Tectonic modeling of non steady-state temperature in the lithosphere

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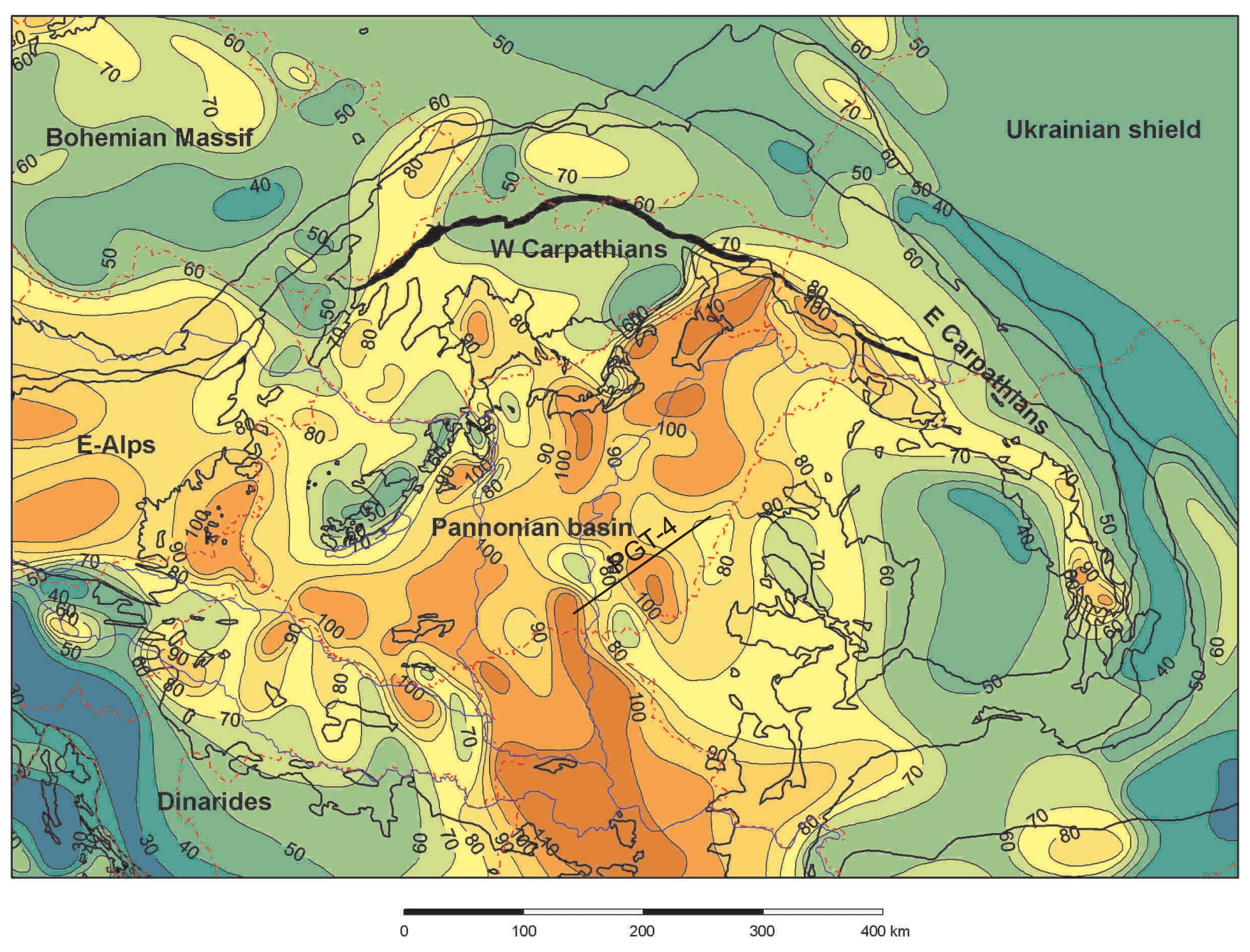
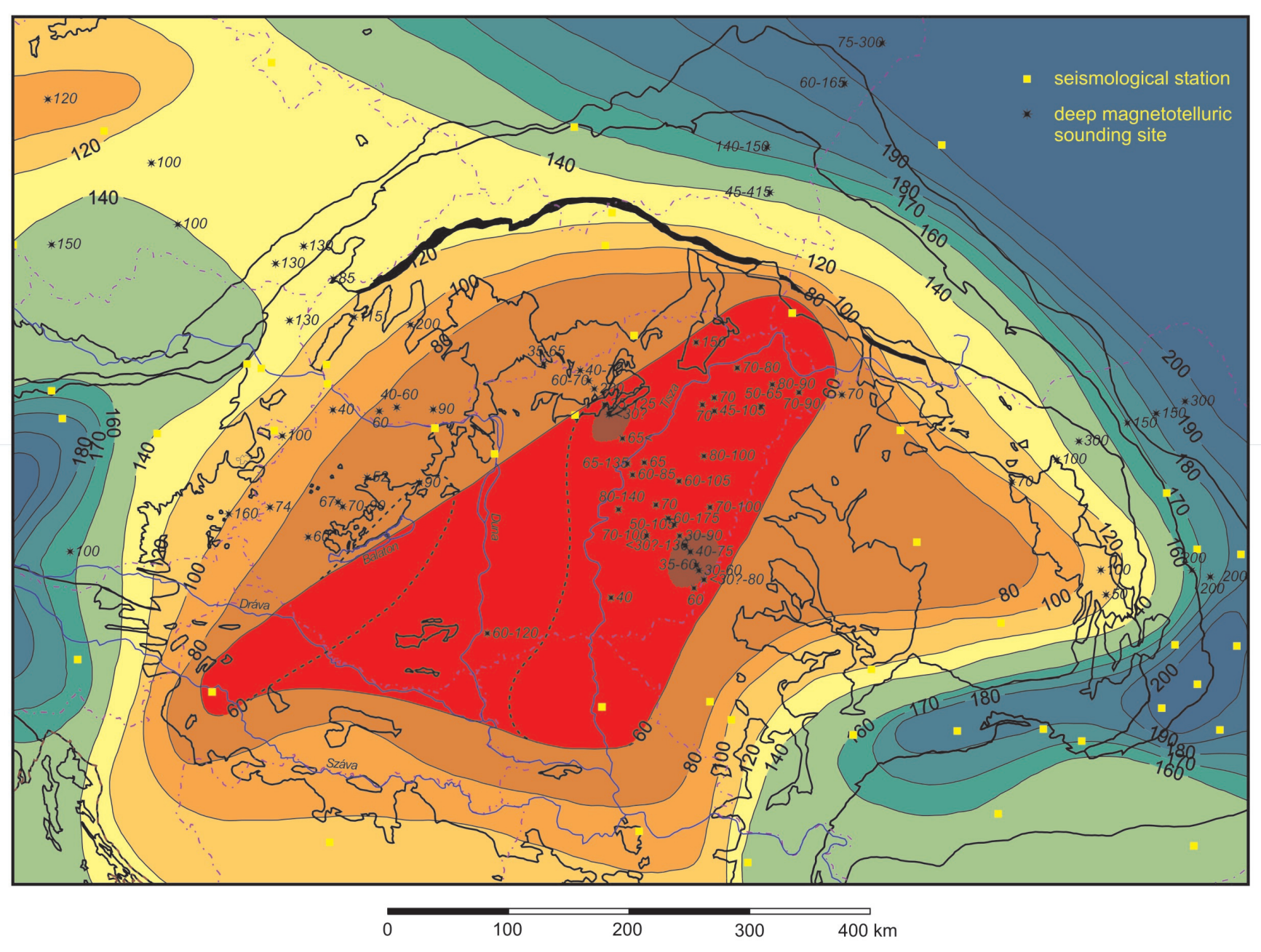
1. Introduction

