Thermo-mechanical modeling of a pull-apart: approaching 3D

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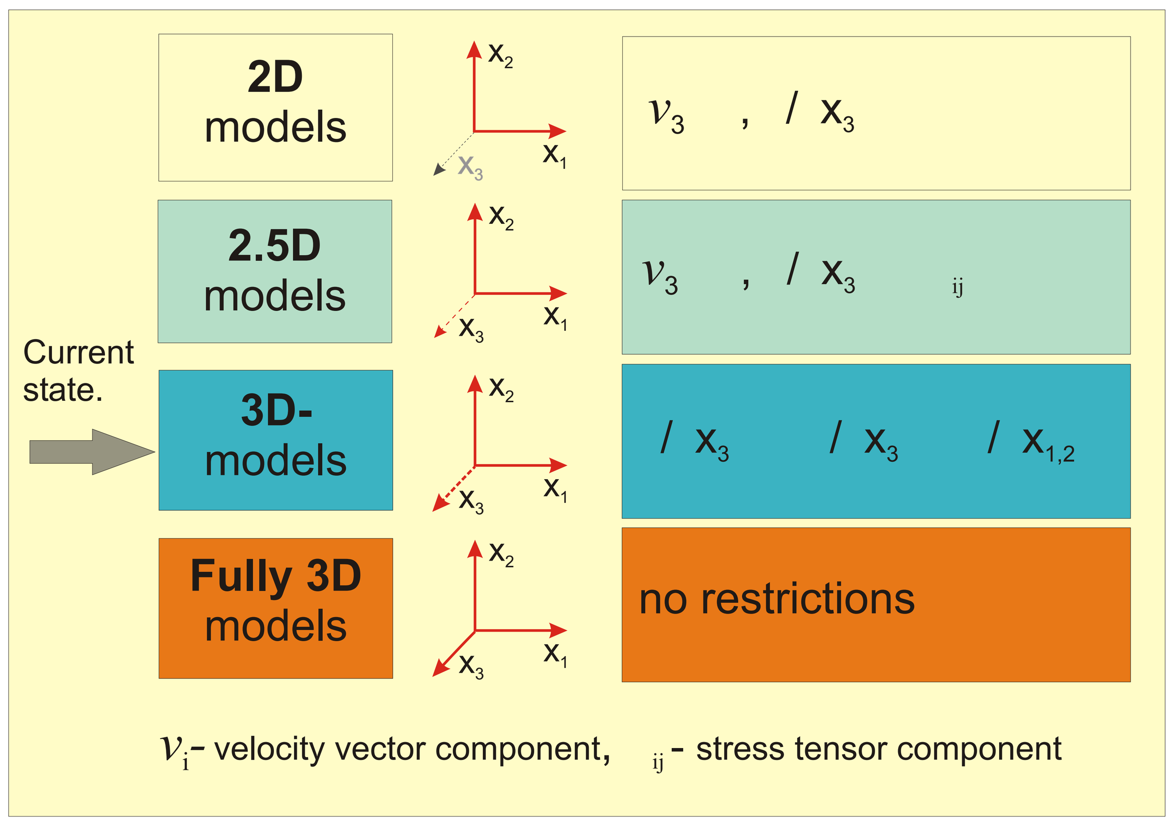
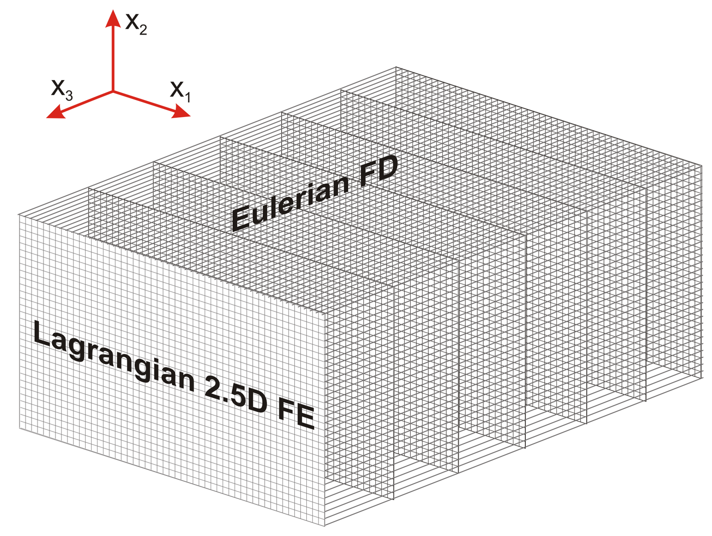
Introduction

