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Thermal state of the lithosphere in the Danube Basin and its relation to tectonics

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Abstract: The area of the Danube Basin is interesting in the light of the evaluation both of the lithosphere structure and of various theories of Carpathian-Pannonian region tectonic evolution. The aim of this paper is to analyse both the thermal conditions in the Danube Basin and the mutual relations to geological structure and tectonic development of the region under study. First the improved distributions of the terrestrial heat flow density and of the lithosphere thickness were constructed using recently gained geophysical and geological knowledge. Then the critical analysis of existing models of the tectonic development of the region under study was carried out. The tectono-thermal interpretation activities were accomplished by new geothermal modelling approach for transient regime which utilizes also the backstriped sedimentology data as a control parameter of model. Finally the McKenzie's "pure-shear" model of the Danube basin was constructed as acceptable conception for used geothermal and tectonic data. The determined stretching parameter has an inhomogeneous horizontal distribution and the thinning factors express the depth dependency for separate lithospheric layers.

Key words: Western Carpathians, Danube Basin, geothermal field, tectonics, thermal modelling

1. Introduction

The Danube Basin is situated in the territories of Slovakia, Hungary and Austria. In Slovakia it is geographically termed the Danube Lowland while in Hungary and Austria it is referred to as the Little Hungarian Plain. The Danube Basin represents the NW part of the Pannonian backarc basin system. It is situated between the Eastern Alps, the Western Carpathians and the Transdanubian Central Range (*Konečný et al., 2002*).

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The Danube Basin is a structure about 240 km long and 100 km wide with roughly NE-SW orientation (Fig. 1). The north-western border comprises units of the Central Eastern Alps, the Leitha, Hundsheim and Malé Karpaty mountains. The northern margin is represented by the Považský Inovec and Tribeč mountains belonging to the Central Western Carpathians. The Burda Mountains form the margin in the NE while the Hungarian Transdanubian Central Range Mountains represent the SE border of the basin (*Plašienka et al., 1997; Kováč, 2000; Rasser et al., 2008*).

The pre-Cenozoic basement is built up by the Austro-Alpine and Slovako-Carpathian units in the western, northern and central part of the basin. The basement of the SE margin comprises units of the Transdanubicum (*Fusán et al., 1987; Fülöp et al., 1987; Horváth, 1993; Plašienka et al., 1997*).

The basin is divided into several depocentres (Fig. 2). Along the northern margin there are from west to east: the Blatné, Rišňovce and Komjatice depressions (separated by the Považský Inovec and the Tribeč mountains). In

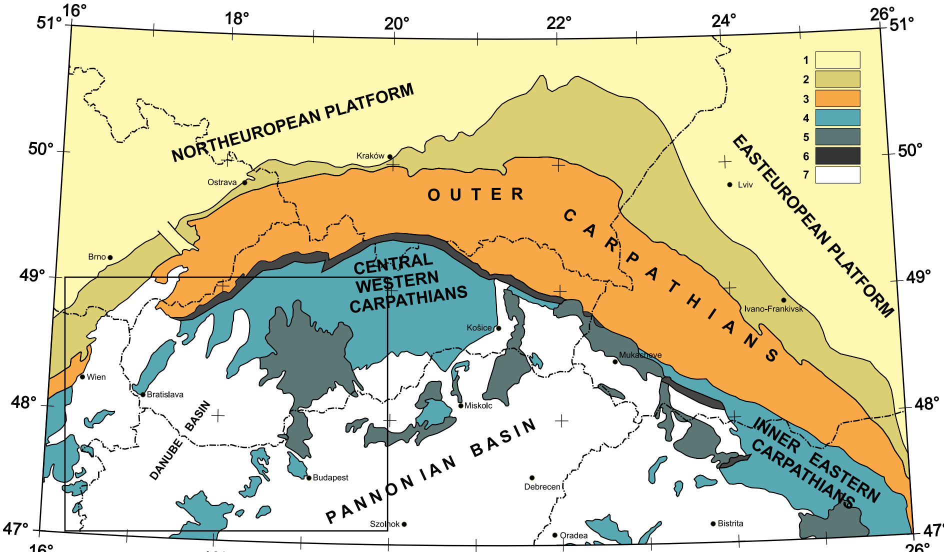

Fig. 1. Position of our region under study in western part of the Carpathian-Pannonian region. Map modified after *Kováč (2000)*. Structure description: 1 – European platform, 2 – Foredeep units, 3 – Alpine-Outer Carpathian Flysch Belt, 4 – Inner Alpine-Carpathian units, 5 – Neogene volcanites on the surface, 6 – Pieniny Klippen Belt, 7 – Neogene and Quaternary sediments.

the NE part, the Želiezovce sub-basin is located between the Levice Horst and the Transdanubian Central Range Mountains. The southern, Hungarian part of the Danube Basin is separated by the NNE-SSW trending Mihályi High into two major sub-basins parallel with the Répce Fault in the west and the Rába Fault in the east. The deepest part of the Danube Basin is in the Gabčíkovo sub-basin with a maximum thickness of Neogene sediments of more than 8.5 km (*Kilényi and Šefara, 1989; Hrušecký et al., 1993, 1996*). The Tertiary-Quaternary filling of the basin mainly consists of sands, clays, shales, sandstones with isolalted limestones and evaporites,