Tectonic and geologic processes often distort the temperature field resulting in non steady-state field. Very often we have thermal data (temperature, and rock physical properties) from shallow depth and we would like to interpolate the temperature to larger depth. In the interpolation we assume undisturbed steady state, or by other words, linear temperature increase with depth (neglecting also groundwater flow). It is evident that for lithospheric scales we cannot follow this procedure. In this study it is investigated whether for depth scales applied in geothermal energy research (1-6 km) the temperature increase with depth is linear or not. We present a few geologic processes, synthetic thermal models and examples.

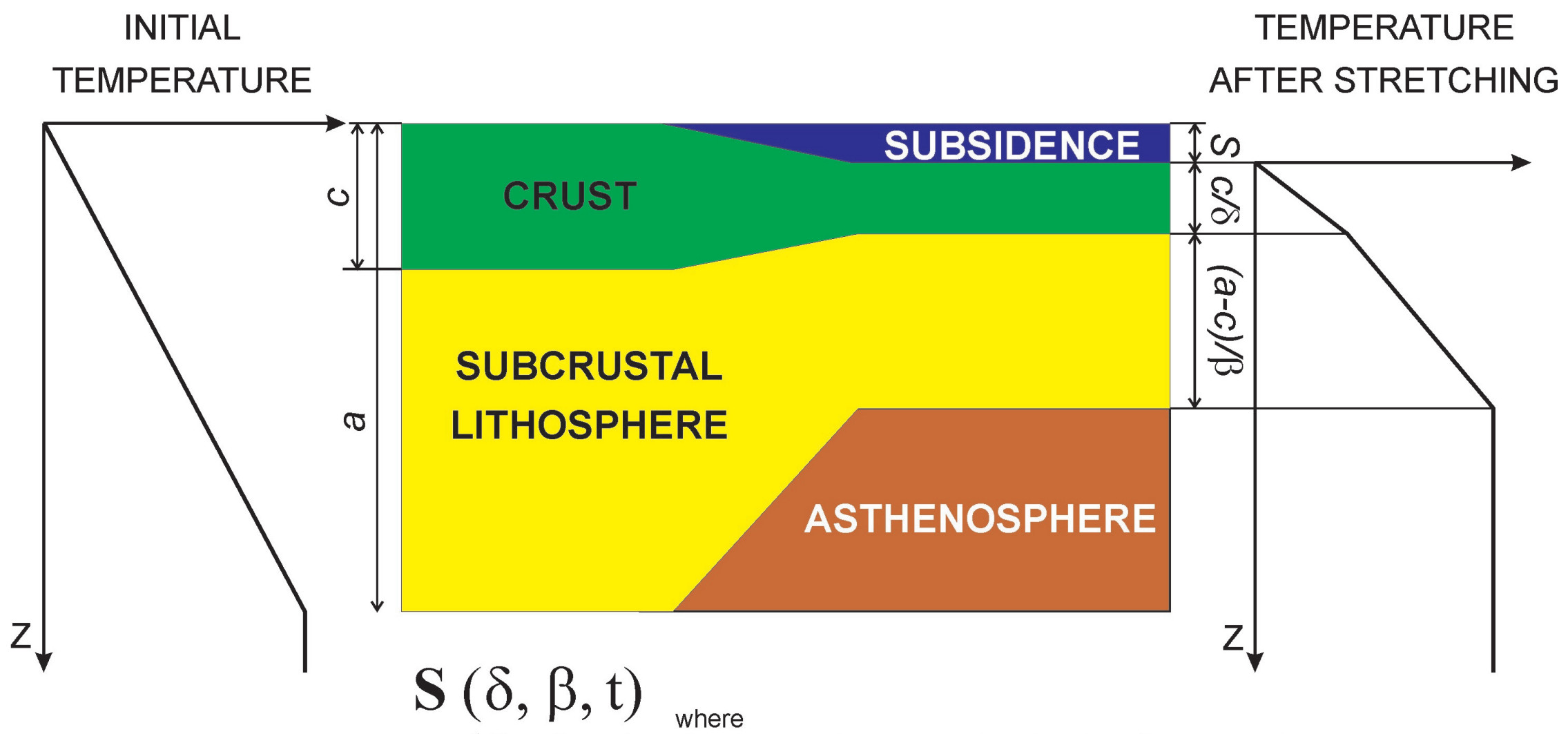
HEAT FLOW IN THE PANNONIAN REGION



THICKNESS OF THE LITHOSPHERE IN THE PANNONIAN REGION



2. Kinematic model of lithospheric stretching



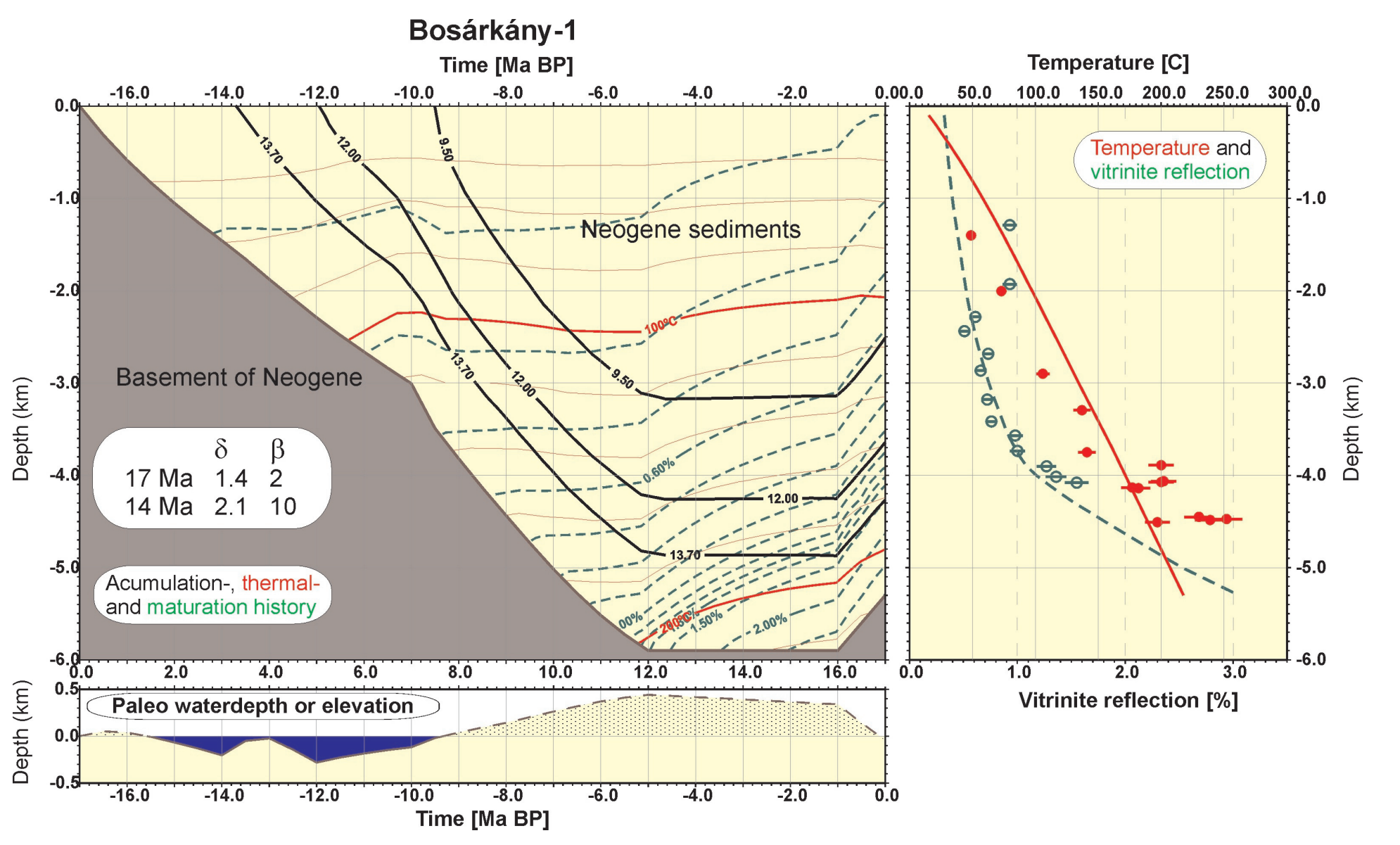
$\mathbf{S}\,(\delta, \beta, t)$