Pull-apart basins belong to a special type of sedimentary basins associated withcontinental transform faults. They are depressions that are formed as a result of crustal extension in domains where the sense of fault overstepping or bending coincides with the fault motion sense. The outstanding classic example of a pull-apart basin is the 150 km long Dead Sea basin which is located at the Dead Sea Transform and where more than 8 km of sedimentary cover has accumulated since 15-17 Ma. In this poster we show an example of coupled FE-FD technique as applied to simplified 3D thermo-mechanical model of a pull-apart basin formation.



To solve the problem in 2.5D, we use a finite-element modeling technique based on the dynamic relaxation algorithm. In case of 3D-, the finite difference is used to combine the 2.5 "slices" and evaluate spatial derivatives in third direction. The numerical code we use (LAPEX-2.5D, LAPEX-3D), as well as its prototype PARAVOZ, applies an explicit time-marching calculation scheme, which allows strongly non-linear visco-elasto-plastic rheologies. To trace an advection of material properties and to minimize numerical diffusion due to remeshing, material markers are used.



Schematic representation of the coupled FE-FD spatial descretization.

Thermo-mechanical modeling

Momentum conservation equation:

$$-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i=0, \quad i=1,3$$

Mass conservation equation and constitutive laws:

$$\frac{dp}{dt}-\alpha K\frac{dT}{dt}=-K\frac{\partial v_i}{\partial x_i}, \quad \begin{cases}\frac{\partial}{\partial x_3}=0 & \text{for 2.5D}\\ \frac{\partial}{\partial x_3}\neq 0 & \text{for 3D}\end{cases}$$

$$\frac{1}{2G}\frac{\hat{d}\tau_{ij}}{dt}+\frac{1}{2\eta}\tau_{ij}=\dot{\varepsilon}_{ij};\ \eta=\frac{1}{2}B^{-\frac{1}{n}}(J_{\dot{\varepsilon}2})^{(\frac{1}{n}-1)/2}\exp\left(\frac{E_a}{nRT}\right)$$ Maxwell visco-elastic body

$$\sigma_1-\sigma_3\frac{1+\sin\phi}{1-\sin\phi}+2c\sqrt{\frac{1+\sin\phi}{1-\sin\phi}}=0$$ Mohr-Coulomb failure criterion