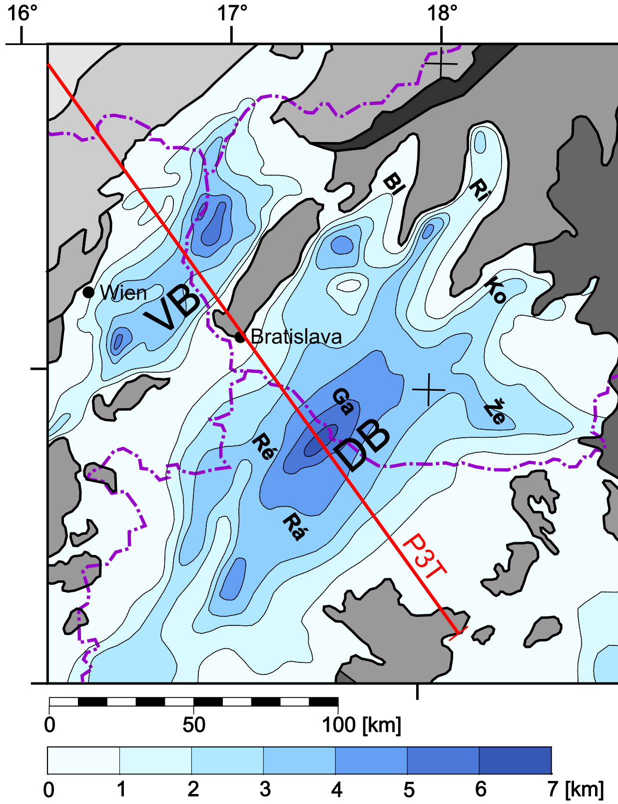

Fig. 2. Danube Basin – position both of basin depocenters and of the main interpretation profile (*Kováč, 2000*). DB – Danube Basin, VB – Vienna Basin, GHP – Great Hungarian Plane. Depressions: Ga – Gabčíkovo, Bl – Blatné, Ri – Rišňovce, Ko – Komjatice, Že – Želiezovce, Re – Répcze, Ra – Rába depression. Blue scale – depths of the Pre-Tertiary basement.

and also clays and marls in the layer closest to the surface (*Bielik, 1988*).

The area of the Danube Basin is interesting in the light of the evaluation both of the lithosphere structure and of various theories of the Carpathian-Pannonian region tectonic evolution in relation to the geothermal data. Both the terrestrial heat flow and the temperature distributions provide the basic information on the geothermal processes at depth. The present lithosphere thickness determined by geophysical data (including the geothermic ones) also provides an important check parameter for tectonic hypotheses. The knowledge about the structure, tectonics, and the thermal state of the lithosphere becomes significant information for the determination of geothermal energy source parameters.

The basic geothermic knowledge within the region under study is built on the direct geothermic methods – measurements of temperatures and thermo-physical parameters. The data from Slovakia were published in plenty of partial studies and were summarized mainly in *Král et al. (1985)* and in *Franko et al. (1995)*. These publications also contain interpretations of geothermic data in the form of terrestrial heat flow density distribution, temperature distribution maps both in various depth levels and on cross sections within upper parts of the upper crust. The publications *Čermák (1978, 1979)* and *Čermák et al. (1992)* fold the data both from Czech Republic and from Slovakia into the geothermic interpretations. The determined Hungarian heat flow density values of *Dövényi et al. (1983)* and *Dövényi, Horváth (1988)* were interpreted by *Lenkey et al. (2002)*. The subsurface temperature distribution maps from the Hungarian region were constructed in the project *"Altener II" (2005)*. The *"Transenergy" project report (2013)* provides the geothermic data and their interpretations over the predominant part of the Danube Basin. The data from Austria are also included in these project analyses. Some synthetic works have tried to interconnect the selected geothermic data (most of them was the terrestrial heat flow data) over wider areas containing our studied region (e.g. *Čermák and Hurtig 1979; Hurtig et al., 1992; Lenkey et al., 2002*).

The geothermal modelling results along the profiles crossing the studied geological units of the Western Carpathians provide very important information about both the temperature and heat flow density distributions in the lithosphere, and moreover, about the relations of geothermal data with structures and tectonics. The models calculated in steady state regime were made by *Bielik et al. (1991), Majcin (1993)* and others. The results of the geophysical integrated modelling approaches were presented in *Zeyen et al. (2002), Dérerová et al. (2012, 2014)* and *Grinč et al. (2014)*. Both classic geothermic and integrated modelling approaches contributed to the determination of the main structural boundaries, namely the lithosphere-asthenosphere (LIAS) transition zone, MOHO and others in the region under study (*Bielik et al., 1991; Majcin, 1993; Zeyen et al., 2002; Bielik et al., 2004; Bielik et al., 2010; Grinč et al., 2014*). The geothermal results complemented the attempts of other geophysical branches (such as *Babuška et al., 1987; Praus et al., 1990*, and others) or tried to include them into their analyses.

In this study we focused our activities on analysis both of the thermal conditions in the Danube Basin and surrounding units and of the mutual relations to geological structure and tectonic development of the studied region. First the distributions of the temperature, heat flow density, and lithosphere thickness were constructed on recently gained geophysical and geological knowledge. Then, based on the interpretations of geothermal data, the critical analysis of the existing models of the tectonic evolution was accomplished. Special attention was paid to the role of the thermal subsidence. The modelling methods for the transient temperature fields are part of the applied approaches. They represent the continuation of methods used for the modelling of the heat transfer along various profiles crossing the Western Carpathians (*Majcin et al., 1994, 1998, 2014*).

2. Methods and results

2.1. Geothermic modelling methods

The numerical calculations of the temperature fields for tectono-thermal interpretations were carried out for both the steady state and transient regime of the heat transfer equation. Derived math-physical tasks in bounded 2D/3D areas were solved by means of finite difference methods (*Majcin, 1982*) and/or by finite element approaches (using the COMSOL Multiphysics® modelling software with the Heat Transfer Module). In selected geothermal modelling tasks with simple structures and for 1D problem, we employed known analytical solutions of the heat transfer equation (*Buntebarth, 1984; Kutas et al., 1989)*. For construction of structural models we used the thermophysical parameters from *Majcin (1993)* and the temperature for the lithosphere asthenosphere boundary was fixed to 1330 °C because of compatibility with specialized tectono-thermal modelling approaches used in this paper.

2.2. Geothermic data interpretation

The primary tectono-thermal analysis is based on the geothermic data interpretation. First we constructed the map of the terrestrial heat flow density distribution and then also the map of the lithosphere-asthenosphere transition zone depth.

The first map came from heat flow density determinations from the studied region or wider area stored in databases and/or interpreted in the form of the isoline maps (*Global heat flow database, 2011; Čermák et al., 1992; Hurtig et al., 1992; Franko et al., 1995; Lenkey et al., 2002* and others). In addition we used the knowledge from geothermic and integrated modelling along profiles coming through the Danube Basin *(Bielik et al., 1991; Majcin, 1993; Zeyen et al., 2002; Dérerová et al., 2012*) and the temperature distribution maps in various depths from the surface (*Franko et al., 1995; "Altener II", 2005; "Transenergy", 2013).* Last but not least we applied the results of geothermic modelling related to refraction effects on structures with great thermal conductivity contrast (*Majcin, 1992; Majcin and Polák, 1995; Hvoždara, 2008; Majcin et al., 2012*, and others). The final map of the terrestrial heat flow density distribution for studied area is presented in Fig. 3.

