3D NUMERICAL MODELS OF THE PULL-APPART BASINS AT THE DEAD SEA TRANSFORM

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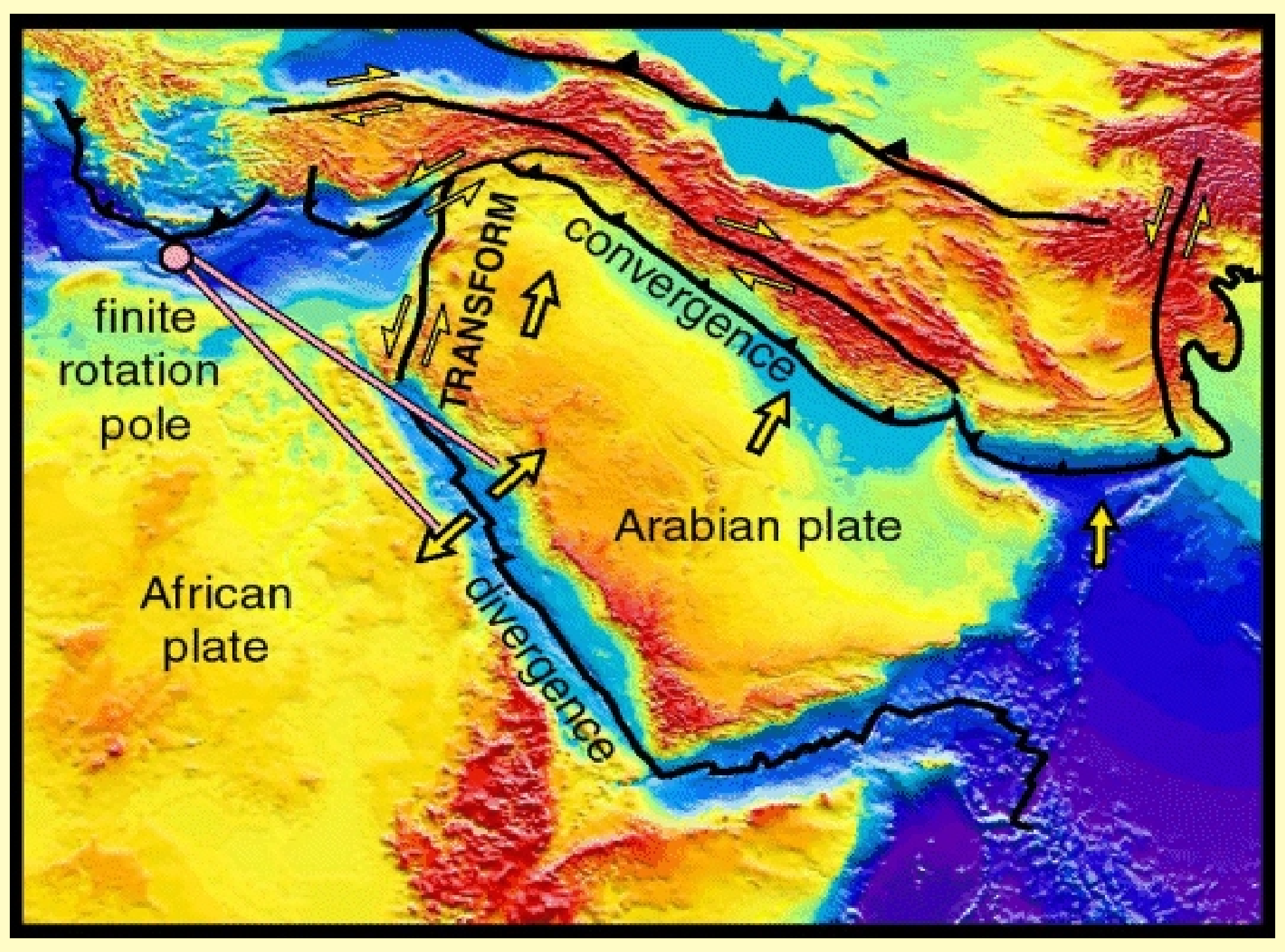
Introduction

The Dead Sea transform system (DST) is the boundary between the Arabian and African plates, where left-lateral transform motion has largely accommodated the opening of the Red Sea basin during the last 15-20 Myr. The transform motion along the DST was accompanied by the uplift of the large portion of the Arabian plate at the right flank of the DST. In this poster we use the internally consistent finite element 2.5 D thermo-mechanical modeling technique to study factors controlling localization and partitioning of the strain during strike-slip lithospheric-scale deformation. Also in this poster we present preliminary results of the 3D thermo-mechanical modeling of the two major pull-apart basins located along the DST: the Gulf of Aqaba and the Dead Sea basins. The preliminary results of 3D numerical simulation of Riedel Shears, shows features similar to the of analogue transpression

