A 2D/3D numerical modelling benchmark of slab detachment

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Introduction

Subduction is likely to be the most studied phenomenon in Numerical Geodynamics. Over the past 20 years, hundreds of publications have focused on its various aspects (influence of the rheology and thermal state of the plates, slab-mantle coupling, roll-back, mantle wedge evolution, buoyancy changes due to phase change, ...) and results were obtained with a variety of codes.

Slab detachment has recently received some attention but remains a field worth exploring due to its profound influence on dynamic topography, mantle flow and subsequent stress state of the plates, and is believed to have occured in the Zagros, Carpathians and beneath eastern Anatolia, to name only a few regions.

Following the work of Schmalholz (EPSL, vol. 304, 2011), we propose a two- and three-dimensional numerical benchmark of slab detachment. The geometry is simple: a power-law T-shaped plate including an already subducted slab overlies the mantle whose viscosity is either linear or power-law. Boundary conditions are free-slip on the top and the bottom of the domain, and no-slip on the sides.

When the system evolves in time, the slab stretches out vertically and shows buoyancy-driven necking, until it finally detaches. The benchmark is subdivided into several sub-experiments with a gradual increase in complexity. An array of objective measurements is recorded throughout the simulation such as the width of the necked slab over time and the exact time of detachment. The experiments will be run in two-dimensions and repeated in three-dimensional, the latter case being designed so as to allow both poloidal and toroidal flow.

Numerical setup

In this work, we assume that all materials (unless stated otherwise) are incompressible and obey the following mass and momentum conservation equations:

$$\nabla \cdot v = 0 \qquad \nabla \cdot \sigma = \rho g \tag{1}$$

Temperature effects are not taken into account. The stress tensor σ can be decomposed as

$$\sigma = -p\mathbf{1} + 2\mu\dot{\epsilon} \tag{2}$$

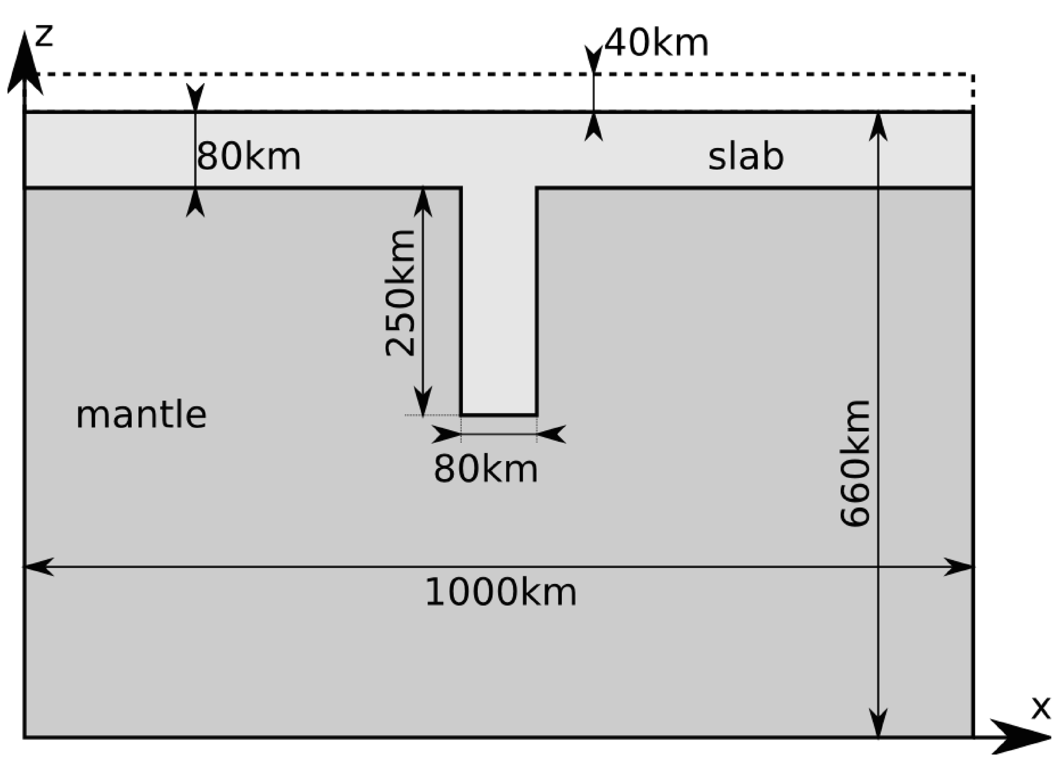
and fluids are either linear viscous (Newtonian) and therefore described by a unique dynamic viscosity μ or nonlinear viscous and therefore described by means of a power-law equation which yields the following effective viscosity:

$$\mu_{eff} = \frac{1}{2} A^{-1/n} I_2^{1/n-1} = \mu_0 I_2^{1/n-1} \tag{3}$$

where A and n are material constants and I_2 is the square root of the second invariant of the deviatoric strainrate

The computational domain is 1000×660km. No-slip boundary conditions are imposed on the sides of the system while free-slip boundary conditions are imposed at the top and bottom. The total run time is fixed at $t_c = 22.56Myr$. Computed effective viscosities are kept within the range $10^{18}Pa.s$ and $10^{25}Pa.s$.

Two materials are present in the domain: the lithosphere (mat.1) and the mantle (mat.2). Their geometry is shown hereunder:



The overriding plate (mat.1) is $80km$ thick and is placed at the top of the domain. An already subducted slab (mat.1) of $250km$ length hangs vertically under this plate. The mantle occupies the rest of the domain.

Codes & Participants

- ASPECT (A. Glerum):
- ELEFANT (C. Thieulot): resolution 400x280
- FEMS-2D (S. Schmalholz):
- FLUIDITY (R. Davies, C. Wilson and S. Kramer)
- SEPRAN (B. Hillebrand):
- SLIM3D (J. Quinteros and S. Brune):
- SULEC (S. Buiter): resolution 500x330
- TIB2D (T. Duretz): 300x400

Numerical cases

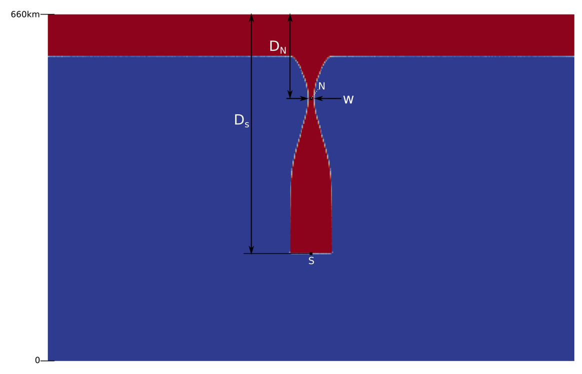
Several experiments with increasing levels of complexity are detailed hereafter:

- Case 1a: linear mantle, no free surface
- Case 1b: nonlinear mantle, no free surface
- Case 2a: linear mantle, free surface
- Case 2b: nonlinear mantle, free surface

Measurements

In order to compare the results from the different numerical codes, both qualitatively and quantitatively, we carry out the following measurements:

- viscosity values at the end of the first time step (i.e. when the system is converged). In 2D, these measurements are carried out along two lines: $x = 500km$ and $z = 550km$ (i.e. $110km$ under the free surface).
- the dimensionless slab tip depth $D_s^\star = (660km - z_S)/660km$, where the slab tip coordinate z_S is defined as the lowest vertical coordinate of the slab;
- the dimensionless slab width $W^\star = W/W_0$. At startup the slab has a width $W_0 = 80km$ but due to the negative buyancy of the slab and the boundary conditions it is expected to neck over time;
- the depth $D_N^\star = (660km - z_N)/660km$ at which the necking is most pronounced;



- the dimensionless root mean square velocity V_{rms}/V_c of the whole system (air excluded, if applicable) and of the lithosphere over time;
- the viscous dissipation of the whole system (air excluded, if applicable) and of the lithosphere;
- for models with a free surface, the dimensionless minimum $Z^\star_{min} = (Z_{min} - 660)/660km$ and maximum $Z^\star_{max} = (Z_{max} - 660km)/660km$ vertical coordinate of the free surface elevation.

