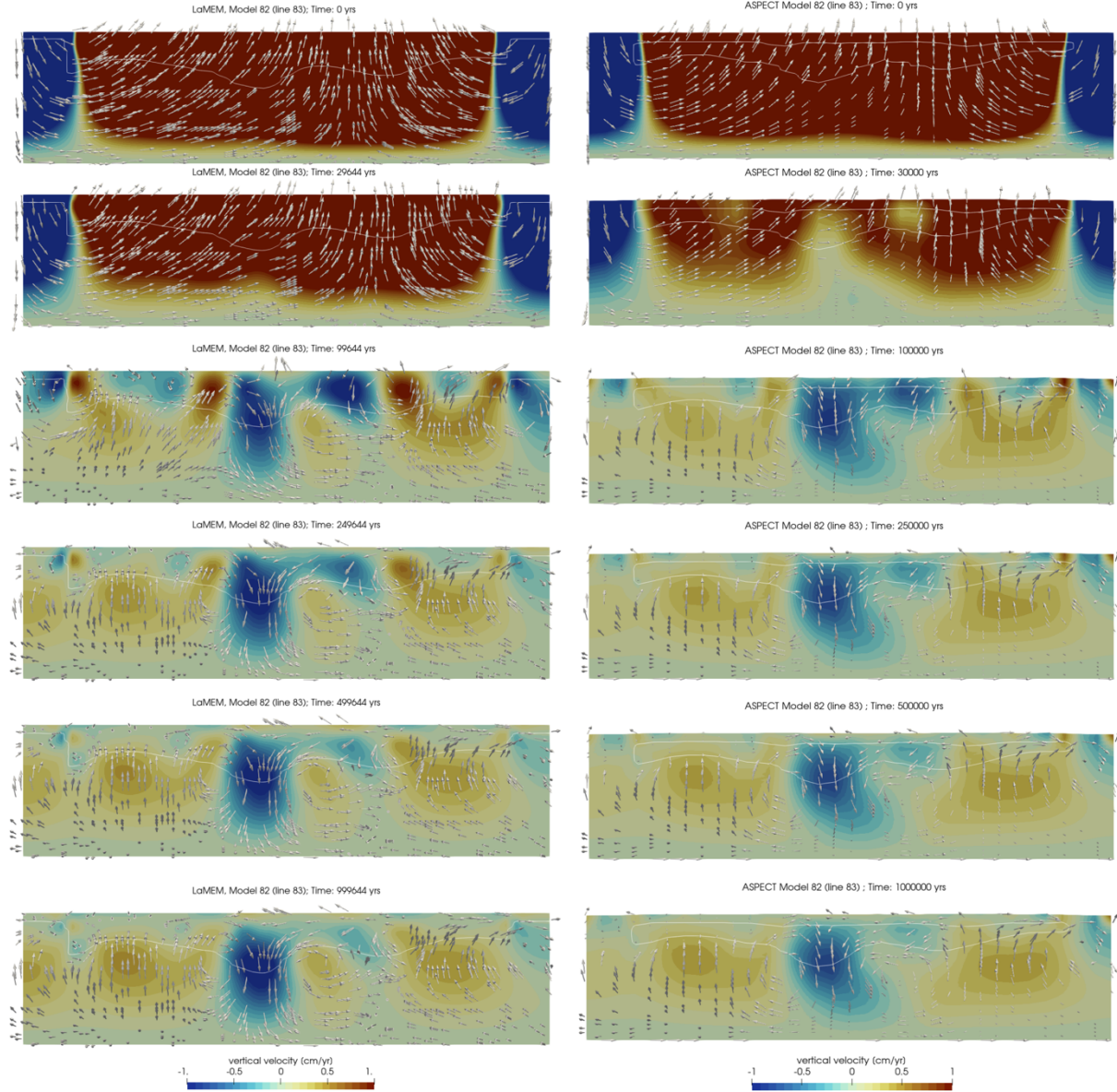
Some readers may wonder why we don't use models that start with an initial nonzero topography (say constructed following Airy isostasy). That is of course possible; yet a key assumption that underlies Airy isostasy is that lithospheric columns deform independently of each other – a situation that is only reached when the viscosity of the mantle and lithosphere is zero. The finite viscosity of the lithosphere on Earth results in a regional deformation if columns are moved upwards. In my experience, starting with an initial zero topography causes fewer small-scale velocity perturbations, but both situations can be performed.