$$g_s=\sigma_1-\sigma_3$$ non-associated shear flow potential

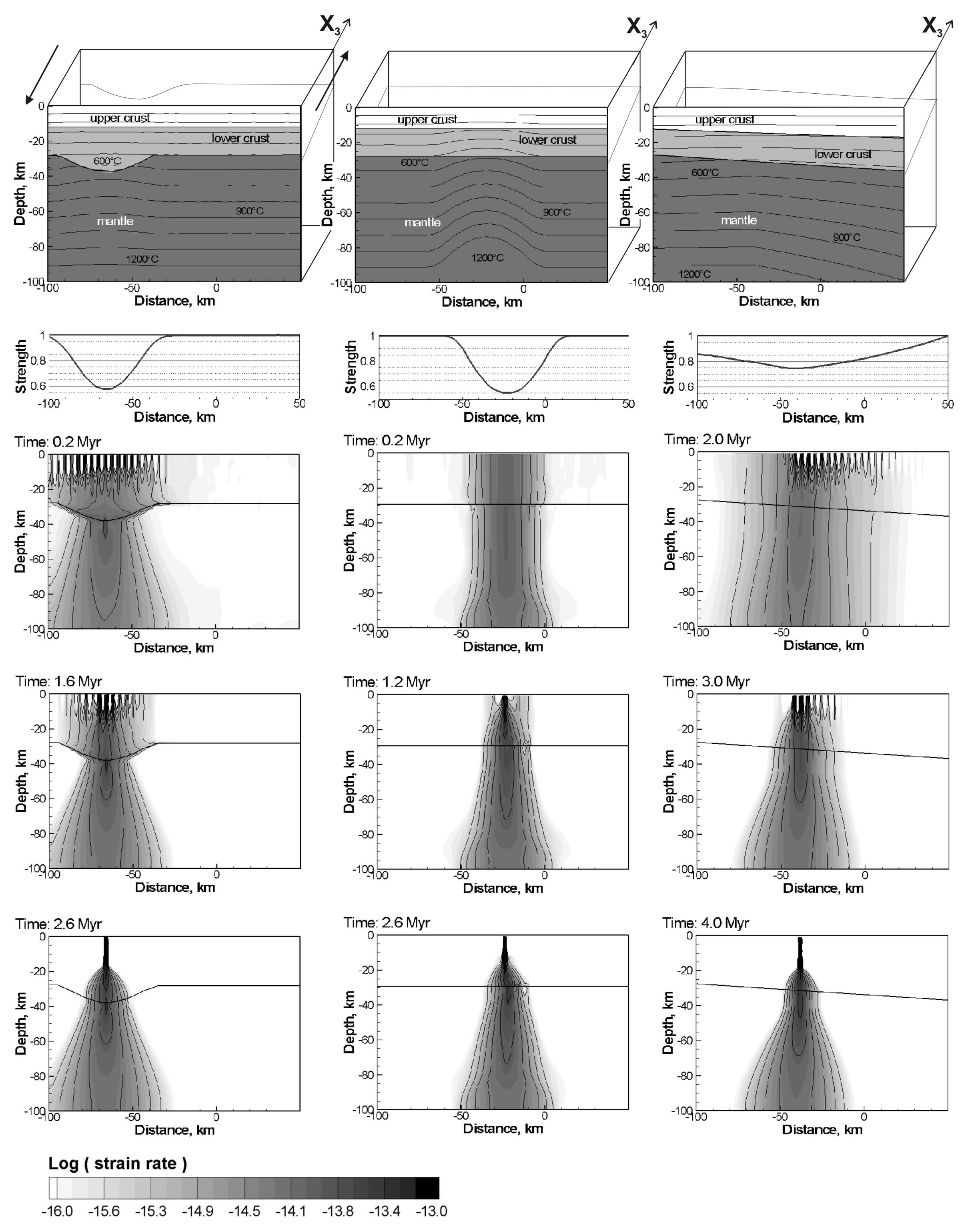
Energy conservation equation including shear heating term:

$$\rho C_p\frac{dT}{dt}=\frac{\partial}{\partial x_i}\left(\lambda(x_i,T)\frac{\partial T}{\partial x_i}\right)+\tau_{ij}\dot{\varepsilon}_{ij}+\rho A$$

Implementation: Explicit dynamic relaxation FE (Cundall and Board,1988)
Code: 2.5-D
Code prototypes: 2-D codes by Babeyko et al (2002) and by Poliakov et al (1993)

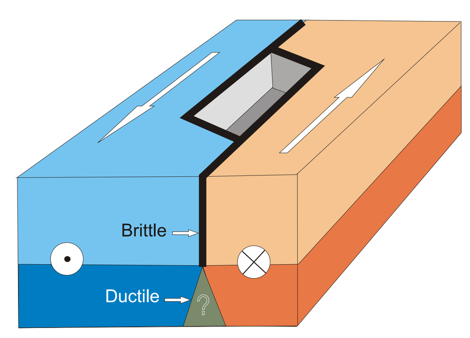
2.5 D models

Setup and results of the simplified strike-slip models. Columns correspond to the models with different initial crustal structure and temperature distribution. These initial conditions are shown in the upper row. Next row presents calculated relative strength function for corresponding models. Lower rows show time snapshots of the distribution of the strain rate demonstrating the strain localization process. The left column presents the model with local crustal thickening and minor temperature heterogeneity. The middle column presents the model with homogeneous crust and strong temperature heterogeneity. The right column presents the model combining both crustal structure- and temperature heterogeneities.



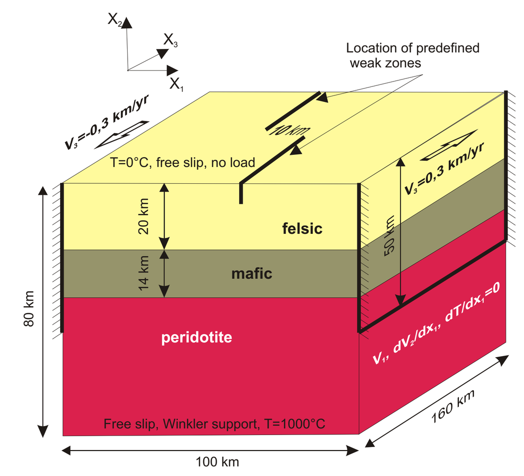
Strain is localized in one finite element column in the upper crust and in 10-30 km wide zone in the lower crust and mantle lithosphere. Width of this zone is controlled by the shear heating and kinematic boundary conditions at the sides.