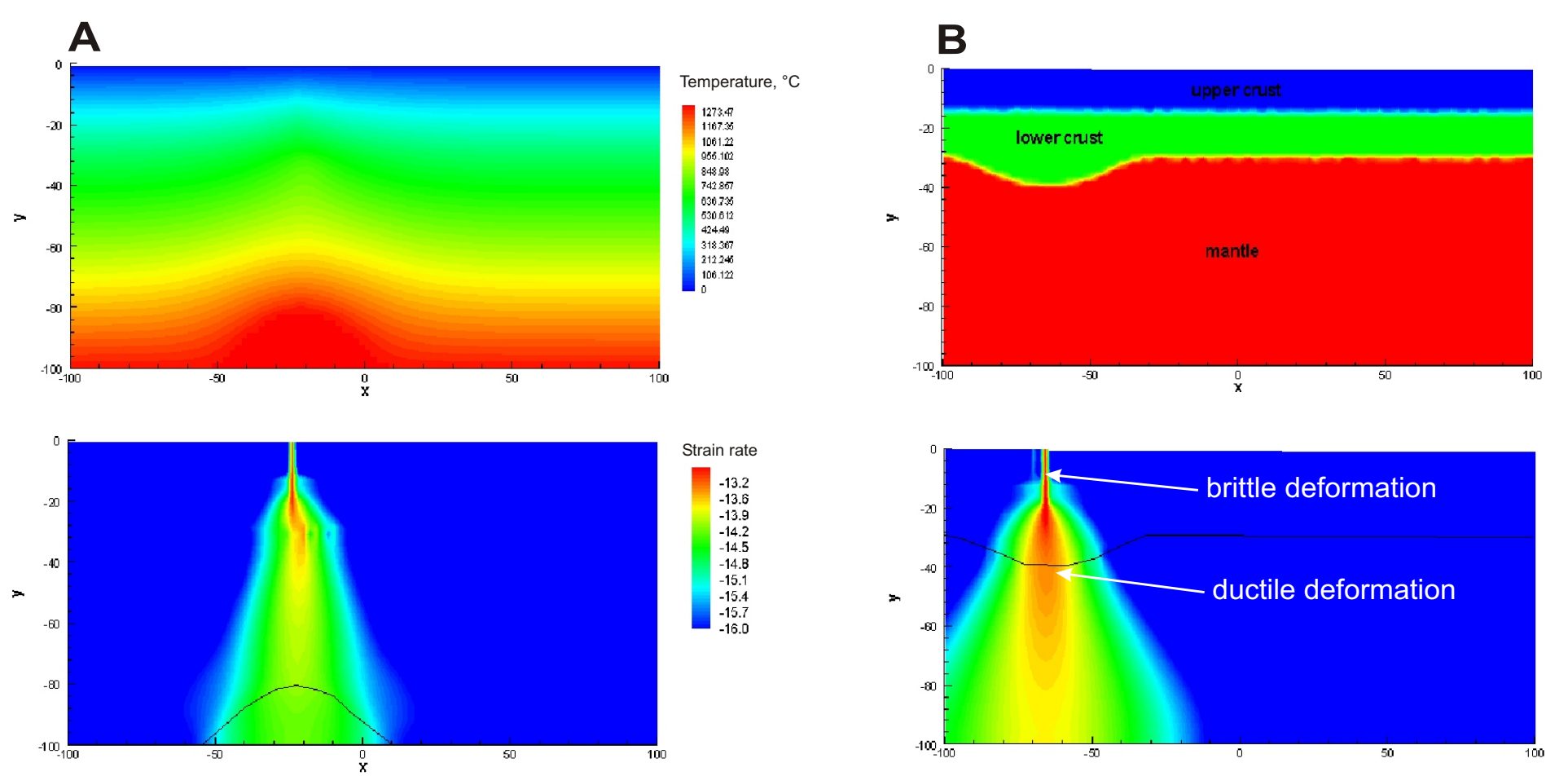
The Dead Sea Transform setting



Main controls (2.5 D), / x = 0

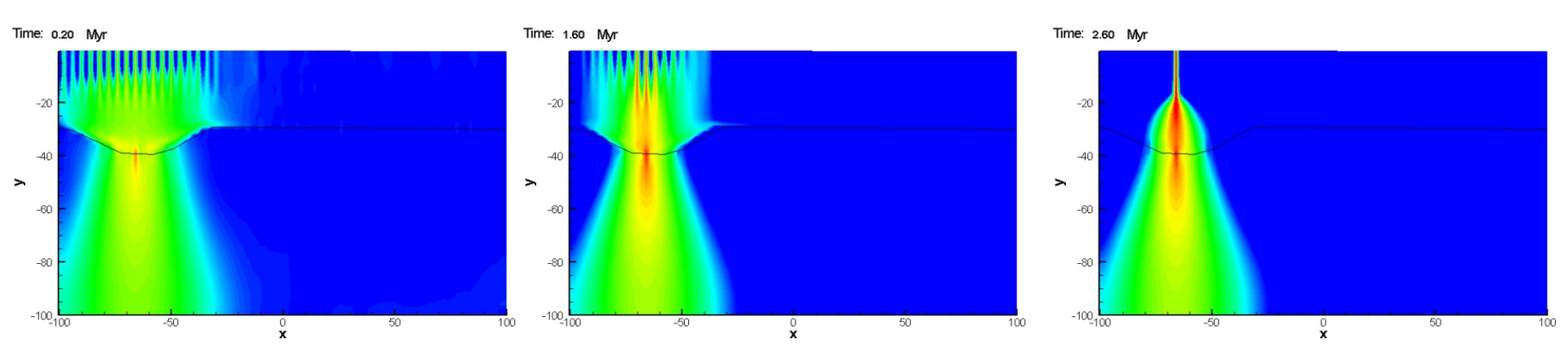
The strike-slip deformation is applied to the 3-layerd lithosphere with either lithological (thick crust) or thermal (thin lithosphere) heterogeneity or both. The rheological models for each rock type are either Mohr-Coloumb elasto-plastic with strain softening, simulating deformation of the brittle material, or non-linear temperature-dependent visco-elastic in the ductile deformation regime. Temperature at the lower boundary is 1300°C

Fault localization

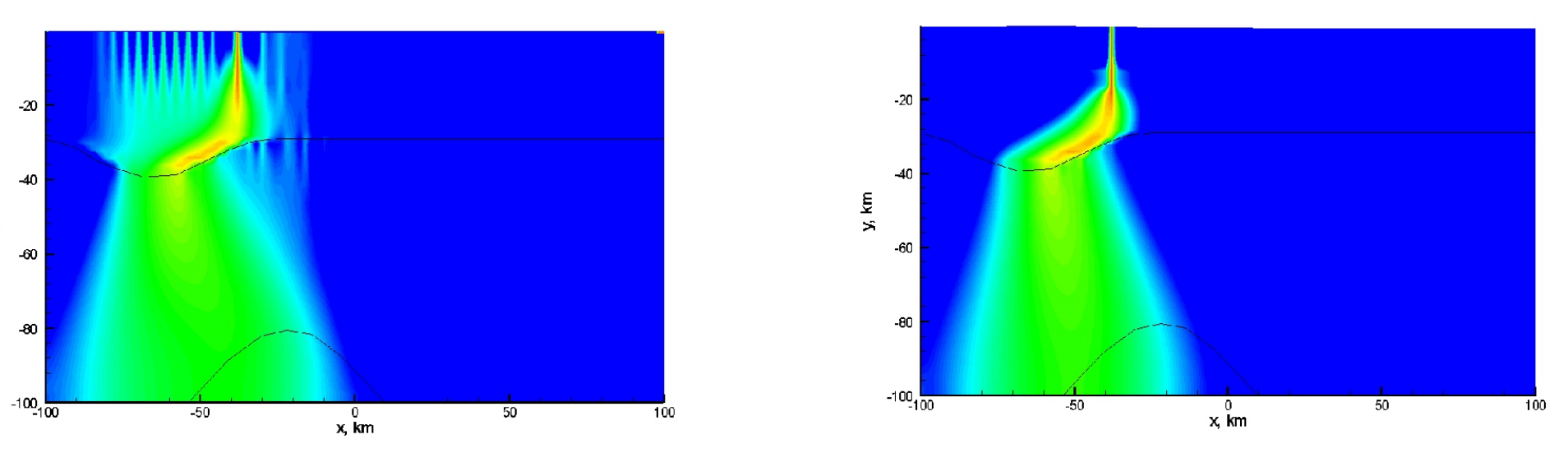


A. Thermal heterogeneity. Strain is localized at the place of the maximal temperature in the mantle lithosphere.

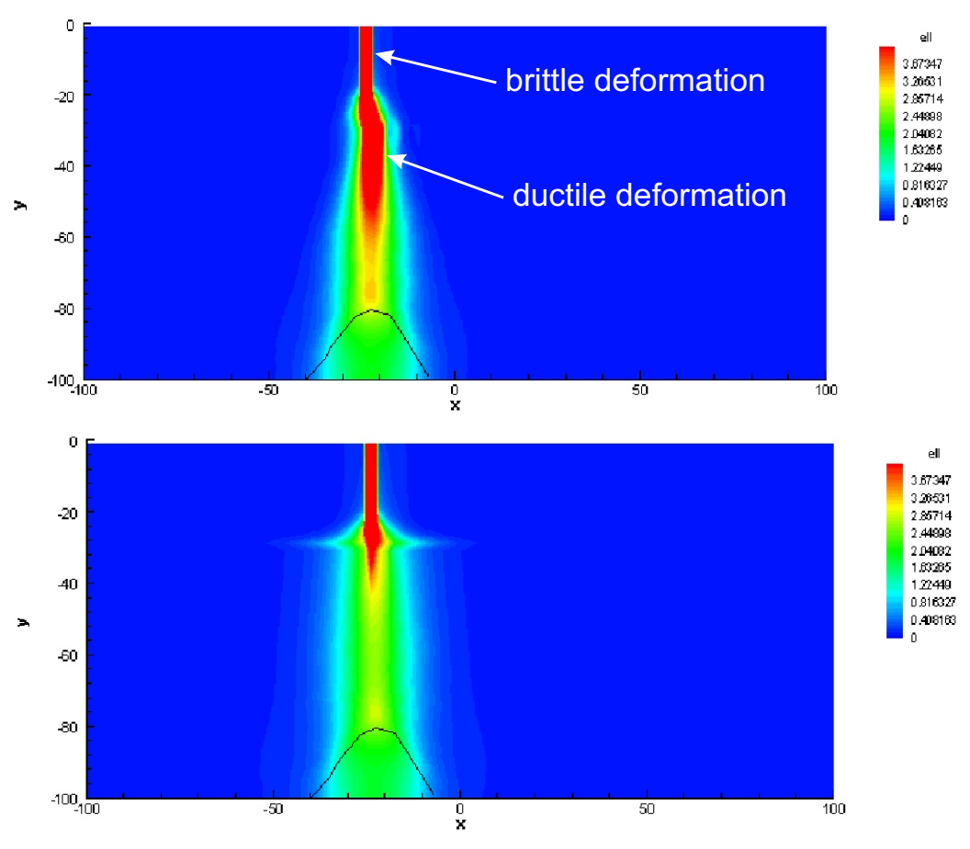
B. Crustal thickness heterogeneity. Strain is localized at the place of the maximal thickness of the crust.