The heat flow density values greater than 70 mW/m^2 are typical for the prevailing part of the Danube Basin. In the central area of the basin the values are greater than 90 mW/m^2. This area of the highest heat flows extends to the deepest parts of the Gabčíkovo depression in the northern Danubian Lowland. In the southern Little Hungarian Plain the anomalous region bounded by isoline of 90 mW/m^2 looks like a superposition of increased heat flux along the separate fault zones in the Répcze and Rába depressions. Generally the values of the terrestrial heat flow density in Danube Basin are directly proportional to depths of the pre-Tertiary basement (Fig. 2 and Fig. 3). The shapes of the terrestrial heat flow distribution isolines indicate that the main anomaly is nearly symmetrical to the line

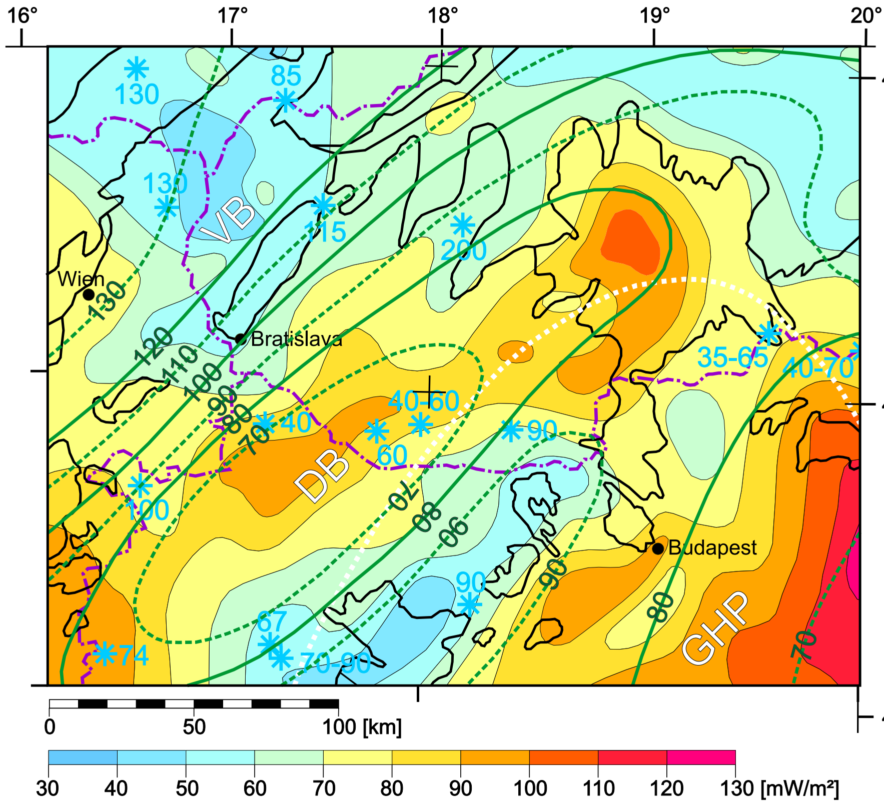

Fig. 3. Correlation map of the terrestrial heat flow density distribution (colour scale in mW/m^2) and lithosphere thickness distribution (in km) both from geothermal data (military green solid and dashed isolines) and from magnetotelluric data at the determination positions (blue colour stars and values). Dotted white line – the projection of the NW boundary of the subducted slab's remains to the Earth's surface (*Konečný et al., 2002*).

with SW-NE orientation. The line is parallel with the Rába fault zone.

The heat flow density strongly decreases in the direction of the Vienna basin. The greatest horizontal gradients exist at the Malé Karpaty Mts. We suppose that in deeper parts of the Earth's crust the greatest horizontal changes of the heat flow density distribution are related to the Mur-Mürz-Leitha fault zone representing the contact of the Eastern Alps with the block of the Western Carpathian internides.

The similar decrease tendency of the surface heat flows on the Earth's surface is also observed in the opposite direction namely on the contact zone of the Inner Carpathian units with the Transdanubian Central Range block. In both these neighbouring geological units the terrestrial heat flow densities are smaller than the value of the 50 mW/m^2. This is evidently visible on the interpretation profile P3T (Figs 2, 3, 4). The terrestrial heat flow density distribution in the Danube Basin shows that the increased values are limited also in the direction of the main anomaly axis both in the north and the south side.

When constructing the lithosphere thickness map for the Danube Basin and surrounding units we used the results both of the stationary geothermic modelling (*Majcin, 1993; Čermák, 1993)* and of the integrated modelling (*Bielik et al., 2004; Dérerová et al., 2006*) along the profiles crossing the region under study and the associated interpretations. The papers also contain critical analysis of the earlier models and/or of the models obtained from other geophysical approaches. The character of the lithosphere thickness distribution coincides there in global features. The thickness of around or less than 80 km is typical for the main part of the Danube Basin region. In the central part of the basin we suppose the LIAS transition zone position at depths coming near the values of 65–60 km. In the Vienna basin and farther in the Bohemian Massif the lithosphere thickness increases to 120–130 km. The greatest horizontal changes exist southeasterly from the fault zone Mur-Mürz-Leitha-Láb-Dobrá Voda and they are observed in the direction perpendicular to this fault system. The main interpretation attention was paid to the SW part of the Transdanubian Central Range with the zone of very low heat flows. The simple 1D extrapolation models suggests that the thickness of the lithosphere is markedly higher than 100 km. Similarly high values were supposed also by *Čermák (1993)* and besides the greatest values were plotted by him in the southern part of the studied Transdanubian lithospheric block. Even if the influence of hydrological factors and refraction effects on the determined surface heat flow densities will be assumed, the actual thickness of the lithosphere below the SW part of the Transdanubian Central Range will be from the interval 90–100 km. The contribution of *Dérerova et al. (2006)*, integrating the results of various geophysical approaches, suggests the values between 80 km and 100 km. The isolines with the value 90 km is not drawn on their map, but from the shape of the isoline of the 100 km we deduced that the result thick-