Results are be plotted as a function of the nondimensional time $t^\star = t/t_c$ using the following characteristic time

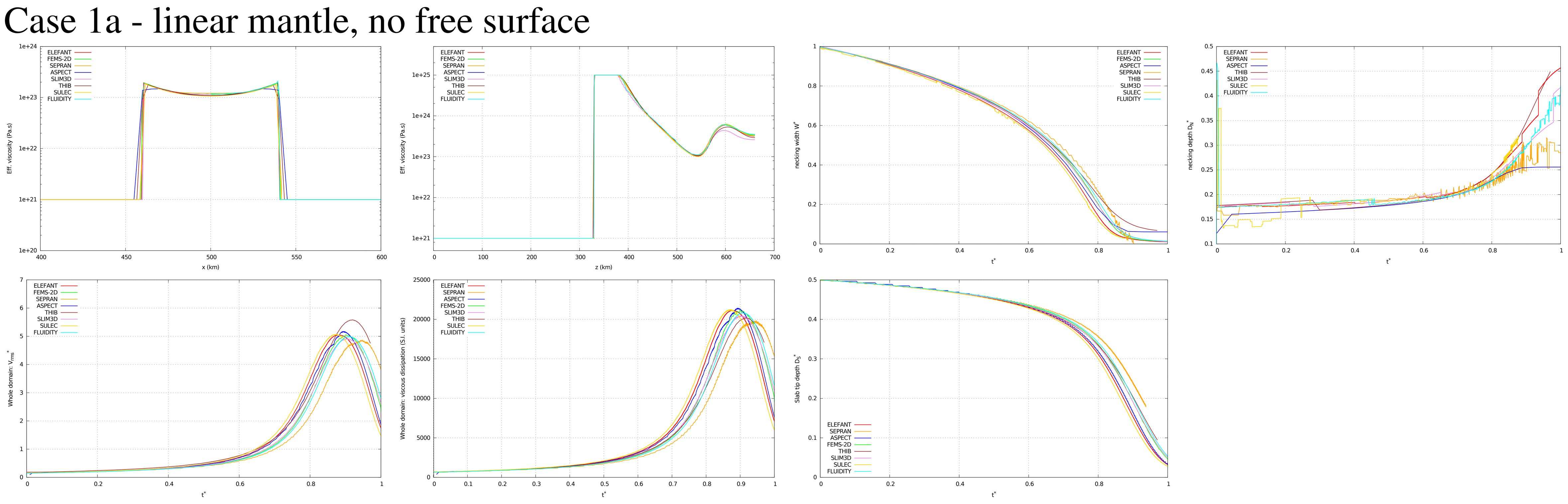
$$t_c = \frac{1}{A(\frac{1}{2}\Delta\rho\, gH)^n} \simeq 22.56Myr \tag{4}$$

and are shown hereunder.