Evolution of the strain localization shown in time snapshots of the strain rate distribution (red high strain rate). The deformation process is "searching for" the best place for the shear strain localization. In brittle domain multiple faults are formed during first1-2 Myr. Their number gradually decrease until one single fault takes over at about 2 Myr. Sumultaniously the zone of the



Both thermal and crustal-thickness heterogeneity displaced. Inclined zone of strain localization is formed. Note that strain localization occurs after some 3 Ma after beginning of the strike slip deformation (right section) and is much less pronounced at 1 Ma.



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 it is narrow with shear heating (upper section) and wide without shear heating.

Thermomechanical Modelling

Momentum conservation equation: $\frac{p}{x_i}\ \frac{ij}{x_j}\ g_i\ 0,\ i\ 1,3$ $\qquad \frac{}{x_3}\ 0$ for 2.5D

Mass conservation equation and constitutive laws: $\frac{dp}{dt}\ K\frac{dT}{dt}\ K\frac{v_i}{x_i},$ $\qquad \frac{}{x_3}\ 0$ for 3D

$$\frac{1}{2G}\frac{\hat{d}_{ij}}{dt}\ \frac{1}{2}\ _{ij}\ \dot{}_{ij};\quad \frac{1}{2}B^{\frac{1}{n}}J_{\cdot 2}^{(\frac{1}{n}\ 1)/2}\exp\frac{E_a}{nRT}$$ Maxwell visco-elastic body

$$_1\ \ _3\frac{1\ \sin}{1\ \sin}\ 2c\sqrt{\frac{1\ \sin}{1\ \sin}}\ 0$$ Mohr-Coulomb failure criterion

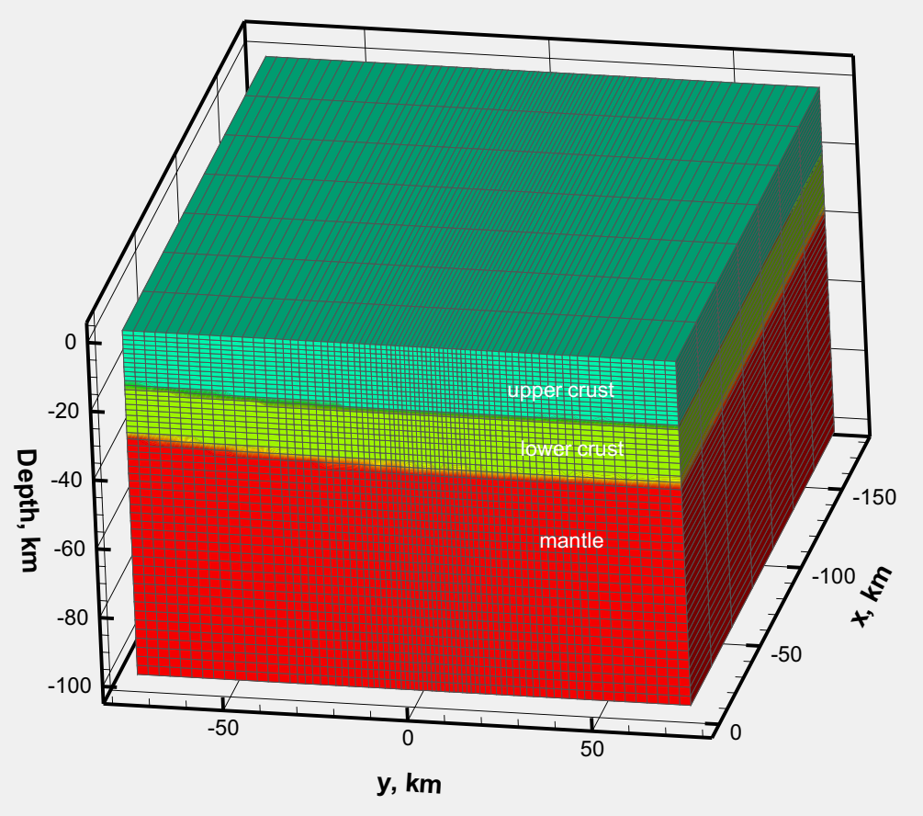
$$g_s\ \ _1\ \ _3$$ non-associated shear flow potential

Energy conservation equation including shear heating term: $C_p\frac{dT}{dt}\ \frac{}{x_i}(\ (x_i,T)\frac{T}{x_i})\ \ _{ij}\dot{}_{ij}\ \ A$

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)

The **2.5 D** model includes all three components of velocity vector, but assumes that all parameters and variables are constant parallel to the strike-slip motion. In this case 2D computation mesh can be used.
The **3 D** model allows variations of parameters and variables in all directions. However we assume that these variations are much smaller parallel to the strike-slip motion than perpendicular to it. In this case we can use 3D computation mesh with larger spacing between the grids parallel to the strike-slip motion.

3D models, / x 0



The crustal structure for both Gulf of Aqaba and Dead Sea models is the same as in the "big picture" model, but the kinematic boundary conditions are pure strike-slip without perpendicular extension. Temperature condition at the base of the Gulf of Aqaba model generates the three-dimensional temperature distribution, while the base temperature condition in the Dead Sea model generates the two-dimensional temperature distribution.

In addition, for the Dead Sea model we assume that there is week zone at the northern boundary of the model simulating continuation of the DST north of the model boundary.

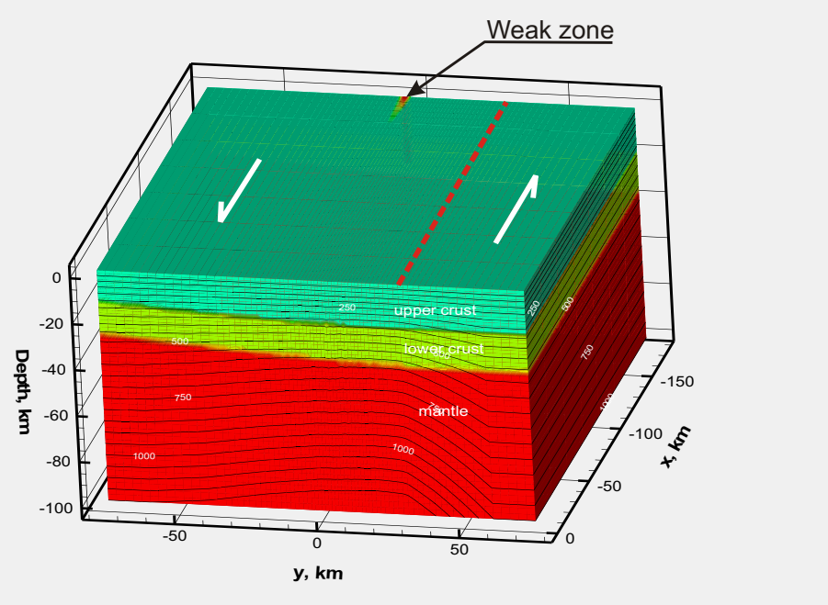
To simulate a sedimentation process we introduce sediments with density 2200 kg/m3 at the free surface section subsided at the depth more than critical (500 m).