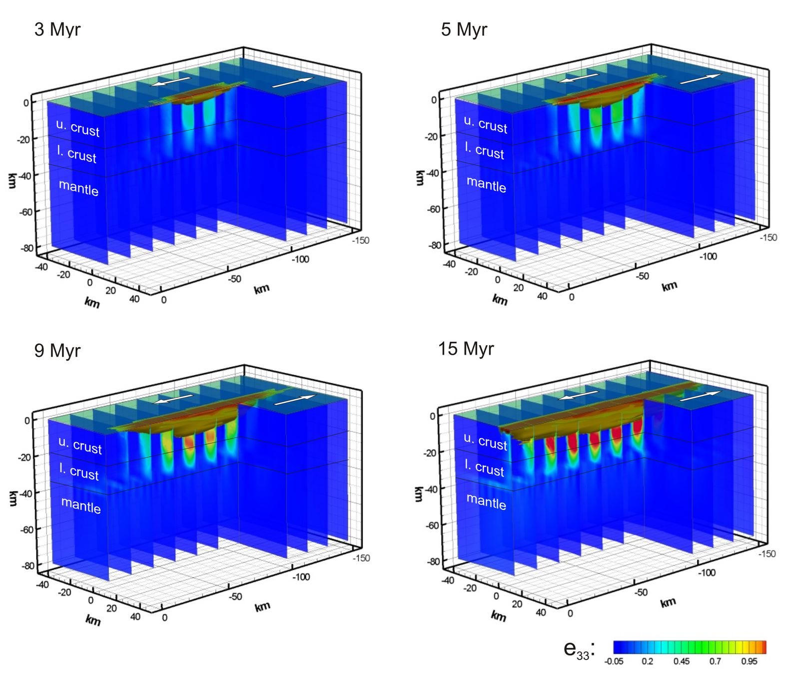
3D- models



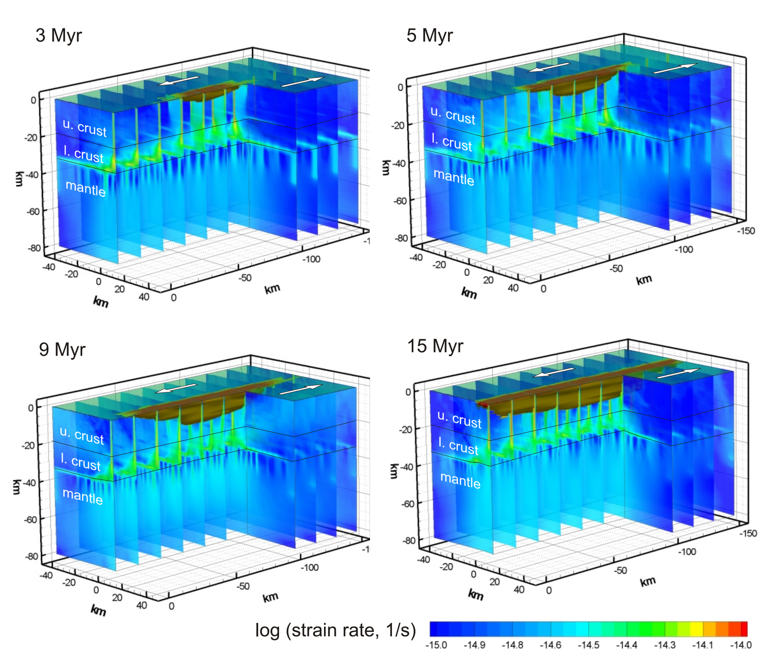
Conceptual model of a pull-apart basin formed at an overstepping of a transform fault (left)

Model setup (right). We consider a model box of 100x160x80 km simulating a domain of continental lithosphere . The lithosphere is lithologically layered and thermally heterogeneous, including a twol-layered crust and a mantle lithosphere.