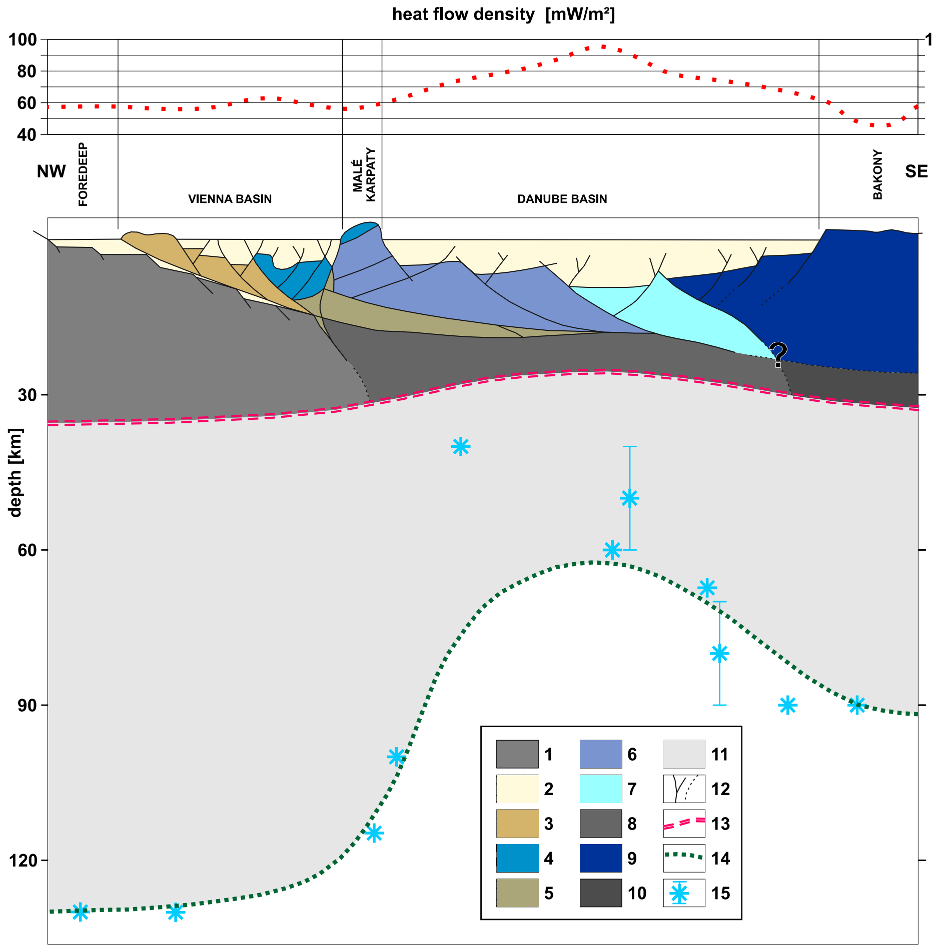

Fig. 4. Sketch of geological structure along the interpretation profile crossing the Danube Basin and surrounding units (*Kováč, 2000*) with the geothermic and magnetotelluric data. 1 – Bohemian massif units, 2 – Neogene sediments, 3 – Flysch zone, 4 – Northern Calcereous Alps, 5 – Peninic-Vahic, 6 – Central Western Carpathians Tatric upper crust, 7 – Central Western Carpathians Veporic upper crust, 8 – Central Western Carpathians lower crust, 9, 10 – Pelso units, 11 – mantle lithosphere part, 12 – faults and boundaries, 13 – atectonic MOHO boundary (according *Bielik et al., 2004*), 14 – lithosphere/asthenosphere transition zone determined from geothermal data, 15 – lithosphere thickness data from magnetotelluric sounding (*Praus et al., 1990*). Terrestrial heat flow distribution is plotted in upper part.

ness should be closer to the value of 100 km than to a lower plotted value. The interpreted rigid block of the Transdanubian lithosphere lies between the Danubian basin and the Great Hungarian Plain with the lithosphere-asthenosphere transition zones located at 60 km in their central parts. It is necessary to mention, that the rest of the subducted slab, lying bellow the Transdanubian Central Range (*Spakman et al., 1993; Konečný et al., 2002*), does not explain the very low observed heat flows. The buried body is too great in relation to the terrestrial heat flow density anomaly dimensions and the amplitude of anomalous heat flow caused by a body located at depths of 300–400 km will also not be sufficient.

We confronted our actual geothermal results (Fig. 3) with the measured magnetotelluric data (*Praus et al., 1990*), because we suppose that the electric definition of the lithosphere thickness is the most compatible with the geothermic one (sensu *Artemieva, 2011*). The geothermic and magnetotelluric results in the region under study are in high coincidence. Fig. 4 shows that on the interpretation profile P3T, crossing the central part of the Danube Basin, the magnetotelluric data suggest steeper change of the lithosphere thickness below the contact of the Central Carpathian units and of the Transdanubian block in the pre-Tertiary basement. Moreover from the magnetotelluric data we have the existence of two zones with higher conductivity in the depths up to 40 km. The stronger zone lies below the previously mentioned contact and the second zone (not so reliably affirmed) is placed nearly to the probable contact of the thick lithosphere of the Eastern Alps and Bohemian massif. Both zones may be explained by mechanically rebuilt areas/fault zones containing materials of higher electric conductivity and probably also with the somehow increased transfer of heat from deeper parts.

The existence of the mechanically rigid block of the lithosphere (with thicker crust determined in *Bielik et al., 2004; Horváth et al., 2015*) has great importance for the recent tectonic development of the studied region of the Danube Basin. From geothermic models based on transient approaches we have found that the thermal erosion of the lower parts of the studied Transdanubian lithosphere block for various reasonable starting configurations of the lithosphere thickness suggests that the block should be thicker in relation to surrounding units going back in time (i.e. to Miocene). Moreover the palinspastic reconstruction of the Carpatho-Pannonian region and volcanic activities in this region starting in the Early Miocene (*Konečný et al., 2002*) show that the thick lithospheric block in studied part of the Transdanubian Central Range acts as an impermeable area for volcanism. Some products of volcanism exist only around the area bounded by the 90 km lithosphere thickness isoline within SW part of the Transdanubian Central Range.