3D Model setup

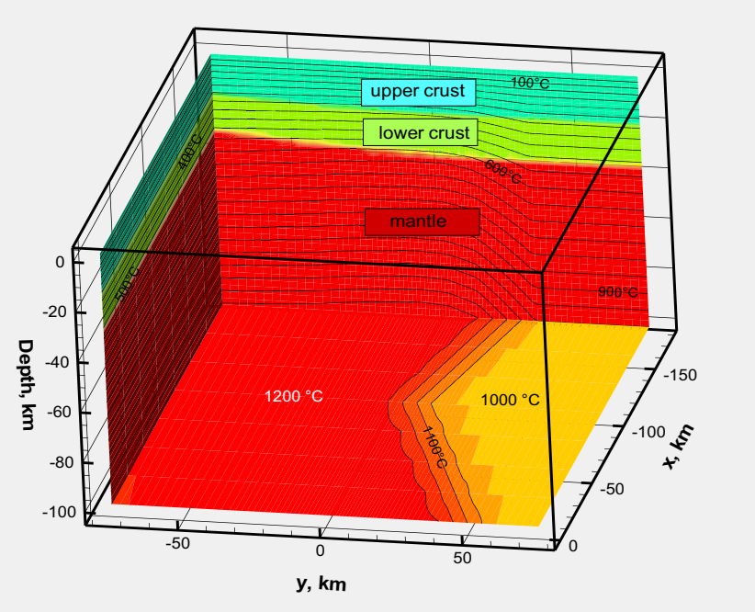
Model size: 100X175X150 km
Number of elements: $3*10^4$
Modeling time interval: 17 Myr
Number of time steps: $2*10^5$

Grid spacing: strike ⊥ 0.8 - 3 km.
strike ∥ 25 km.