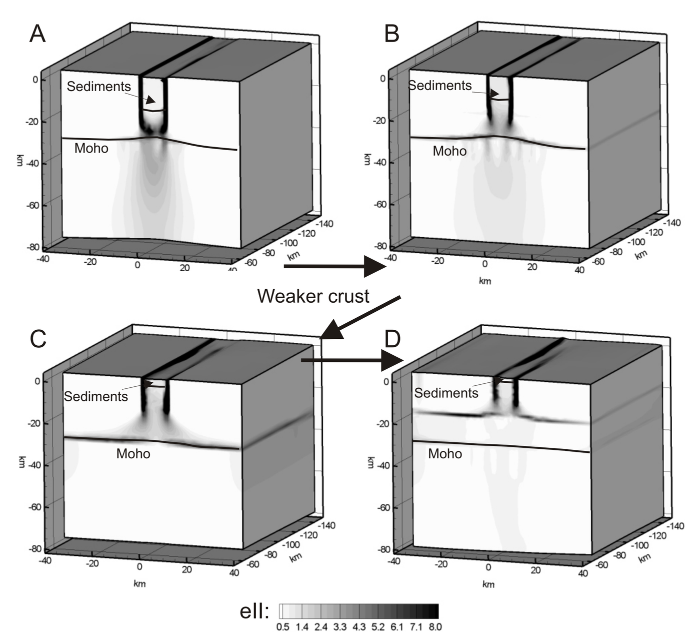




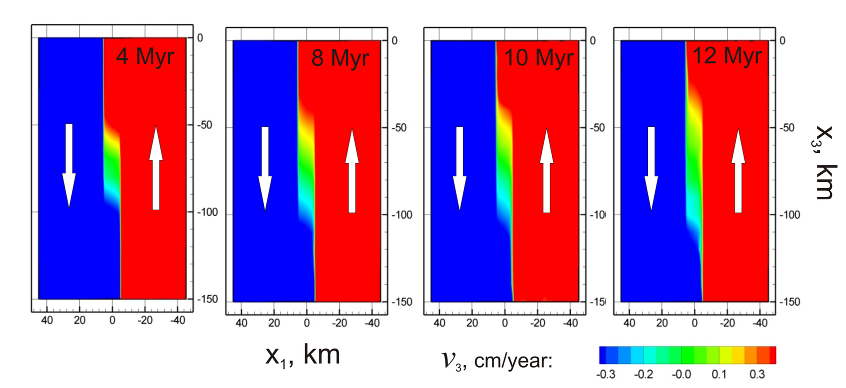
Growing pull-apart sedimentary basin (brown) together with distribution of transform parallel extensional strain (shown at a number of cross-sections).



Evolution of the strain rate distribution for the pull-apart model. The colours show log strain rate distribution at cross-sections. Note that the upper-middle crust beneath the growing basin (brown) is almost completely detached from the lower crust and upper mantle

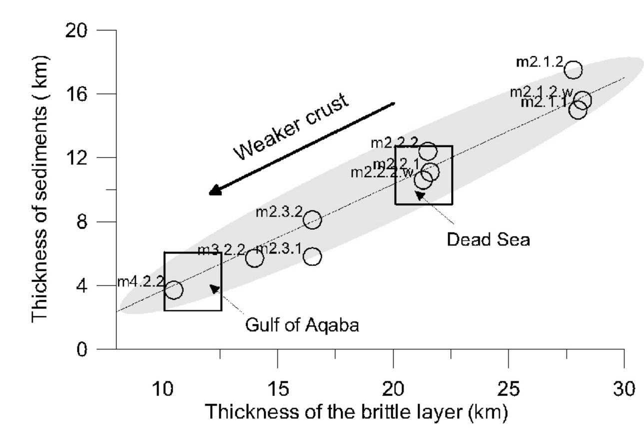


(a-d) Distribution of cumulative finite strain after 100 km of strike-slip displacement in the sections crossing the central part of a pull-apart basin for models with gradually decreasing crustal viscosity. Note that the stronger the crust the deeper is the detachment (indicated as domain of high strain) and the thicker is the sedimentary fill of the basin.