We suppose that the model of the classical "simple-shear" Wernicke subduction (*Wernicke, 1985*) with the delamination zone coming through the Transdanubian lithospheric block is less likely for recent tectonic activations (tectonic cycles) of the studied region of the Danube Basin and surrounding units. Such zone should not exist because of not suitable lithological and rheological conditions. However the Transdanubian lithospheric block may play the role of the transferring element in the tectonic movements/activities/pressure changes etc. between the Danube Basin and the Great Pannonian Plain. The tectono-thermal analysis will be focused more to the tectonic evolution theories/hypotheses based on the "pure-shear" approaches of the sedimentary basin development defined in *McKenzie (1978)* and/or on special (mixed) approaches. However we do not disclaim the existence of a delamination zone in the Central Carpathian units according to *Lankreijer et al. (1995)*. From structural and tectonic data (*Šefara et al. 1998)* and from our geothermal interpretation we find that the SE end of this should be bent down within suture structures. The oceanic crust in the suture was probably accompanied by a crust-mantle area influenced by higher thermal activity (thermally weakened zone). This may affect the thermal activations within the studied time section.

2.3. Geothermic modelling approach and tectonics

The geothermic modelling approaches in transient mode (with structural and geothermic parameters depending on time) have a high ambiguity level. The reliable and sufficiently well determined/defined outputs can be received only by application of a great amount of check parameters, by fixation of some input and process parameters and/or by selection from alternative models. The parameters prepared in the previous analytical part of this section play a great role in the modelling process. Other geological and geophysical data will also be used. We will also strongly focus on the thermal subsidence component in the global subsidence development of the Danube Basin.

It is also necessary to mention that the means of the transient geothermal modelling are able to explain sufficiently precisely the last geothermal activations in the sense of the time sequence, the space covering of separate activation effects, and the ordering according to the relative intensity of compared activation (at the moment the newer activation starts).

The "previous" thermal activations (in accordance with the introduced definition) are omitted or included in some way in the initial conditions of the model. Nevertheless some of them should be analysed partially up to the level of the independent information. The subsidence (accordingly the thermal subsidence component) is one of the applicable parameters for this purpose.

2.4. Thermal subsidence calculation methods

A. Calculation of maximum thermal subsidence

Uniform and instantaneous stretching of the lithosphere results in thermal expansion and thermal uplift that causes subsequent subsidence. Applying the principle of isostasy the following expression can be derived (*Wangen, 2010*) for the initial subsidence S_i:

$$S_i = h_a \left(1 - \frac{1}{\beta}\right) \frac{\left[(\rho_{m,0} - \rho_{c,0})\frac{h_c}{h_a}\left(1 - \frac{1}{2}\alpha_T T_a \frac{h_c}{h_a}\right) - \frac{1}{2}\rho_{m,0}\alpha_T T_a\right]}{\rho_{m,0}\left(1 - \frac{1}{2}\alpha_T T_a\right) - \rho_s} \,. \tag{1}$$

The list of symbols as well as values of parameters used in this work is given in Table 1.

Using an approximation of expression $1-(1/2)\alpha_T\, T_a \approx 1$ (in our case this is equal to 0.976) in the relation (1), the right hand side can be rewritten as a difference of two parts – one is for maximum subsidence S_{max} without thermal expansion, and the other is for maximum thermal subsidence $S_{T,max}$:

$$S_i = S_{max} - S_{T,max} \,, \tag{2}$$

$$S_{max} = \left(1 - \frac{1}{\beta}\right) \frac{(\rho_{m,0} - \rho_{c,0})}{(\rho_{m,0} - \rho_s} \, h_c \,, \tag{3}$$

$$S_{T,max} = \frac{1}{2}\left(1 - \frac{1}{\beta}\right)\frac{\rho_{m,0}}{(\rho_{m,0} - \rho_s)}\,\alpha_T\,T_a\,h_a\,. \tag{4}$$

Thermal expansion of the lithospheric mantle causes the reduction of subsidence by conductive cooling which leads to long-term thermal subsidence. The dependence of values S_i and $S_{T,max}$ on stretching coefficient β is illustrated on Fig. 5. The perturbed thermal state of the lithosphere returns very slowly to its steady-state thermal regime and this cooling process will take approximately 100 Ma (*Wangen, 2010*) for the case with lithosphere thickness $h_a = 120$ km and its thermal diffusivity $\kappa = 1.10^{-6}\ \mathrm{m^2\,s^{-1}}$.

Table 1. Values and description of parameters in the expression (1). References labeling: [1] *Wangen (2010)*; [2] *Cloetingh et al. (2004)*.

h_a	80, 100, 120 km	thickness of lithosphere
h_c	30 km	thickness of crust
T_a	1330 °C	temperature at the lithosphere base [2]
α_T	$4 \times 10^{-5}\ \mathrm{K^{-1}}$	thermal expansibility coefficient for crustal and lithospheric rocks [1]
ρ_s	$2300\ \mathrm{kg\,m^{-3}}$	sediment density [2]
$\rho_{m,0}$	$3330\ \mathrm{kg\,m^{-3}}$	mantle density at reference temperature (0 °C) [2]
$\rho_{c,0}$	$2900\ \mathrm{kg\,m^{-3}}$	crust density [2]
β	1.15 – 3	value interval of stretching factor for lithosphere

B. Numerical calculation of thermal subsidence history

To calculate the thermal subsidence values at selected time intervals we have used a numerical model (created by the COMSOL Multiphysics® modelling software with the Heat Transfer Module) for the solution of transient heat transfer equation with internal heat generation by the finite element method. In addition to parameters listed in Table 1 the model calculations have adopted several input thermophysical parameters which are listed in Table 2. Transient solution was confined to time interval (1, 20) Ma after the stretching event.

Model geometry design was driven by the adopted interval (1.0, 3.0) of stretching factor β for the whole lithosphere. Based on this choice of β values several variations of thickness (40 km, 60 km and 80 km) of compressed lithosphere layer in the Danube Basin location were assumed in the