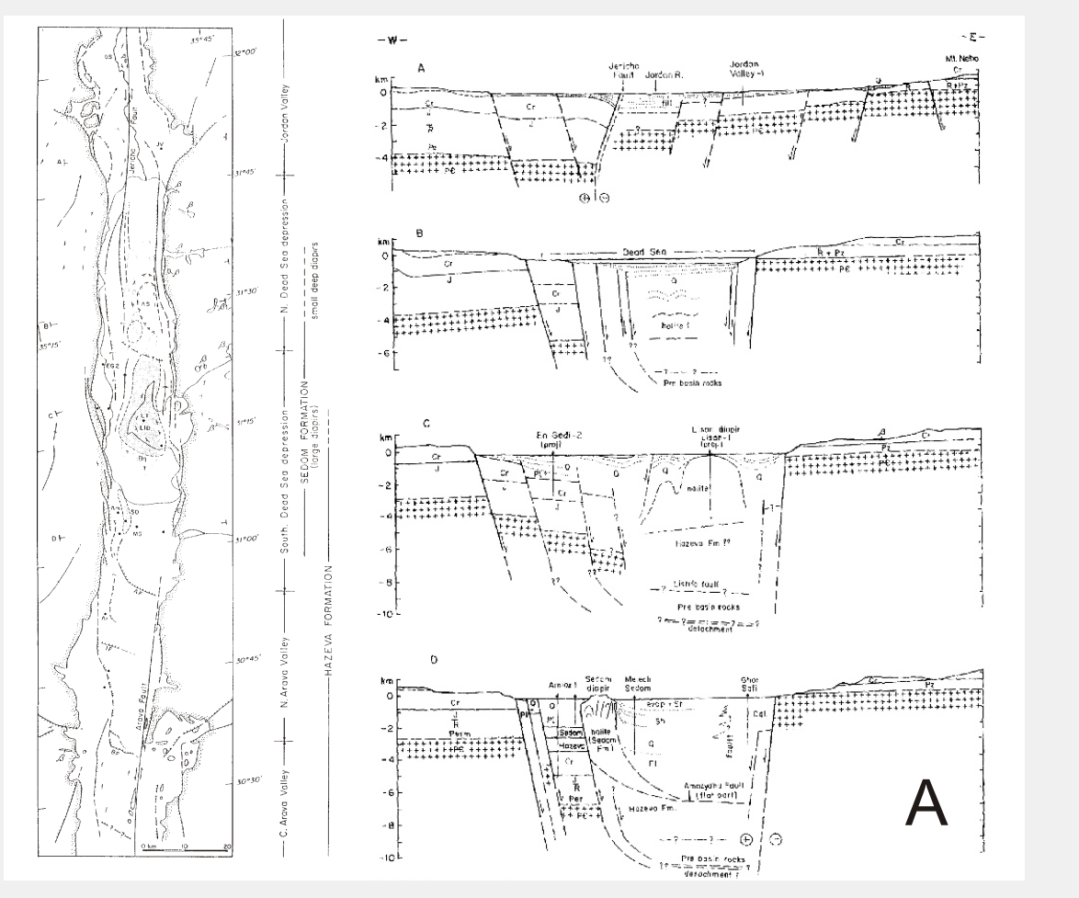
Model Dead Sea



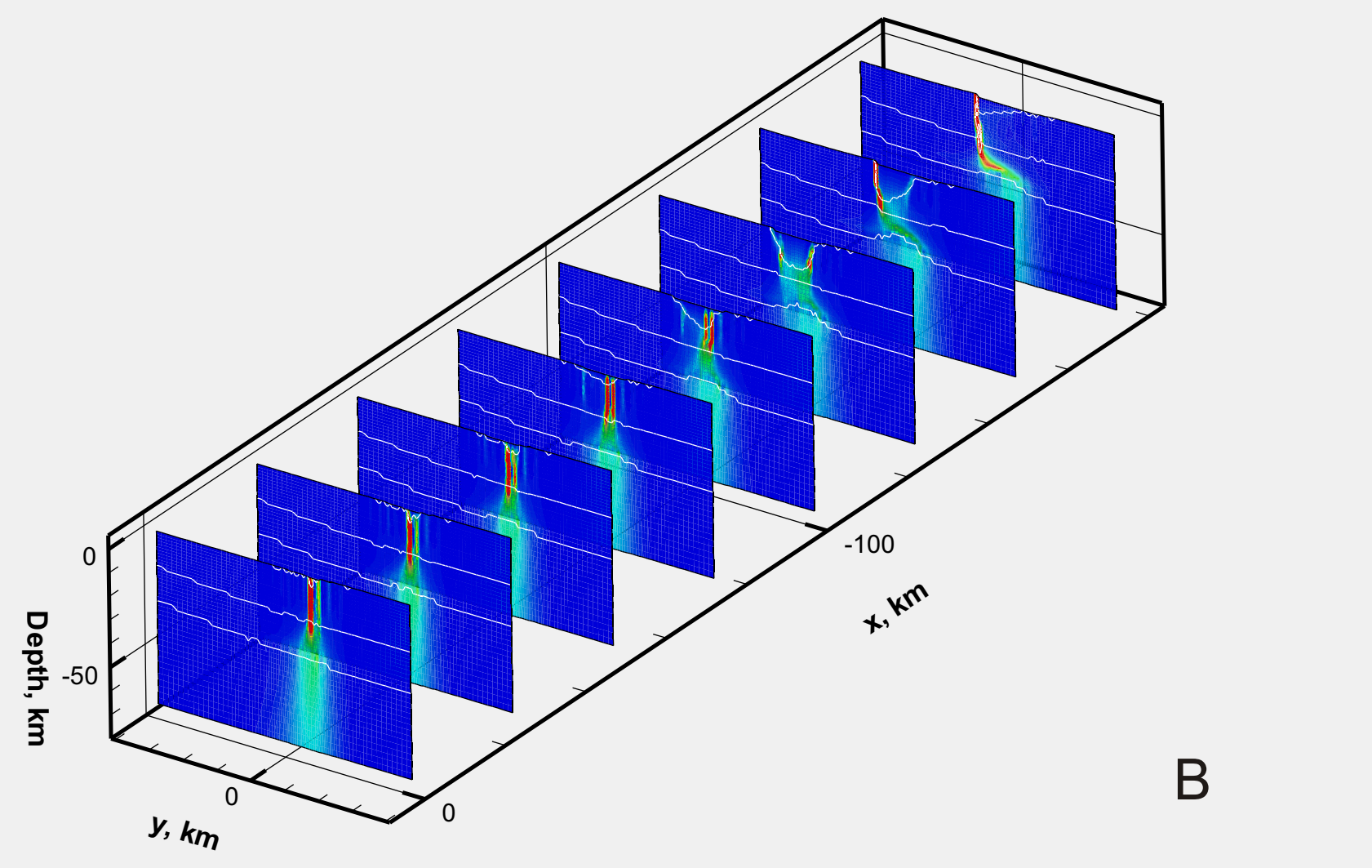
Model Aqaba

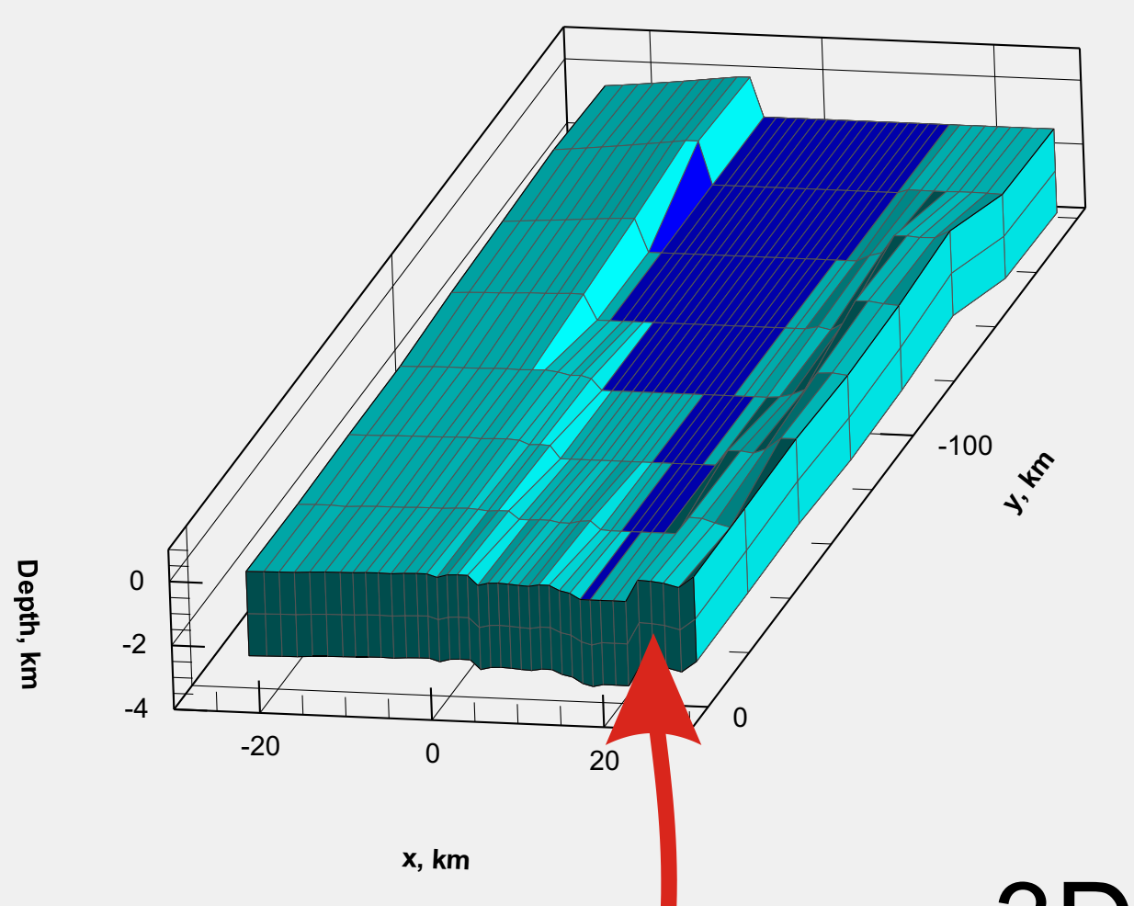


3D modeling results: Dead Sea basin

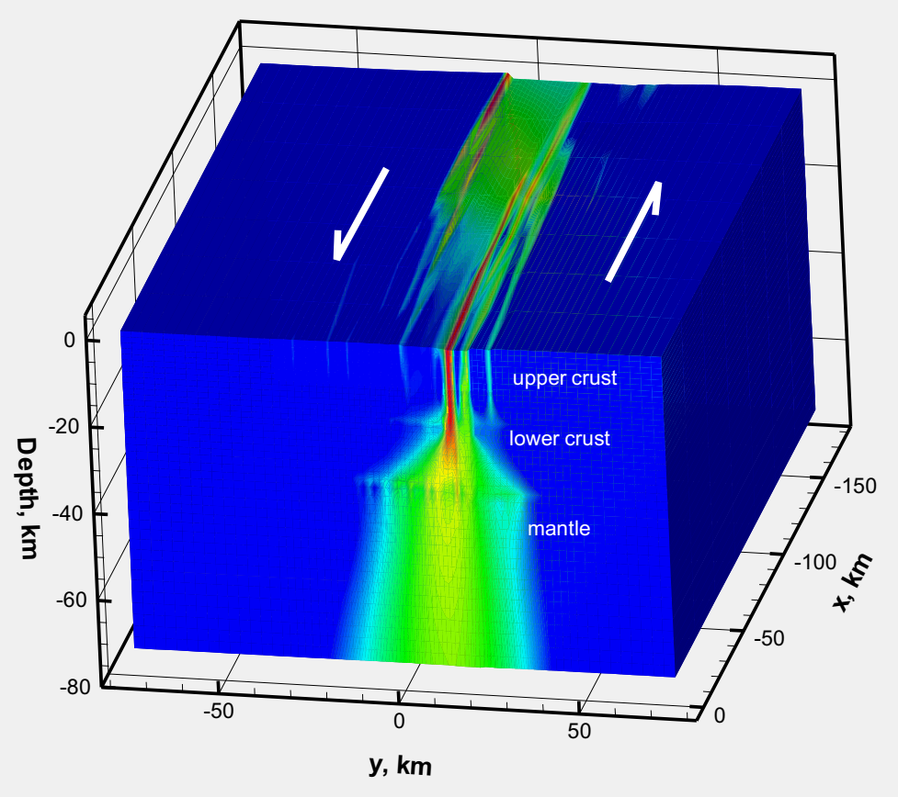


Geological structure of the Dead Sea basin after Z Garfunkel and Z. Ben-Avraham 1996 (A) versus modeled cumulative finite strain (B). The geologic cross-sections (A) show asymmetric structure and extraordinary depth (ca. 10 km) of the basin. For the most part of the basin the eastern shoulder is the steepest. The exception is the northernmost part of the basin where the steepest is the western shoulder. The modeling shows similar features. The cumulative strain shows zones of largest strike-slip displacement (colored in red). It is noticeable that these zones coincide with the steepest shoulder of the basin. Therefore the modeling suggests that the eastern (Arava) fault has taken larger strike-slip motion than the western fault at the most part of the Dead Sea and it is responsible for the asymmetry of the Dead Sea basin.