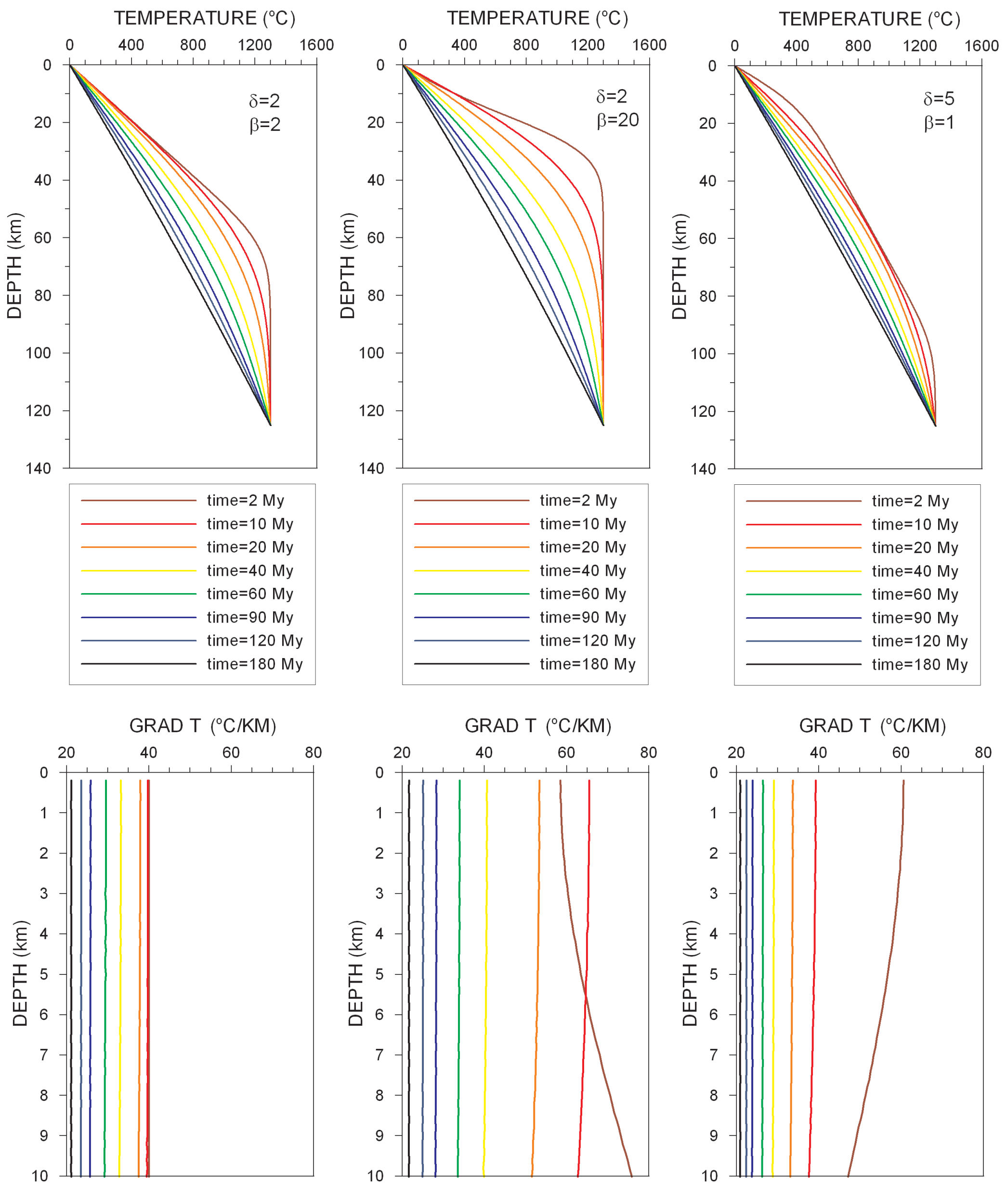
$\mathbf{q}\,(\delta, \beta, t)$

where
S and q are subsidence and surface heat flow, respectively
δ and β are the crustal and mantle stretching factors, respectively

Lithospheric stretching results in high temperature gradient, therefore high heat flow. Stretching is accompanied by the syn-rfit subsidence caused by isostatic restoring forces. Later, as the lithosphere cools it results in further subsidence (post-rift or thermal subsidence) due thermal contraction. The stretching factors can be determined from the subsidence history. Alternatively, the recent observed heat flow, temperatures and vitrinite reflectances can also be used to constrain the stretching factors.
Applying the lithospheric stretching model the thermal history of sediments can be calculated. In case of good fit to the observed temperatures and vitrinite reflectances the chances that the model predicts the deep temperatures correctly are bigger.