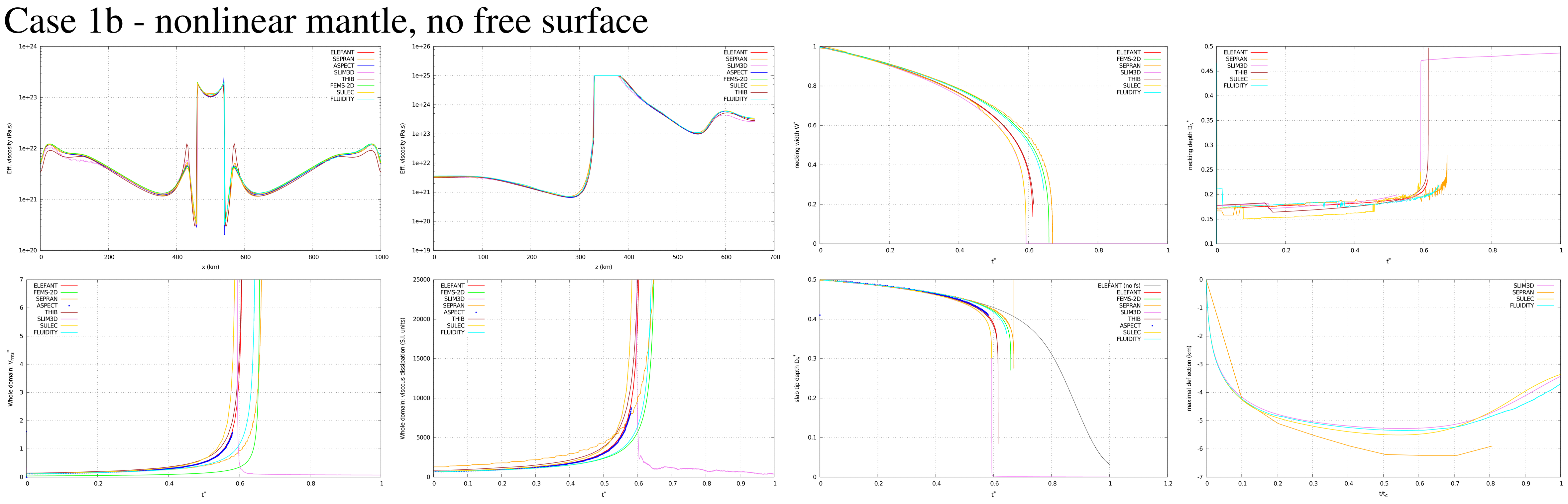
Conclusions

- More than reasonable agreement across codes and cases
- When all results are in, the following parameters will be discussed:
  - influence of resolution
  - influence of viscosity averaging
  - sticky air vs. real free surface
  - influence of slab length
- Extension to thermo-mechanically coupled models ?
- EGU2015: presentation of all 2D and 3D results
- It is not too late ! join us !

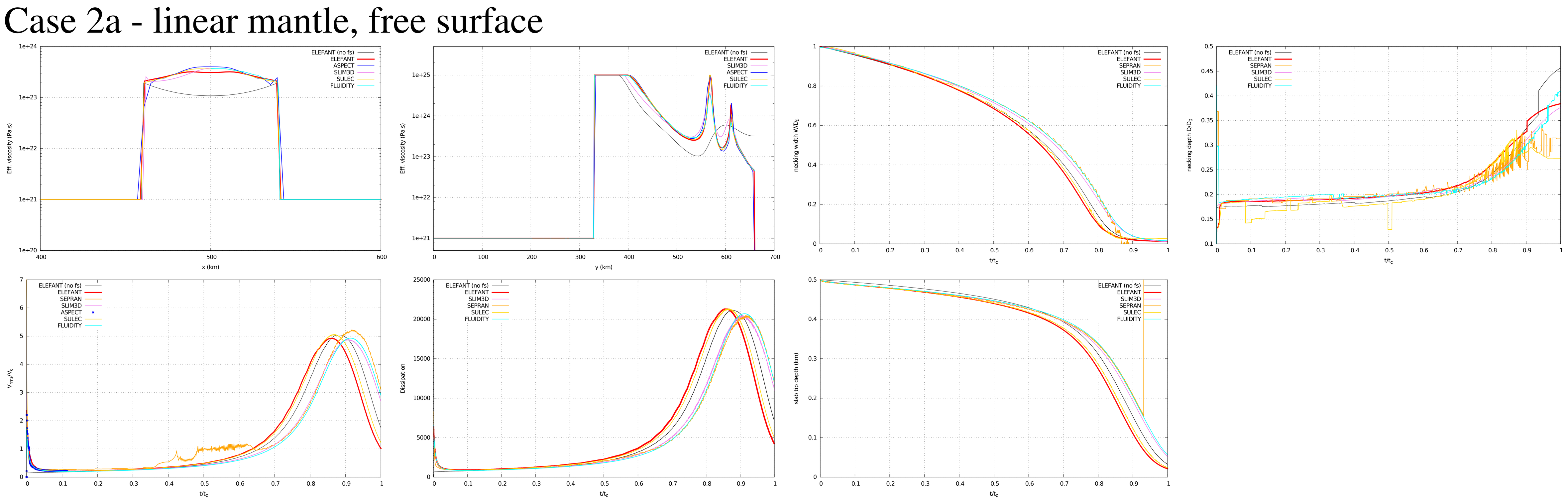
Case 1a - linear mantle, no free surface



Case 1b - nonlinear mantle, no free surface



Case 2a - linear mantle, free surface



Case 2b - non linear mantle, free surface