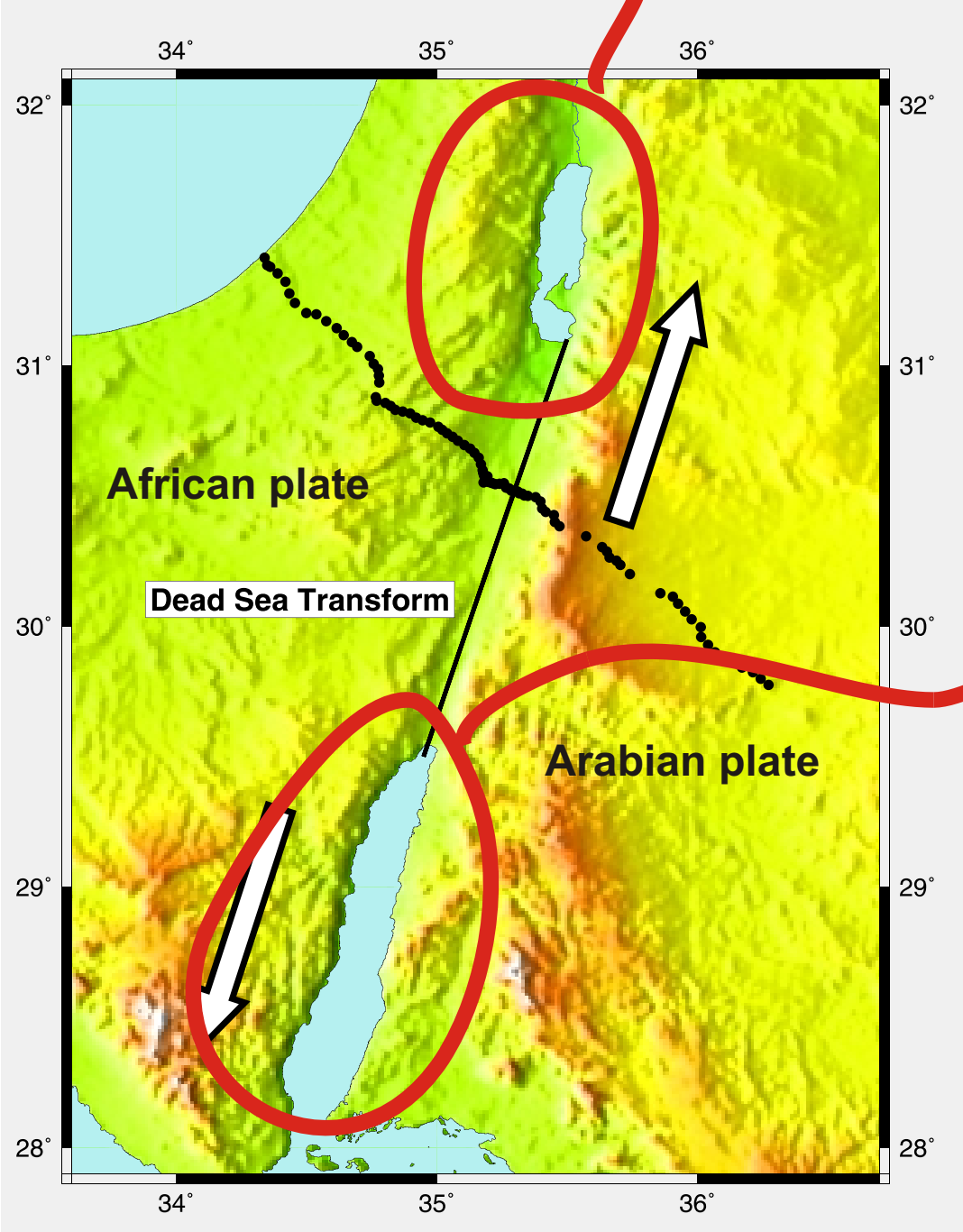


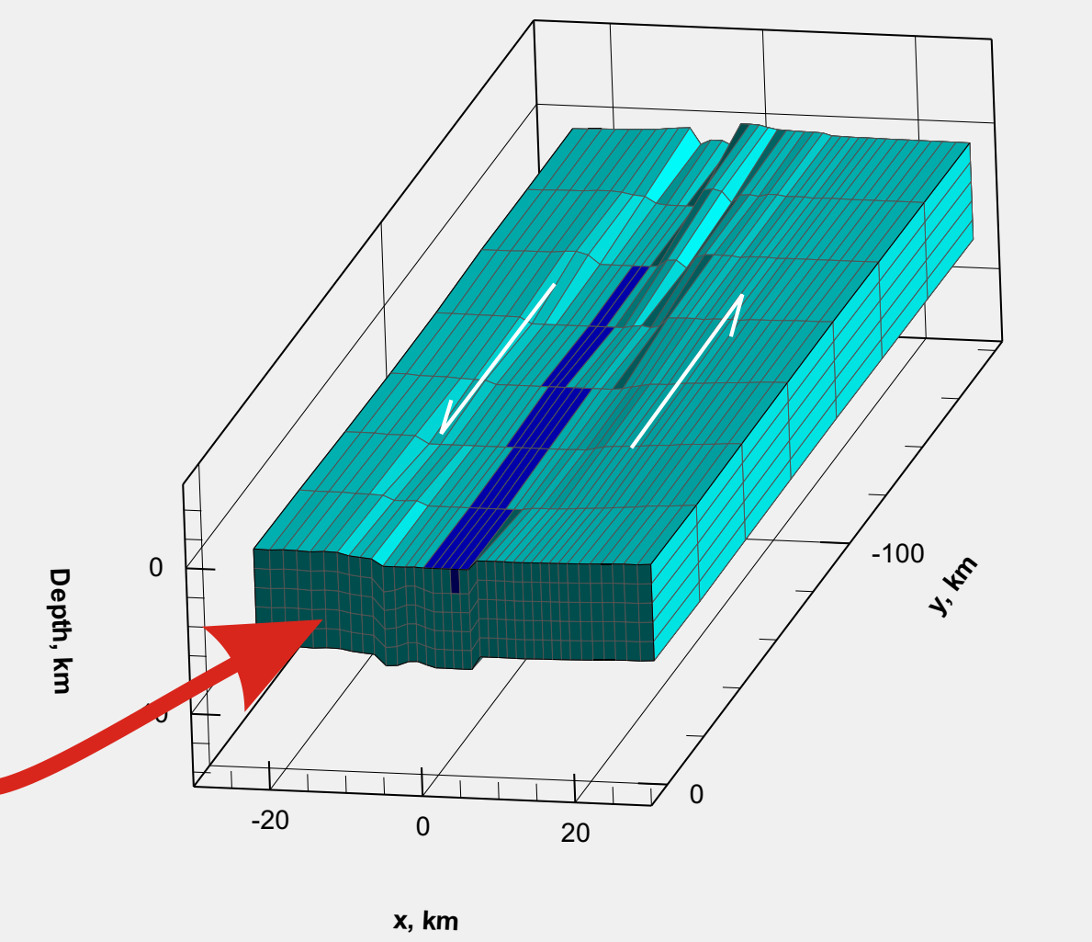
Calculated surface topography of the Dead Sea area. Blue color marks a sedimentary basin shape. The model basin is up to 20 km wide, slightly more than 10 km deep in deepest part and becomes narrower and shallower to south.



Strain rate after 105 km of strike-slip motion. Red color corresponds to the highest strain rate, which mark faults. The green zone between the faults indicates an area of the relatively high strain rate due to an along strike-slip stretching during the pull-apart formation. The reason for the pull-apart structure in the Dead Sea model is the **interaction of two inherited rheologically weak zones and strike-slip motion**. The first zone is due to the joint effect of heterogeneity of the crust and thermal boundary condition at the base of the model. The second zone is simulated as a boundary condition at the back (northern) side boundary of the model. The joint between these two zones is **oblique (rotated to the left)** to the direction of the strike-slip motion imposed by kinematic boundary conditions.