Thermal maturation of sediments calculated using the stretching model





uniform stretching

subcrustal dominated stretching

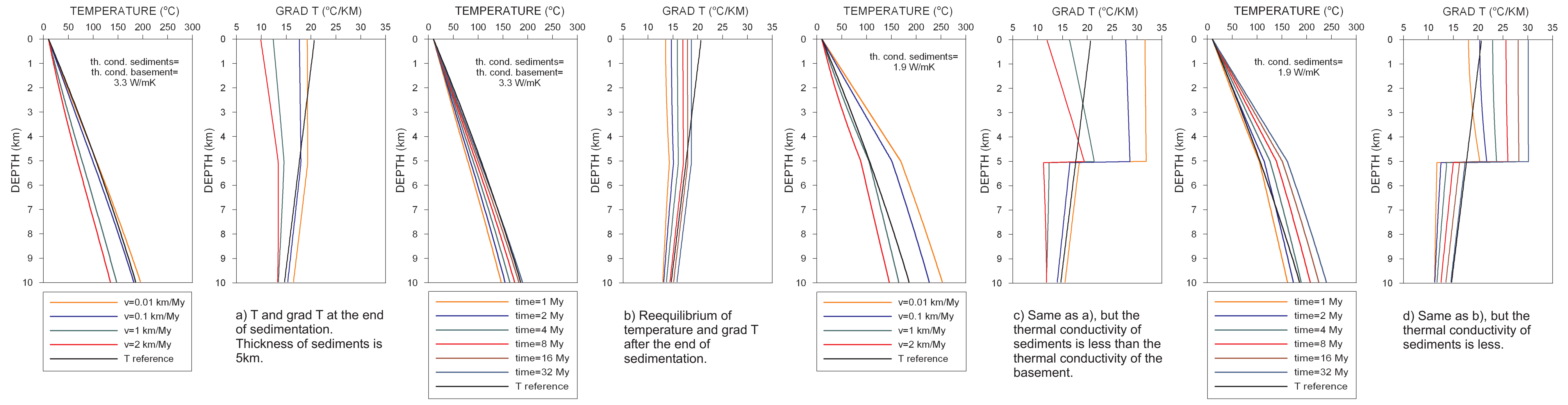
only crustal stretching

Parameters of the thermal models in the synthetic results

Parameter	Value
initial crustal thickness	30 km
initial lithospheric thickness	120 km
temperature at 125 km depth	1300 °C
thermal diffusivity	8.710^{-7} m^2/s
thermal conductivity of crust	3.3 W/mK
thermal conductivity of mantle	4 W/mK
thermal conductivity of sediments	3.3 or 1.9 W/mK
heat production in the upper crust	2 $\mu W/m^3$

3 Sedimentation

Sedimentation distorts the thermal field due to two reasons: 1) the deposited sediments are cold. It takes time for them to be heated up and reach steady state. During and following sedimentation they cool the underlying lithosphere. 2) The thermal conductivity of sediments is generally lower than the thermal conductivity of crystal rocks (their basement). Due to their lower conductivity the thermal gradient in the sediments will be higher than in the underlying rocks. They insulate the underlying rocks resulting in higher temperatures, called “blanketing effect”. The decay time of high thermal anomalies is also prolonged. During sedimentation the first effect prevails, as the sediment approach steady state the second effect becomes dominant.
Erosion has the opposite effect on the thermal field than the cooling effect of sedimentation. Therefore, it is not shown here. An extreme mode of erosion, the tectonic unroofing is shown at the model of metamorphic core complexes.



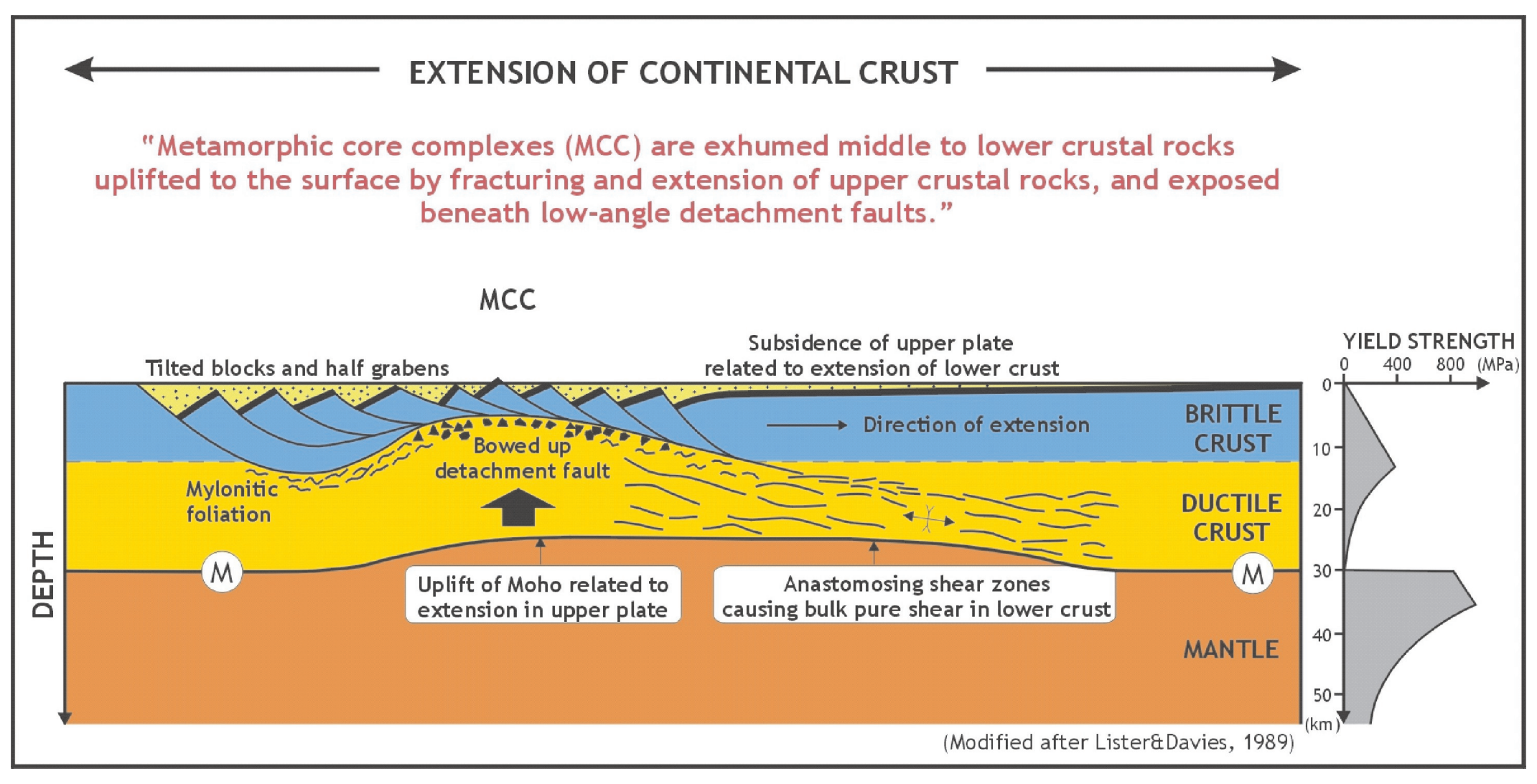
a) T and grad T at the end of sedimentation. Thickness of sediments is 5km.