## LaMEM Model 82

96x96x128 resolution

## ASPECT Model 82

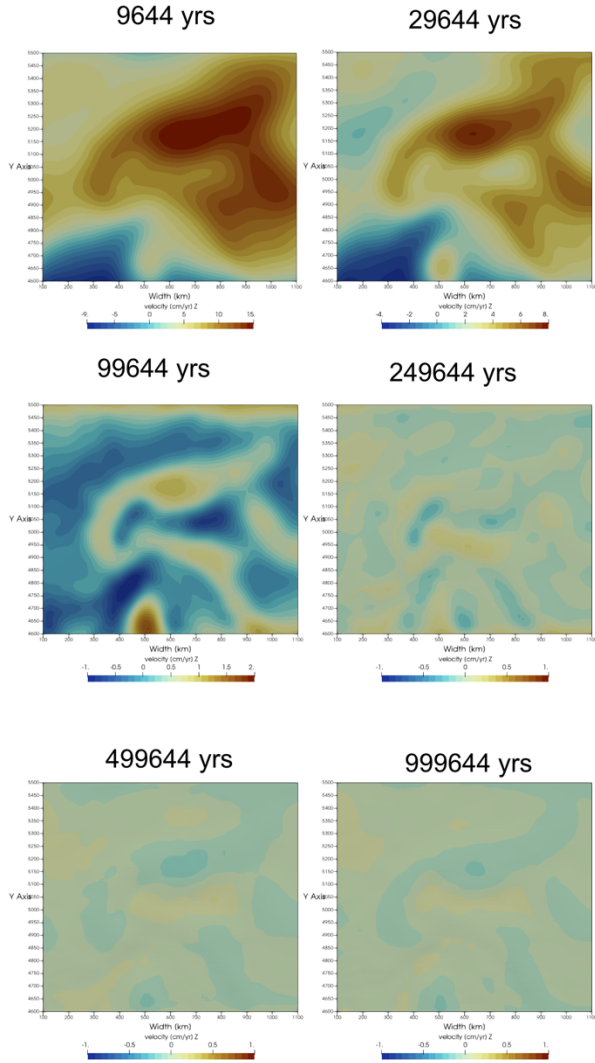
corrected setup - 16x16x16 resolution



**Figure 5.** Temporal evolution of a vertical velocity along a vertical cross-section through the middle of the model domain of model 82 (figure 3), with a corrected ASPECT setup that employs a free surface. Initially, the free surface (ASPECT) or internal free surface (LaMEM) rises, for the model to re-establish isostatic equilibrium. After some time, this transitions into a case where the surface topography is not dominated by isostatic equilibrium but by dynamic processes. Here this occurs somewhere between 100 and 250 kyrs. The transition between stage 1 (rebound) and stage 2 (dynamic processes) depends on the employed viscosity and density values and is not always clearly defined.