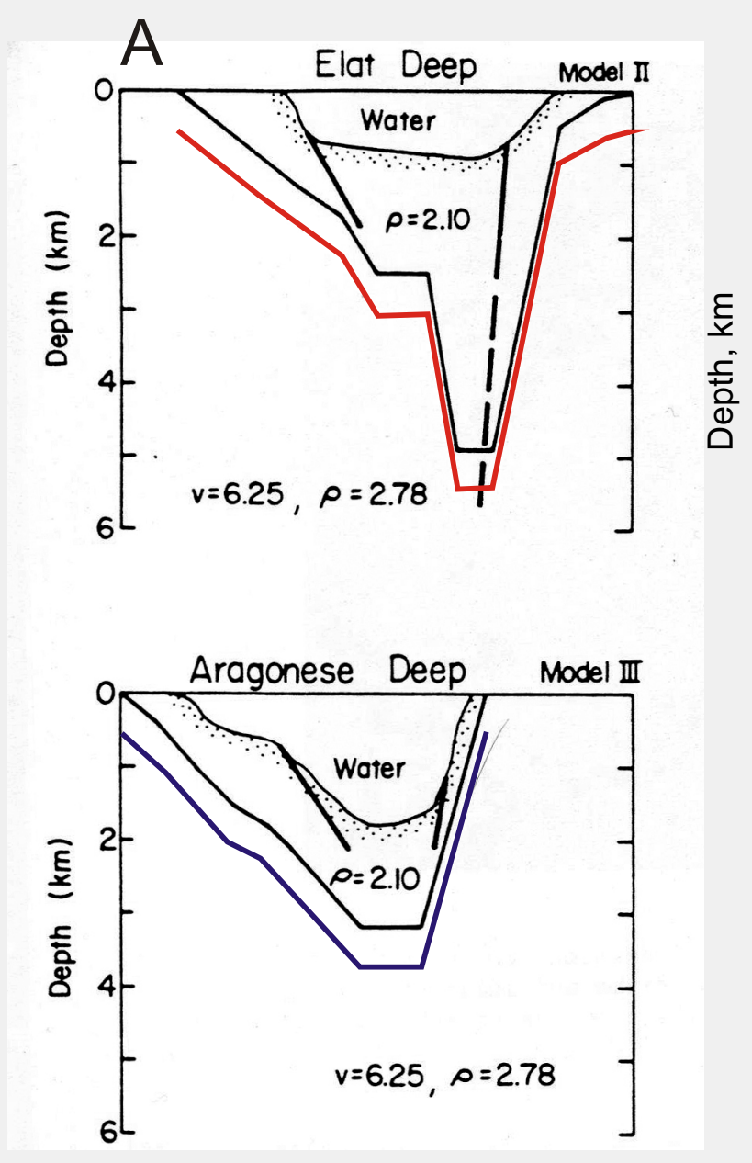
3D modeling results: Gulf of Aqaba

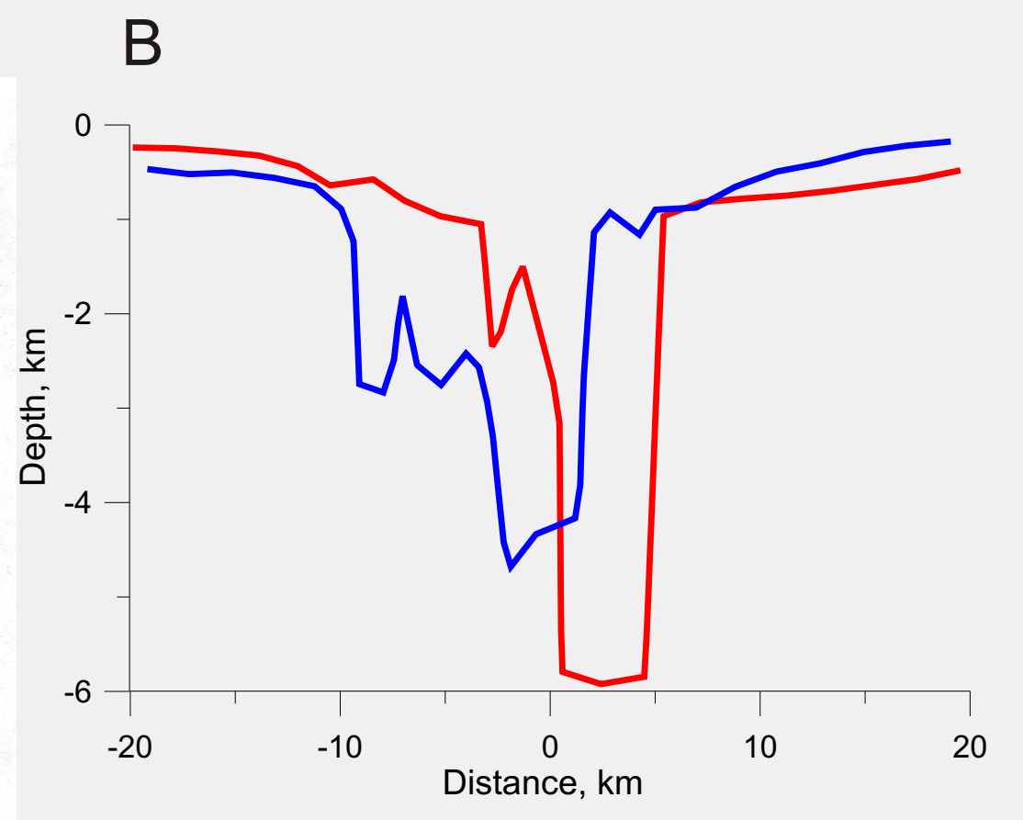




Modeled surface topography of the Gulf of Aqaba. Sediments are deep blue. Depth of the basin reaches 4-6 km in its deepest part. Note an en-echelon structure of the model basin in accordance with real situation.

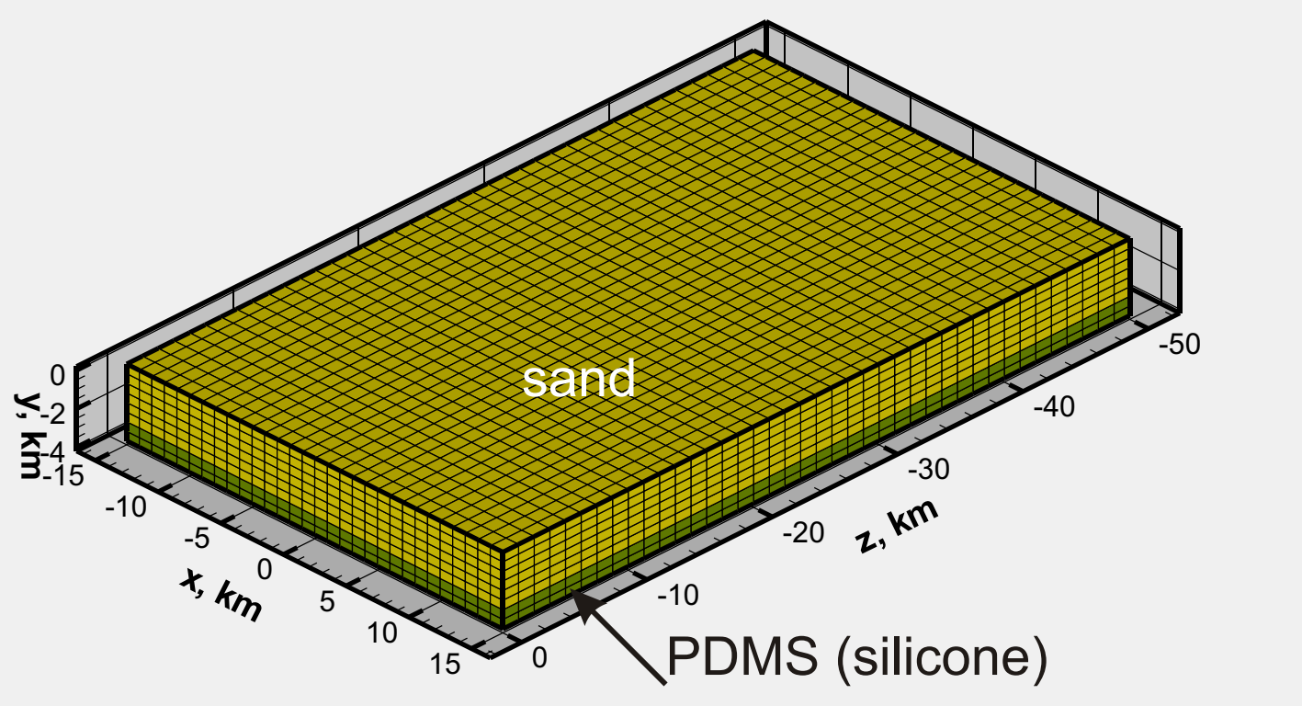
Strain is localized in two sub parallel strike-slip faults. Stretching parallel to the strike-slip leads to the formation of a narrow (less than 15 km) pull-apart basin. The reason for this structure is that the strike of the minimal lithospheric strength in the model controlled by basal temperature distribution and crustal structure **is oblique (rotated to the left)** to the direction of the strike-slip imposed by kinematic boundary conditions.