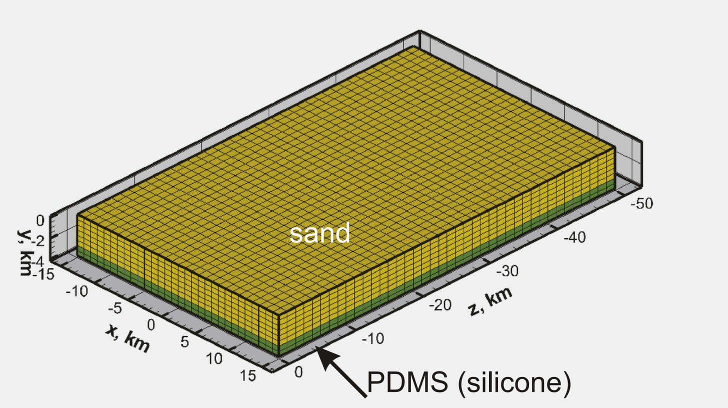


Dynamics of the basin's grow. Field of v_3 component of the velocity vector for 4,8,10 and 12 Myr of the model's time.

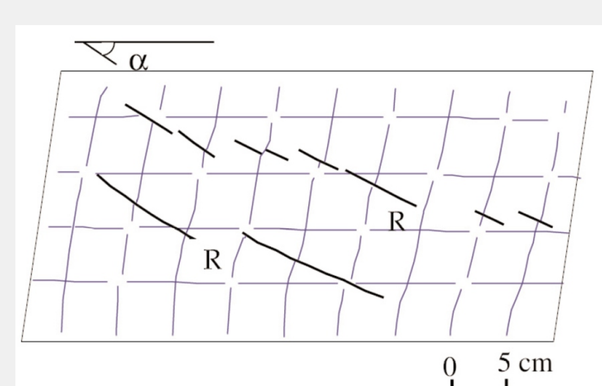
Maximum depth of a pull-apart basin after 100 km of strike-slip displacement versus thickness of the brittle layer (right). Each point indicates a particular model with different rheology of the crust. Boxes show the most plausible conditions for the Dead Sea basin and Gulf of Aqaba basin based on observed depths of the maximum seismicity. Solid line corresponds to the simple model, when the extensional thinning of the brittle layer of initial thickness h_0 is compensated by a sedimentary layer of thickness h_{sed} and by uplift of the base of the layer by 3 km (similar to the magnitude of the Moho uplift)



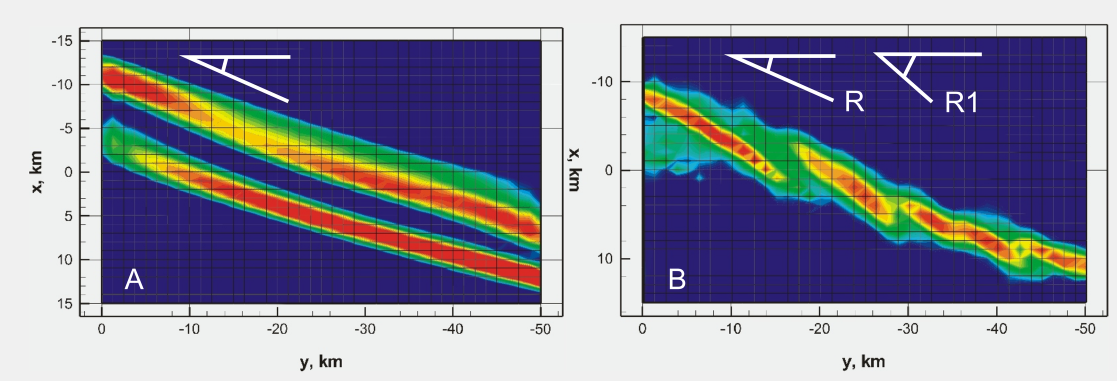
Test: 3D sandbox (Riedel Shears)



The model setup is scaled from analogue experiment by G. Schreurs and B. Colletta (2002). The model consists of two material layers: a sand (upper) layer and a thin silicone (lower) layer. Kinematic boundary conditions for left boundary (x=-15 km) are Vz = -0.16cm/year, Vx =0.01 cm/year. Right boundary (x = 15 km) is fixed (Vz=Vx=0). Upper and lower boundaries are free.



Analogue transpression experiment after G. Schreurs and B. Colletta, 2002. Plan view of early stage of transpression. - synthetic Riedel Shear (R) angle.



Accumulated plastic strain (A) and strain rate (B) for early stage of transpression. Rotation of "subfractures" direction is a result from secondary Riedel Shears (R1). When strain is small, the strain rate localization zone (B) is jumping between two strips of relatively high accumulated plastic strain (A). Further increasing strain leads to faults localization in the zones of highest accumulated plastic strain.