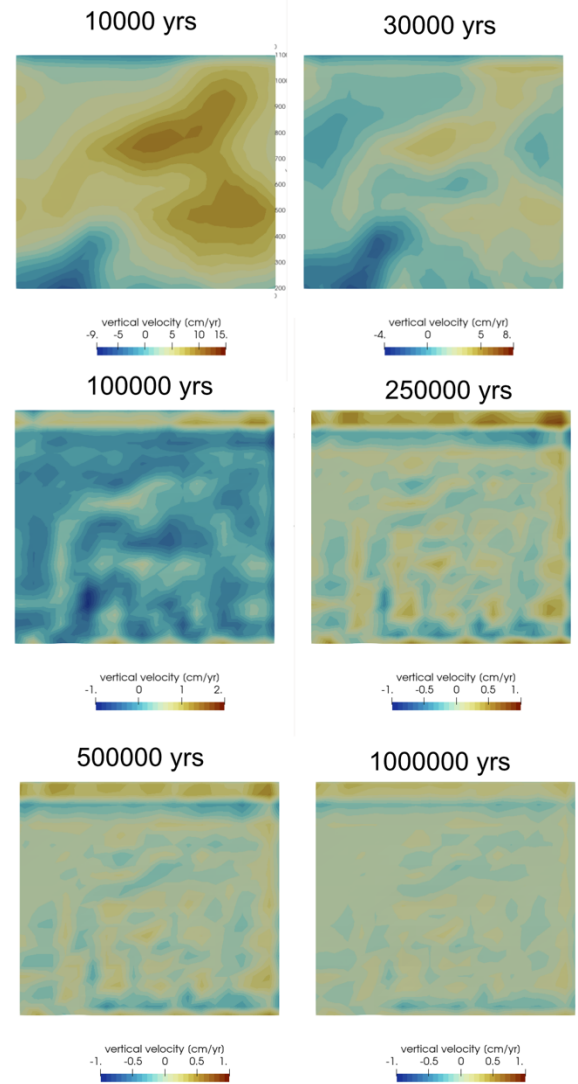
## LaMEM Model 82

96x96x128 resolution



## ASPECT Model 82

corrected setup - 16x16x16 resolution



**Figure 6.** Temporal evolution of the surface velocity of the LaMEM and ASPECT models shown in Fig. 4. During the initial isostatic balancing stage, vertical velocities are very large which is an artefact of the model setup. Once the topography is roughly in isostatic balance, velocities are smaller. Note that surface velocities will only become zero once there is no dynamic motion more in the model (that is when all layers stratified with respect to their density and no far field stresses are applied – lithostatic limit).

Comparing our results as shown on Fig. 6 to those in the manuscript of Degen et al. (2025) (e.g. their Fig. 7, model 82) gives roughly consistent results and velocity patterns. The initial, non-balanced, stages are characterized by small topographies and large surface velocities. The “numerical instabilities” reported by Degen are therefore most likely not instabilities but the result of a non-balanced initial model setup along with terminating the simulation at a

very early stage. Running the model for a longer period of time (and with correct initial layer configuration) should resolve this.

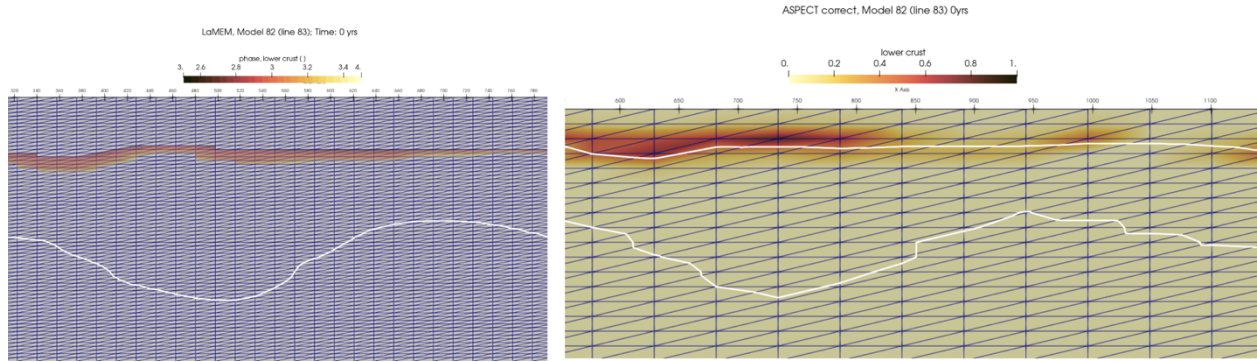
True numerical instabilities can indeed occur in numerical modeling, as exemplified by the drunken sailor instabilities that may arise when explicit timestepping algorithms employ excessively large timesteps (Kaus et al., 2010). However, these instabilities are easily identifiable due to the abrupt sign reversal of the velocity field between consecutive timesteps. Fortunately, stabilization methods can enable the use of larger timesteps (Kaus et al., 2010; Rose et al., 2017), which is the default setting in LaMEM. The feature that Degen et al (2025) attribute to a “numerical instability” appears to be a density (or physical) instability instead, characterized by a relatively smooth evolution of the velocity with time which is correctly captured by both the (corrected) ASPECT and LaMEM simulations (as depicted in Fig. 6).

## **Resolution tests**

The manuscript of Degen et al. (2025) lacks resolution tests. It’s well-known that numerical models are approximations of the governing partial differential equations (Gerya, 2019). Therefore, it’s crucial to ensure that the resolution is adequate for the processes being studied (Van Zelst et al., 2022). In the context of this paper, this involves verifying that the timestep is appropriate, that the grid cells are sufficiently small, and that the thickness and viscosity of the sticky air layer doesn’t significantly impact the surface topography or velocity.