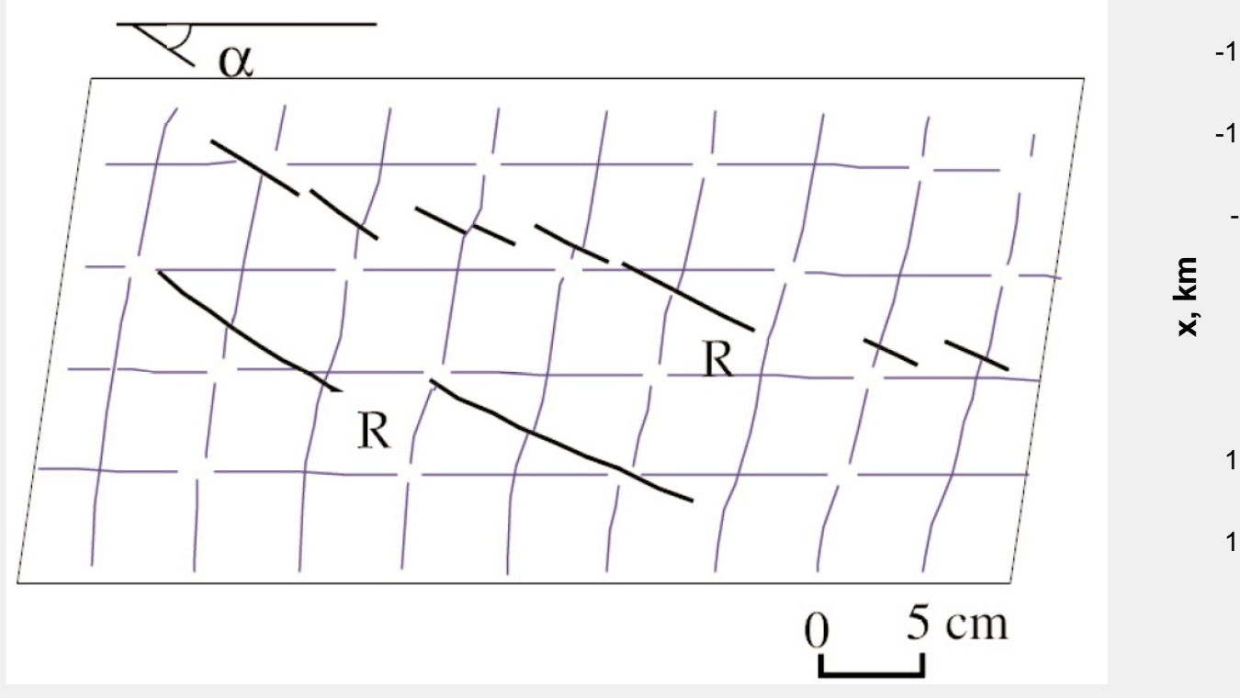


A base of the sedimentary layer after Z. Ben-Avraham, 1985 (A) versus results of the modeling (B). The cross-sections represent the southern end and the middle of the basin.

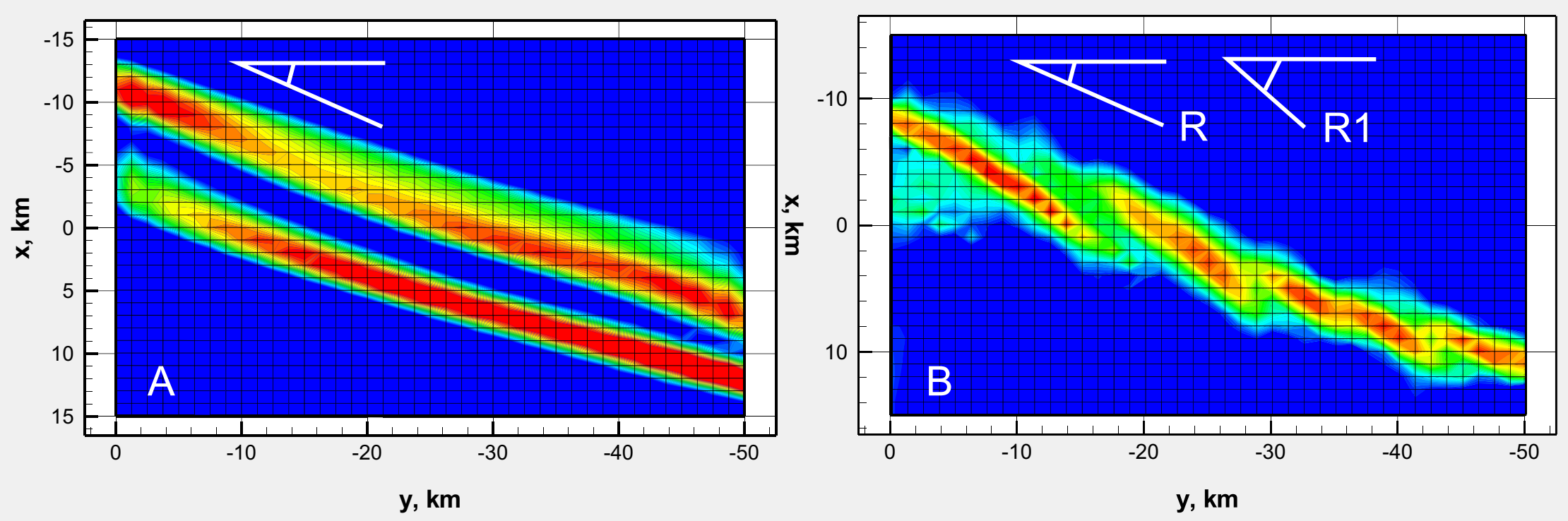
3D sandbox (Riedel Shear)



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 ôsubfracturesö direction is a result from secondary Riedel Shear (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.

Conclusions

Localization of the strike-slip deformation in the lithosphere is mainly controlled by its temperature (localization in the hottest parts) and thickness of the crust (localization in the thickest part of the crust).

Extension of the 2.5-D models to full 3-D is required to address questions on controls of the geographic locations and deformation-styles variability along the DST.

Preliminary results of the 3-D modeling suggest that deep pull-apart basins (Gulf of Aqaba and Dead Sea) may originate due to the inconsistency of the strike of the lithospheric heterogeneity and inherited weakness with the strike of the plate boundary velocities.

The modeling suggests that the eastern (Arava) fault has taken larger strike-slip motion than the western fault at the most part of the Dead Sea and it is responsible for the asymmetry of the Dead Sea basin.

The preliminary results of 3D numerical simulation of Riedel Shears, shows features similar to the of analogue transpression experiment.