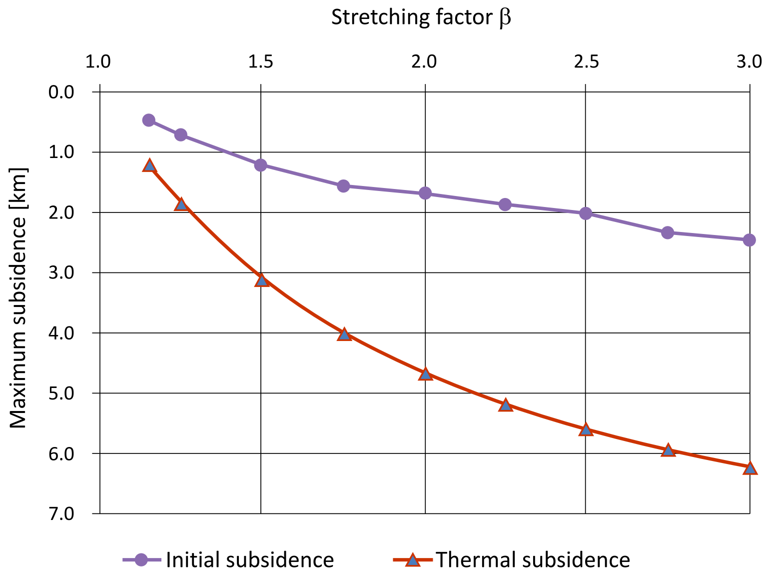

Fig. 5. The dependence of initial and maximum thermal subsidence on stretching factor value for the case of lithosphere initial thickness 120 km.

model. The depth of the Danube Basin in the model area had a constant value of 3 km. For the crust layer the thickness of 30 km was taken as that which corresponds most suitably to current knowledge about the area under study. For the lithosphere layer the reference initial thickness $h_a = 120$ km (*Wangen, 2010*) and initial temperature depth dependence similar to that assumed in *Corver et al. (2009)* have been adopted in the model.

To calculate thermal subsidence history $S_T(t)$ for a given position on the surface the distribution of temperature as a function of depth and time T(z,t) has been derived from the model outputs and then the following expression was used:

$$S_T(t) = \frac{1}{[\rho_m(T_a) - \rho_s]} \int_0^{h_a} [\rho_m\,(T(z,t)) - \rho_m\,(T_i(z))]\;\mathrm{d}z\,, \tag{5}$$

where $\rho_m(T_a) = \rho_{m,0}(1 - \alpha_T T_a)$ and $T_i(z)$ is the temperature depth profile at initial (perturbed) state. This formula is derived using the simplified assumption $\rho_c \approx \rho_m$ *(Wangen, 2010)* along with employing the principle of isostasy. The illustration of obtained temperature distribution in the model area is given on Fig. 6 and the calculated values of thermal subsidence as a function of time at the position of the basin centre are shown on Fig. 7.

Table 2. Values and description of thermophysical parameters used in model calculation. References: [2] *Cloetingh et al. (2004)*; [3] *Jaupart and Mareshall (2011)*; [4] *Eppelbaum et al. (2014)*; [5] *Majcin (1993)*.

Symbol	Value	Description
T_{surf}	$0\,^{\circ}\mathrm{C}$	surface temperature
ρ_s	$2300\ \mathrm{kg\,m^{-3}}$	sediment density [2]
ρ_m	$3300\ \mathrm{kg\,m^{-3}}$	mantle density [2]
ρ_{uc}	$2650\ \mathrm{kg\,m^{-3}}$	upper crust density [2]
ρ_{lc}	$2900\ \mathrm{kg\,m^{-3}}$	lower crust density [2]
ρ_a	$3250\ \mathrm{kg\,m^{-3}}$	astenosphere density [2]
κ_{uc}	$8.3 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$	upper crust thermal diffusivity [2]
κ_{lc}	$6.7 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$	lower crust thermal diffusivity [2]
κ_m	$8.75 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$	mantle thermal diffusivity [2]
κ_s	$2.3 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$	sediments thermal diffusivity [4]
k_{uc}	$2.5\ \mathrm{W\,m^{-1}\,K^{-1}}$	upper crust thermal conductivity [2]
k_{lc}	$2.0\ \mathrm{W\,m^{-1}\,K^{-1}}$	lower crust thermal conductivity [2]
k_m	$3.5\ \mathrm{W\,m^{-1}\,K^{-1}}$	mantle thermal conductivity [2]
k_s	$1.6\ \mathrm{W\,m^{-1}\,K^{-1}}$	sediments thermal conductivity [2]
k_a	$2.0\ \mathrm{W\,m^{-1}\,K^{-1}}$	asthenosphere thermal conductivity [3]
Q_{uc}	$1.5 \times 10^{-6}\ \mathrm{W\,m^{-3}}$	radiogenic heat source in upper crust [5]
Q_{lc}	$0.5 \times 10^{-6}\ \mathrm{W\,m^{-3}}$	radiogenic heat source in lower crust [5]

2.5. Geological setting and interpretation of data

For the purposes of the model parameters determination for recent thermal events in the tectonic development of the Danube Basin it is necessary to use the information from the wider surrounding area. The basin is a part of the Pannonian Basin System and some features are compatible with this part of the system (*Cloetingh et al., 2013*). *Royden et al. (1983)* provided a two-stage evolution of the Pannonian basin with a syn-rift (tectonic) phase during Early and Middle Miocene times and a post-rift subsidence phase during the Late Miocene–Pliocene. Later, based on development of

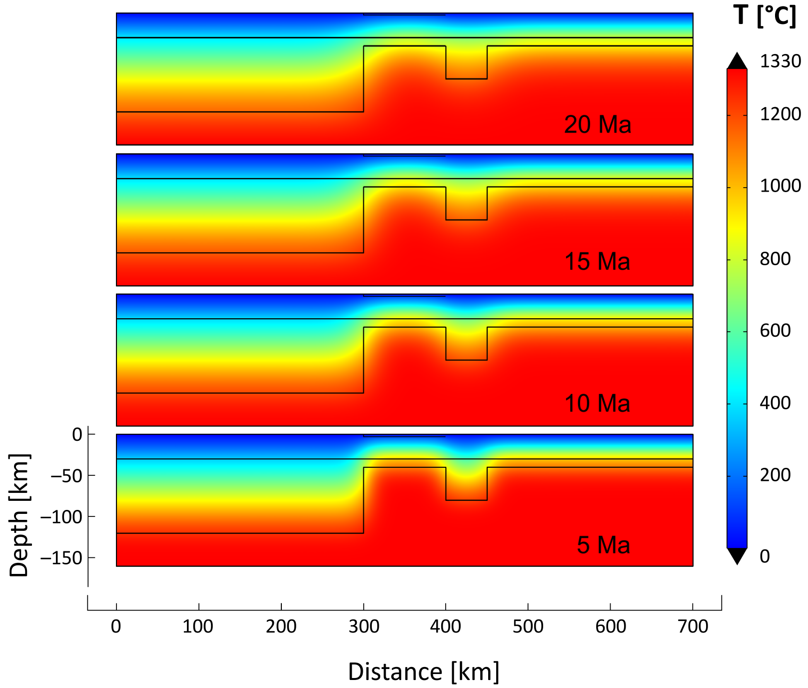

Fig. 6. Calculated temperature distribution in the model area for selected time intervals.