### *Spatial resolution*

The LaMEM simulations used a fixed resolution of 96x96x128 staggered finite difference cells, which implies a vertical resolution of around 3 km in the crust (as no grid refinement was employed). Some of the lithospheric layers appear to be only 5-10 km in thickness, and depending on the setup, this may further thin with time (in some setups the mantle lithosphere has a lower density than the asthenosphere, resulting in thinning of crustal layers). As a rule of thumb, one needs around 5-10 gridpoints to resolve viscosity or density heterogeneities so the employed resolution is likely insufficient (Fig. 67). The ASPECT simulations use only 16 quadratic elements in the vertical direction with a regular grid spacing, which implies a 25 km resolution. Viscosities within a higher-order finite element must be smoothly varying to avoid numerical artefacts (Deubelbeiss and Kaus, 2008; Thieulot and Bangerth, 2025, 2022), which makes it certainly somewhat questionable whether the crustal layers in Degen et al. (2025) are appropriately resolved.



**Figure 7** Illustration of how the lower crustal layer is resolved in the LaMEM (left) and ASPECT (right) simulations for the models shown in Fig. 5 & 6. Note that the triangles are an artefact of the ParaView visualization as both codes use quadrilateral cells; the size of the elements in LaMEM is correctly represented, whereas the ASPECT output divides every quadratic element into 8 sub-elements for visualization purposes, so the actual finite element is twice coarser than what is shown here. LaMEM uses a marker and cell approach to track material parameters, whereas ASPECT employs a field-based advection approach in this setup.

Since Degen et al. (2025) only uploaded the marker files for LaMEM, but not the MATLAB or Julia scripts that generated them, I was not able to perform resolution tests with the data provided. For ASPECT cases this is in principle possible as ASPECT can use low resolution input grids as input for higher resolution simulations (e.g. using a piecewise constant interpolation method); yet, this would not appropriately resolve thinner crustal layers.

It should also be remarked that neither LaMEM nor ASPECT are ideal codes for the setup studied in this work, which involves sharp and sudden viscosity jumps and limited deformation. A higher numerical convergence rate is obtained with unstructured finite element codes that exactly mesh the viscosity jumps (Deubelbeiss and Kaus, 2008; Thieulot and Bangerth, 2025), which thus require fewer elements to resolve individual viscous layers.

### *Temporal resolution*

The LaMEM setup uses a maximum timestep of 200 years, whereas the ASPECT free surface setup uses a timestep of 1000 years. No timestep convergence tests are shown in the manuscript of Degen et al. (2025). For this reason, I repeated the simulation using a setup in which the initial timestep of 100 years was allowed to ramp up until a maximum of 20kyrs which gave fairly similar results, suggesting that the authors could potentially speed up the simulations quite significantly (if this applies to other cases as well). Yet, it is a good idea to formally demonstrate this.

### *Sticky air thickness*

The sticky air layer has been the focus of a benchmark study in which finite element and various codes with a sticky air layer were compared with each other (Crameri et al., 2012). The previous paper showed that the sticky air method gives reasonable results if it is sufficiently thick and has a sufficiently low viscosity. A non-dimensional parameter,  $C_{isost}$ , was suggested to be a useful criterion in this context:

$$C_{isost} = \frac{3}{16\pi^3} \left( \frac{L}{h_{st}} \right)^3 \frac{\eta_{st}}{\eta_l}$$

Here  $L$  is the width of the model (here the one of the uplifting lithosphere),  $h_{st}$  the thickness of the sticky air layer,  $\eta_{st}$  its viscosity, and  $\eta_l$  the viscosity of the lithosphere. The analysis was done for the relaxation of a topographic perturbation and numerical simulations indicate a reasonably good agreement with numerical simulations when  $C_{isost} < 1$ . For the given model parameters indicated in this study ( $L \sim 1200\text{km}$ ,  $h_{st} = 20\text{km}$ ,  $\eta_{st} = 10^{18}\text{Pas}$ ,  $\eta_l \sim 10^{20} - 10^{23}\text{Pas}$ ), we obtain  $C_{isost} = 0.0131-13.1$ . In some cases, this is therefore likely fine, but in others perhaps not following this rule.

There are differences, however, between the LaMEM simulations and the earlier models used in the Crameri et al. (2012) study that employed free slip boundary conditions above the sticky air layer. LaMEM uses a stress-free upper boundary condition if the “open\_top\_boundary” option is activated (as is the case in the uploaded LaMEM input file). Such a stress-free condition allows for in- and outflow, which is less restraining than a layer with free slip top boundary (this effect is also clearly visible in Figure 4). Accordingly, it is likely that satisfying results can be obtained for larger values of  $C_{isost}$ . A convergence test for the given setup using the extreme values of  $\eta_l$  employed in this study will clarify this.