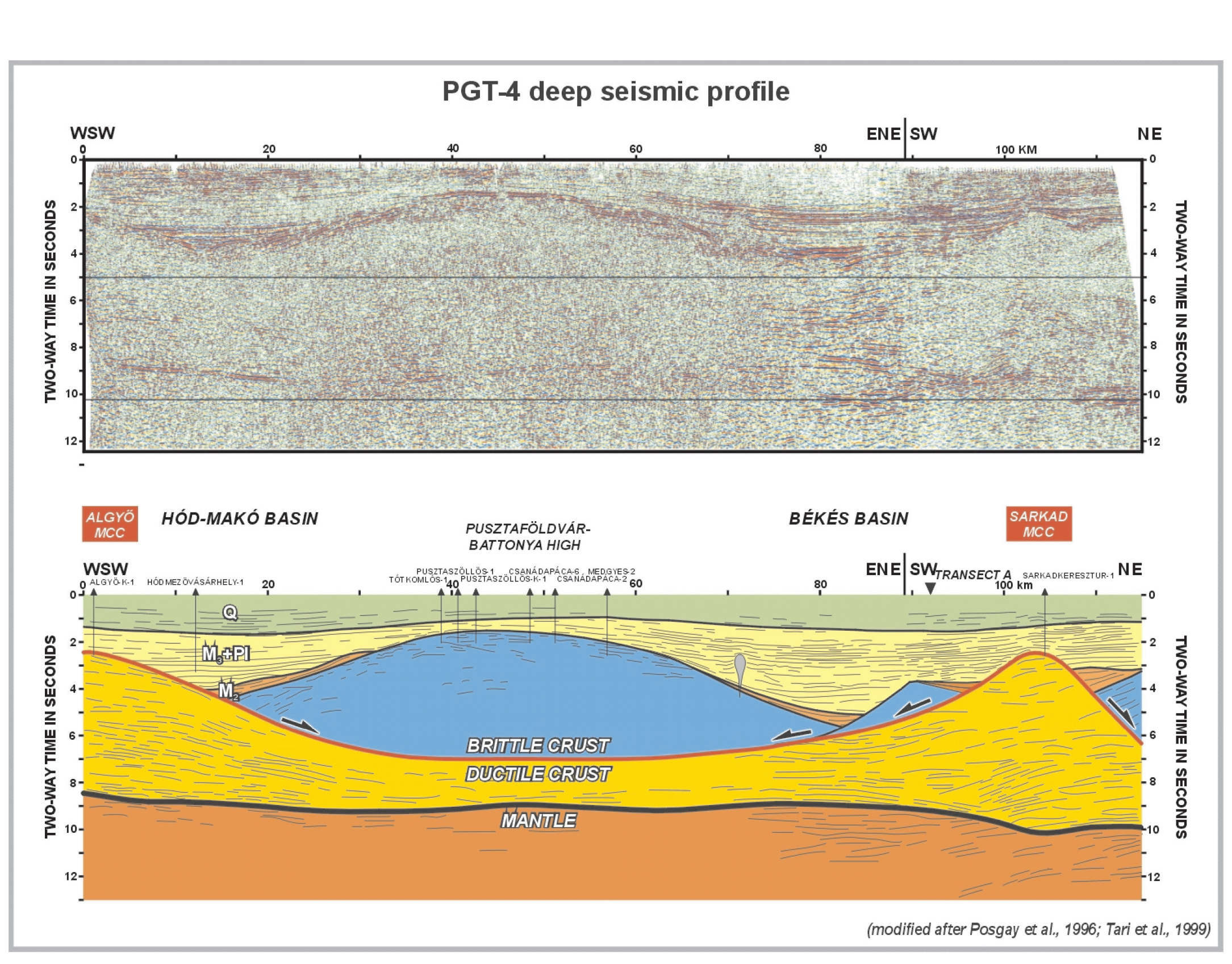
b) Reequilibrium of temperature and grad T after the end of sedimentation.

c) Same as a), but the thermal conductivity of sediments is less than the thermal conductivity of the basement.

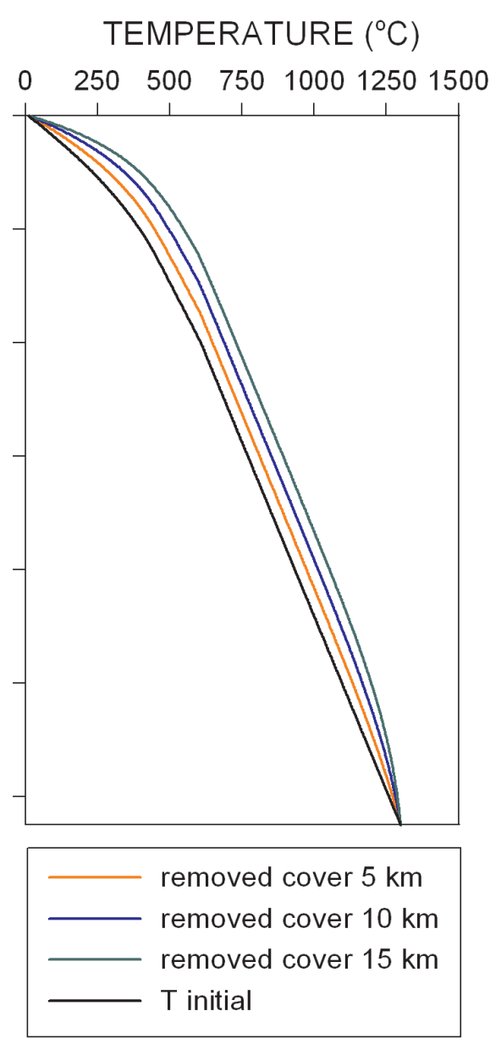
d) Same as b), but the thermal conductivity of sediments is less.