a stratigraphic database and on the subsidence curves of selected Pannonian sub-basins (including the Danube Basin), the scenario of the Pannonian basin subsidence history was refined (*Tari et al., 1999*). The history was divided into three main phases and the transition from syn-rift phase to post-rift phase was shifted to the Middle Badenian unconformity. The initial syn-rift phase is characterized by rapid tectonic subsidence, starting at about 20 Ma in the entire Pannonian Basin (*Cloeting et al., 2013*). This phase of the pronounced crustal extension is recorded everywhere in the basin system but it was mostly limited to relatively narrow, fault bounded grabens or sub-basins. During the subsequent post-rift phase much broader areas began to subside, reflecting general down warping of the lithosphere in response to its thermal subsidence. The third and final phase of the basin evolution is characterized by the gradual structural inversion of the Pannonian Basin system during the Late Pliocene–Quaternary. In the Late Pliocene the subsidence continued only in the basin's central and southern

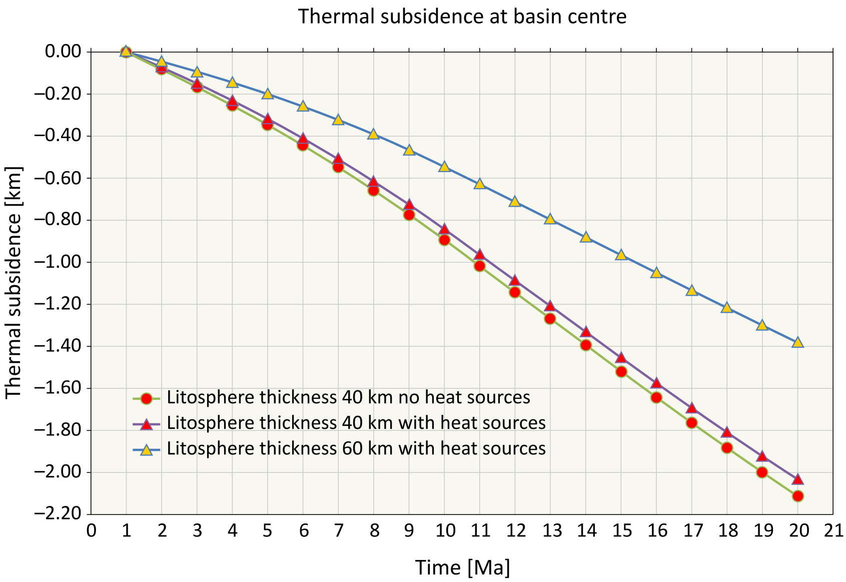

Fig. 7. Calculated thermal subsidence as a function of time at the basin centre for two models with different lithosphere thickness.

parts, while the northern marginal zone suffered inversion and the uplifted sedimentary fill began to be eroded (*Cloeting et al., 2013*).

Every sub-basin of the Pannonian basin system has own specific features in tectonic activities and their time application which is determined by position within the Carpatho-Pannonian realm. The tectono-thermal analysis of the Danube Basin is based on the backstriped (with removed effects both of loading and of compaction) sedimentology data published in *Lankreier et al. (1995), Kováč (2000)* and on realized additional analyses (*Rasser et al., 2008; Kováč et al., 2011* and *Cloetingh et al., 2013*). We took the palinspastic reconstruction of the Neogene evolution with volcanic activities mainly from *Kováč (2000)* and *Konečný et al. (2002).* The basic tectono-thermal analysis was done on the main interpretation profile P3T (Fig. 2) and then enhanced to the whole area of the Danube Basin also using the "equivalency" conditions in three main check parameters: sedimentary history, terrestrial heat flow density and nowadays lithosphere thickness. The basic models (with fixed β parameter, fixed lithosphere thickness in the Danube Basin after stretching) were fitted to these check parameters for every subregion of the Danube Basin (*Lankreijer et al., 1995; Kováč, 2000*). The backstriped sedimentology data and the calculated thermal subsidence data were used for determination of the start of the thermal subsidence activity. The data from the subregions in the northern marginal zone of the Danube Basin influenced by the third (inversion) phase of the basin evolution were not used by optimization process and the sedimentation data from second phase were extrapolated over this time interval. In the subregions where we do not have sufficient sedimentation data for application of our approach only other check parameters were used in models. Lithosphere stretching parameter β is related here to the reference lithosphere thickness value 125 km which was used in calculation formulas (*Wangen, 2010*). The real stretching factors for the studied lithosphere depend on real lithosphere thickness on the start of the tectonic cycle.

The thermal and subsidence modelling results suggest that the regions of the thermal activation in the syn-rift phase compared with that in the post-rift phase are not coincident. The thermal activation related to the Middle Badenian tectonic events cover a narrower area along the SW-NE axis of the Danube Basin centred both on the maximal depths of the pre-Tertiary basement and the greatest terrestrial heat flow density values.

The mechanical stretching of the Danube Basin lithosphere causes the passive asthenospheric flows (i.e. primary not thermally forced) upward into the relatively free space created by attenuation of the lithospheric mantle.

The extension is accompanied by massive volcanic activity. The distribution of the (Early Badenian) extension related andesite volcanism (*Konečný et al., 2002*) shows the covering also of the whole Danubian basin area (yellow coloured geometry in Fig. 8). The direction of the ascending, partially melted mantle material is also influenced by the existence of thermally weakened zones and by the existence of mechanically rebuilt zones in the upper parts of the Earth (fault zones, bent crustal zones).