### **Making data available & using open source software**

I commend the authors for uploading the input files of the forward models, which were crucial for reproducing the research results, even though the model description could have been clarified. This highlights the significance of making such data accessible in geodynamic studies, which will ultimately advance our community.

The reproduction of the results also highlights the fact that open source geodynamic codes cannot be used blindly but require verifications for the application at hand, along with some training in computational geodynamics.

ASPECT was developed from the onset to be an open-source community code and received funding for this purpose by the NSF through the Computational Infrastructure in



Geodynamics (CIG). LaMEM, on the other hand, was mostly developed at the University of Mainz for research applications and has not received dedicated funding to become a community code. Like ASPECT, many years of development have gone into it, and the code is available under an open source license (and certainly welcomes contributions or issues from users). Yet, given the difference in dedicated funding, the documentation of ASPECT is logically much more extensive than that of LaMEM.

As with any software, LaMEM may also have mistakes or bugs that haven't been identified yet. The normal way to deal with that in the open-source software community is to open an issue on the respective github/gitlab page to discuss it, such that other users of the software can also benefit from the discussion.

Lightly made and clearly unfounded claims about “numerical instabilities” of a particular software in a submitted manuscript (or even worse, a paper) are deeply disturbing, even if it is later claimed that the software may still be useful for the community (line 400 and onwards). If the authors of a manuscript still believe it is necessary to make such statements about software packages to which they did not contribute, the least they should do is make their utmost efforts to avoid mistakes on their end and double-check all results before submitting. Following the guidelines of good research practice of the German research foundation which appears to have funded this work (Deutsche Forschungsgemeinschaft, 2025), I would have expected *all four authors* to participate in verifying the numerical results. This would have made it highly likely that at least one of them had spotted that the ASPECT simulations were upside down.

## Summary

Degen et al. (2025) presented new geodynamic model results that were used to train reduced-order models. I have shown that these results were incorrect due to inappropriate initial model configuration and in considering of isostatically non-balanced results. In particular:

- a) The ASPECT simulations, which were used to demonstrate that LaMEM must have “numerical instabilities,” use an initial model setup that is flipped upside down. If the initial geometry is corrected to match the LaMEM setup, the results of LaMEM and ASPECT are quite consistent, especially considering the much lower resolution used in the ASPECT simulation. This error in the model setup is easily detectable by simply viewing the \*.vtu output files created by ASPECT.
- b) Contrary to Degen et al. (2025), we don't observe numerical instabilities in the LaMEM forward simulations. Instead, the large vertical surface velocities observed during the early stages of the simulations are a natural and physical consequence of initiating



simulations with a flat initial topography. It takes time for such models to re-establish isostatic balance. Afterwards, the density differences between different lithospheric layers and the asthenosphere induce further surface deformation, leading to dynamic topography changes. Consequently, the initial, rapid vertical uplift stage should not be interpreted geodynamically because it results from a highly artificial initial configuration. The duration of this initial isostatic balancing stage varies among simulations and is particularly sensitive to the viscosity of the setup. Therefore, verification of the model output is necessary to ensure that one is beyond the initial isostatic adjustment phase.

- c) Degen et al. (2025) do not specify the time point at which they extract the surface velocities from their forward LaMEM simulations. Examining their figures strongly suggests that in certain instances, they rely on results from cases that are not yet in isostatic balance (refer to their figure 6, for instance).
- d) No resolution tests are presented. Since some of the crustal layers appear to be relatively thin compared to the vertical resolution of the LaMEM/ASPECT simulations, they may be unresolved. Additionally, resolution tests for the sticky air and the timestep are lacking.
- e) While trying to reproduce their models, I noticed that there is significant confusion about the parameters used in the simulations as shown in the figures and the uploaded data files, because the employed model numbers are not listed in the parameter tables.
- f) ASPECT input files as provided do not work with version 2.5.0 of ASPECT.

The idea of utilizing the output of geodynamic simulations to train reduced-order models, which is the focus of this manuscript, remains valid. However, it is crucial to use scientifically meaningful forward modeling results as input for this workflow. The forward models employed in the current version of the manuscript thus require either redoing or a careful re-analysis. In its current state, the paper cannot be accepted. However, with significant additional work and rigorous resolution tests, it could become a valuable scientific contribution.

### **Open data**

The input scripts for the LaMEM and ASPECT simulations (corrected such that they work with ASPECT v2.5.0) are made available in a permanent Zenodo repository (Kaus, 2025).

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