4. Metamorphic core complex formation



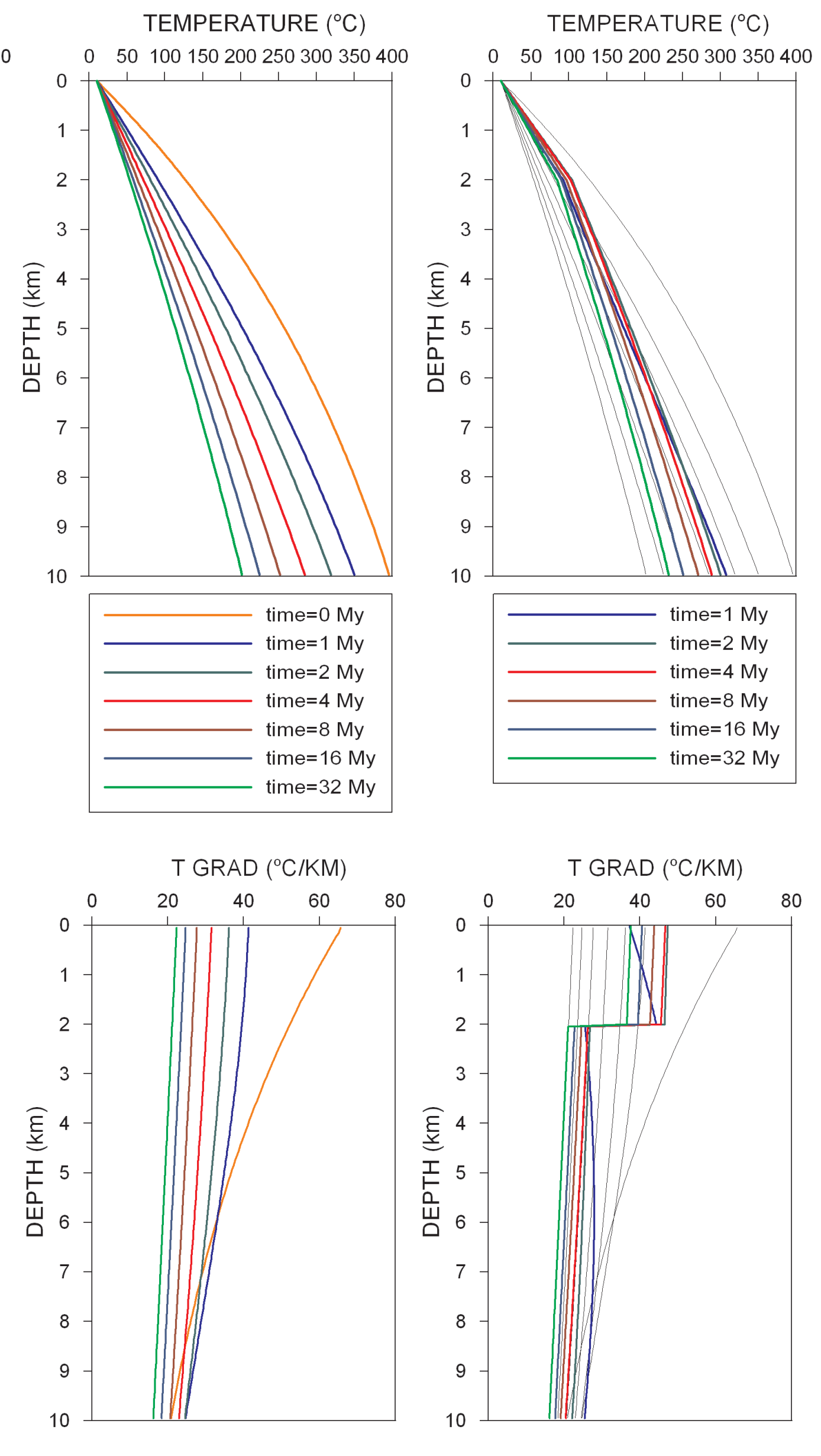


Location of the seismic line see in the heat flow map



Temperature in the lithosphere after the end of metamorphic core complex formation

Parameters of the model:
15 km of upper crust was removed during 5 M years.
After core complex formation 2 km sediments were deposited in 1 M year.
For numerical values see table.