The modelling results suggest that at the time of the Middle Badenian unconformity the mantle materials were partially melted at depths of about 45–50 km in the Danube Basin central zone of the highest terrestrial heat flow density (80–90 mW/m^2) – light orange geometric structure in Fig. 8. The interpreted second rifting phase (*Lankreijer et al., 1998; Kováč, 2000*), dated to the Early Pannonian (11.5–9 Ma) occurs only in the central and southern parts of the Danube Basin. The subsidence was accelerated and

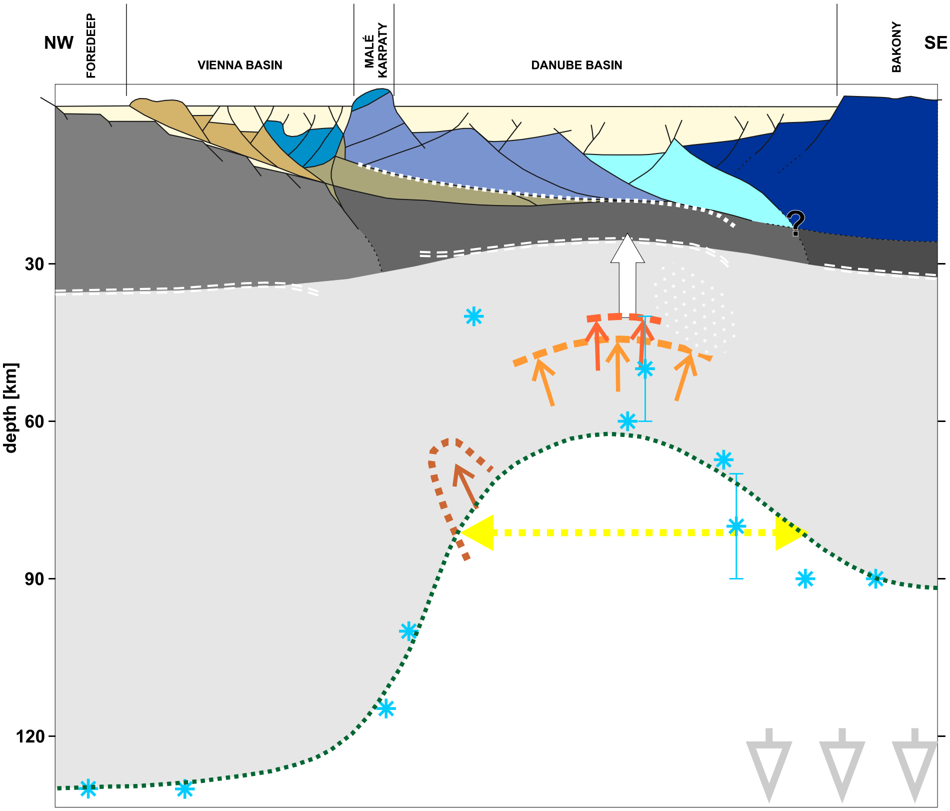

Fig. 8. Interpretation profile crossing the Danube Basin and surrounding units (*Kováč, 2000*) with the results of geothermic and tectono-thermal analysis. Geological structure described in Fig. 4. White dashed double-line – tectonic interpretation of Moho input data. White dotted line – discussed delamination line in Inner Carpathian units. Grey downward arrows – horizontal position of the detached lithosphere remains at depths of 300–400 km. White dotted area – probably weakened zone. The differently coloured geometries are related to interpretation of data and are explained in the related text.

decelerated several times with various intensities. We suppose that it is caused by partial reactivations of the narrow areas in the central part of the rift from syn-rift phase. This may cause small shifting of partially melted materials in the direction of the Earth's surface (dark orange coloured geometry in Fig. 8). The activation events do not explain the narrow anomalies in the terrestrial heat flow distribution bounded by the isoline of 90 mW/m^2. We suppose that the high heat flows are related to increased heat transport along the separate fault zones to the upper crust.

The brown coloured geometry displayed in Fig. 8 indicates the zone which may influence the tectono-thermal events in the NW border of the Danube Basin. The detachment of the subducting slab and position of the slab's remains influence the homogeneity of the asthenospheric material flows mainly in the earlier stages of the syn-rift phase. The inflows of melted material into contact zone of the rigid Bohemian massif and East Alpine lithosphere on one side and of the Central Carpathian lithosphere on the other may play an important part in the thermal activations and partially in the subsidence events. Such inflows are probable by rotation of overriding lithospheric plate such as the counter clockwise rotations in the Ottnangian and Early Badenian (*Konečný et al., 2002*) with relatively great angles (up to 40 ° C).

The interpretation of geothermal and tectonic data suggests that McKenzie's "pure-shear" model of the sedimentary basin development is an acceptable conception for the Danube Basin.

However it has to be modified by application of various non-symmetrical elements in structure and tectono-thermal activations. The stretching parameter has an inhomogeneous horizontal distribution and the greatest values are expected in the Danube Basin regions both with the greatest observed terrestrial heat flow densities and with the deepest parts of pre-Tertiary basement. The structure and contact character of the crustal and mantle part of the Danube Basin lithosphere with surrounding geological units (East Alpine and Bohemian Massif in the western part and Transdanubian in the east) support the idea of depth dependency of thinning factors of the separate lithospheric layers.

3. Conclusion, discussion

Our contribution provides tectono-thermal interpretations in the studied region of the Danube Basin. The activities were accomplished both by classic and also completely new methodological approaches.

We applied the analysis of the existing geothermal data acquired by direct (measuring) methods and by approaches of the modelling of temperature fields both by classic geothermal methods and by methods of integrated modelling. From the interpretation of the geothermal knowledge packet and by utilization of results of other geophysical and geological methods we constructed the new maps of the terrestrial heat flow density and lithosphere thickness distributions in the region under study. The result maps serve as an input for tectono-thermal analyses of the Danube Basin.

The interpreted thickness of the lithosphere below the SW part of the Transdanubian Central Range has a significant importance in global analyses of the tectonic development of the Danube Basin's evolution including the filling upthe basin. We suppose that the thick and rigid Transdanubian lithosphere block plays a great role in the Middle Miocene development of the Danube Basin structural pattern. It should make an obstacle in opening of partial depocentres (Blatné, Rišňovce and Komjatice Depressions) from the west to the east during the Badenian and Sarmatian ages to create the known digit like form (*Kováč et al., 2011*).

Our contribution brings the proposal and approval of a new approach for geothermal modelling in a transient regime. It provides the possibility to reduce the great variance level of the input parameters of constructed models. The universality of the thermal subsidence calculation is given by the fact that it may be connected with arbitrary computations of the not stationary heat transport problems. We applied the calculations to results from the Comsol software package. The results of the approach's application in the Danube Basin have meaningful influence on analyses of tectonic development of the region in various geoscientific branches and especially they are very useful for geothermal modelling of separate tectonic events. The interpretations of the temperature field distribution anomalies and determinations of their sources facilitate the specification of thermal parameters and thermal renewability of the geothermal energy sources.

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