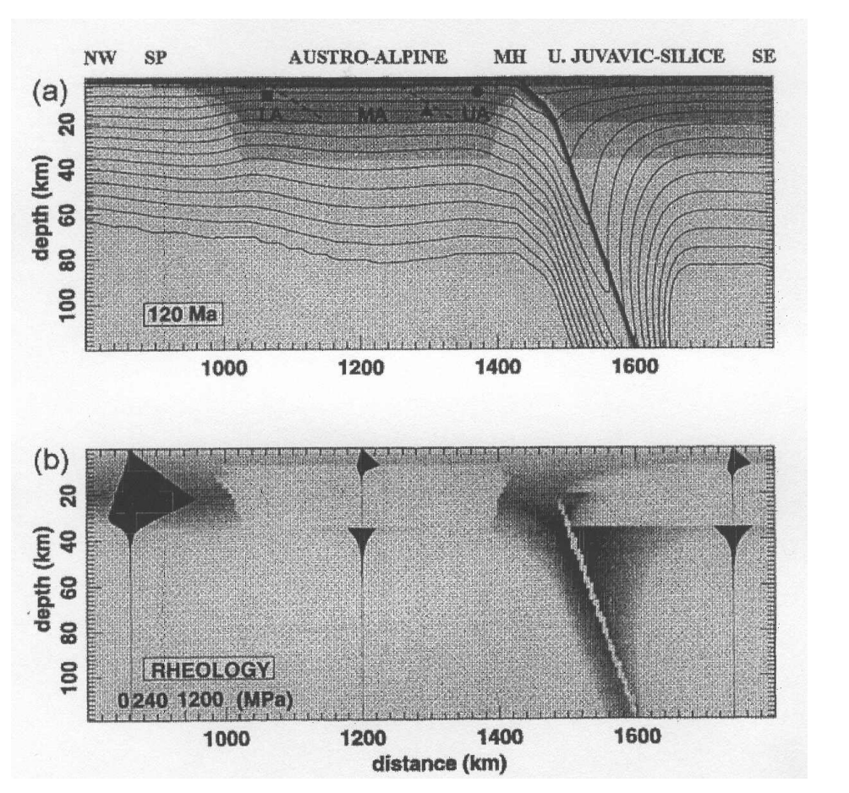


Cooling of the core complex

Cooling with 2 km sediments on top.

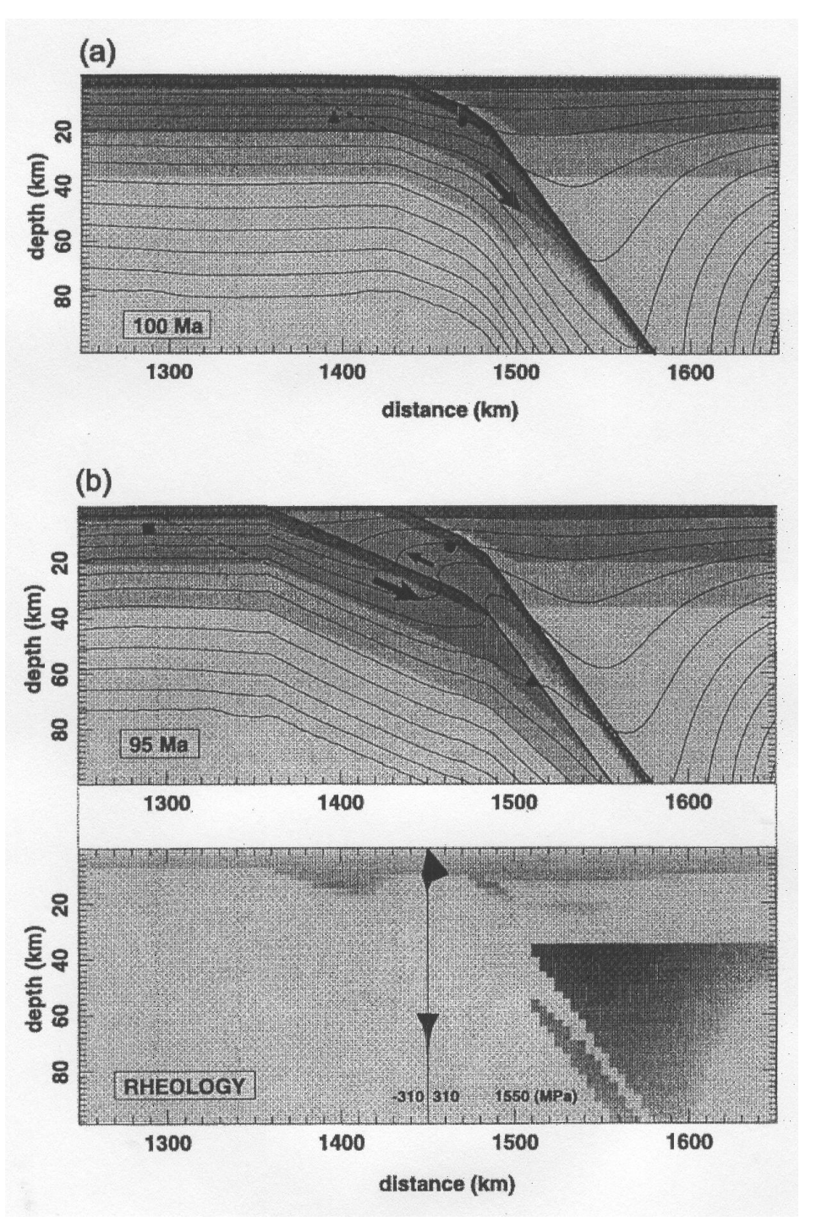
5. Models of subduction

Kinematic models of subduction allow to estimate the deep lithospheric temperatures, and thus calculate the rheology of the lithosphere. The modeling is useful to understand the geologic processes acting during subduction. Similarly to the lithsopheric stretching, it influences the near surface temperature when it is active or shortly after its activity.



a) Temperature model of subduction in the Eastern Alps during Cretaceous after Willingshofer et al., 1999.

b) Lithospheric strength calculated from the temperature distribition of Fig. a.



Same model at a later stage of subduction

6. Conclusions

Lithospheric stretching causes high lithospheric-, core complex formation causes high crustal thermal gradient and heat flow. In both cases the thermal anomalies are transient and decay with time. Immediately after the tectonic events the near surface temperature gradient varies with depth even in case of uniform rocks. After a few million years the upper crustal temperature gradient becomes constant. Therefore, the near surface thermal gradient can be used to interpolate temperature to larger depth, regardless that the thermal field is not steady-state. However, the blanketing effect of sediments results in high near surface thermal gradient, which can be considerably smaller in the basement. Therefore, in case of sediments the near surface temperature gradient cannot be used to interpolate the temperature to greater depth.
To increase the reliability of temperature interpolation we must know the thermal parameters of rocks from larger depth and the geometry of the formations. Additionally, the dependence of thermal conductivity on the temperature must be taken into account.
Thermal models of tectonic processes are useful, because due to the long thermal decay constant of the lithosphere the present day thermal state of the lithosphere may be inherited from geologic processes acted in the past.