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A Software for Thermal Modeling and its Implications for the East-European Craton

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ABSTRACT

A new set of software has been developed to solve the heat conduction equations in a case of homogeneous and heterogeneous environments and to automate fitting the observed field. It accelerates the procedure of thermal modeling and increases the reliability of heat flow interpretation. Based on this approach, the geothermal models for the Earth’s crust along the transect EUROBRIDGE 95-96 and Geotraverse VI have been constructed.

1. INTRODUCTION

The modeling technologies of the geologic objects structures of different level based on the fitting methods in general and on their automated computer modifications in particular are everywhere used in geologic-geophysical investigations practice (Kutas et al, 1989; Tsvjaschenko, 2000; Tsvjaschenko et al, 2000). In recent time, the PC computer resources enable realization of computer technologies of interpretation by use of multi-variant and multi-step fitting strategies. The programmed realization of such technologies with applying a friendly graphical interface for a dialogic contact of the user with modeled geologic-geophysical objects makes them open to general use of broad sections of specialists. The paper considers the main elements of the modeling technology of thermal field in homogeneous and heterogeneous media based on set of software of solving direct and inverse geothermal problem (Kutas et al, 1989; Tsvjaschenko, 2000; Tsvjaschenko et al, 2000; Majcin and Tsvjaschenko, 1994).

The main task of thermal field modeling is to determine the geometrical and time parameters of heat sources and to define the thermo-physical properties of a medium that do not contradict the known geologic-geophysical data, and the model values calculated from these parameters at the Earth’s surface or in boreholes optimally satisfy the measured data (Tsvjaschenko, 2000). The solution of this problem has some features that are defined by the thermal field nature and anomalies. The heat flow (HF) observed at the Earth’s surface is notably, influenced by the radiogenic heat varying in space and time and the temperature-dependent conditions of heat transfer as well as heat coming from the deep tectonosphere and probably associated with global cooling of some its horizons.

The geothermal model of the lithosphere is set up by solving of a succession of problems: 1) construction of a model of stationary (radiogenic) heat sources and thermal conductivity of the medium; 2) determination of the background values of HF; 3) separation of non-stationary thermal field anomalies, their interpretation and determination of the temperature effect produced by non-stationary heat sources and/or the change of the heat transfer conditions; 4) determination of the total temperature effect and construction of a geothermal model of the lithosphere.

2. FORMATION OF MODELS OF HEAT SOURCES AND THERMAL CONDUCTIVITY OF THE MEDIUM

The models of stationary heat sources and heat transfer for the upper horizons of the Earth’s crust are mainly constructed by use of experimental data on the thermal conductivity of rocks of different composition and genesis in each specific region and their radioactive-elements content. Here the dependence of HF on the radiogenic heat generation in near-surface rocks is considered. The design of the dependence of the radiogenic heat generation in near-surface rocks on their density and seismic wave velocity based on the laboratory measurement data is practiced. Such dependences enable us to estimate the radiogenic heat generation of deeper crystal and upper-mantle horizons using density and velocity cross-sections.

The radioactive elements distribution in rocks depends both on the rock crystallization condition, chemical composition and structure of rock-forming minerals and on some factors causing radioactive elements redistribution in rock (metamorphism, hydrothermal activity, underground water movement etc.). As no direct genetic relation exists between the seismic wave velocity and heat generation, the correlation for regions of different structure and geologic evolution may be notably different. Only preserved is the exponential character of the dependences.

The idea of the upper mantle thermal conductivity is mainly based on studies of thermophysical properties of eclogites, peridotites and other mantle formations with considering effect of temperature and pressure, anisotropy etc. (Prodaivoda et al, 2000).

The first stage of modeling is finished with constructing blocks of the study medium, a section that differ from each other in heat generation and thermal conductivity values.

3. ESTIMATION OF THERMAL FIELD BACKGROUND VALUES

An important role in modeling technology is played by the stage of separating the total thermal effect due to many energetic processes on the components (normal, background and anomalous). Usually, the background component is thought to be the thermal field produced by radiogenic sources of the Earth’s crust and upper mantle together with heat coming from the non-activated Earth’s interior. In such approach the flow values measured in tectonically stable regions after respective corrections may be considered the background ones. In some cases one uses the meaning of a reduced heat flow, i.e. a flow from which the radiogenic component of the most radioactive and heterogeneous upper Earth’s crust is excluded. However, the data to be used to determine the lover limit of this horizon are often absent. Tsvjaschenko (2000) proposed to use as the reduced thermal field the observed HF except its crustal component produced by the radiogenic sources of the Earth's crust. In this case it in possible to separately determine the thermal effects produced by the Earth's crust and upper mantle. A normal mantle field is thought to be a field produced by radiogenic sources of the mantle. The role of each component in the ancient platform thermal field was considered in detail by Tsvjaschenko (1995).

Much more difficult is the determination of the background values of field in active regions where the radiogenic component is complicated by repeated processes of tectonomagmatic activization accompanied by both emission or absorption of heat in limited volumes and by its more intensive effect from the interior. The separation of the non-stationary anomalies in such cases consists in subtraction of the radiogenic component and the heat of the non-activized mantle from the observed field. The thermal effects produced by stationary and non-stationary heat sources are calculated using mathematical modeling.

4. METHODS OF MODELING THERMAL FIELD OF THE LITHOSPHERE

The thermal regime is modeled in the Earth's crust and upper mantle (where heat is mainly transferred conductively) on the basis of the theory of thermal conductivity. In this case the stationary and non-stationary thermal fields in the media of homogeneous thermal conductivity are mainly calculated using analytical solutions for heat sources of regular geometric form and different nature. On the basis of such analytical solution for elementary heat sources software of the automated fitting of thermal field anomalies has been worked out (Kutas et al, 1989).

The real geological media are laterally and vertically heterogeneous both in thermal conductivity and in heat generation. The thermal conductivity equation for such media is solved using numerical (network) methods.

The elaborated technology enables us to conduct a full cycle of mathematical modeling of the thermal field of heterogeneous media (Tsvjaschenko, 2000). It was several software packages and a number of auxiliary program modules notably accelerating and simplifying the computer modeling process itself. The technology enables us to determine the background thermal field, to solve a stationary problem for heterogeneous media, to carry out automated fitting of non-stationary heat source parameters, to solve the thermal conductivity equation numerically and, finally to obtain the temperature and HF distribution in heterogeneous media.

In general case, in conductive heat transfer the thermal field value at any point of the heterogeneous medium is determined by the equation:

$$div\lambda(x,y,z)grad T(x,y,z,t) = -Q(x,y,z,t) + $$
$$+C(x,y,z)\rho(x,y,z)\frac{\partial T(x,y,z,t)}{\partial t} \quad (1)$$

with respective boundary conditions formed by a specific geologic-geophysical situation. Here λ – thermal conductivity; T – temperature at an arbitrary point of the medium; C – heat capacity; ρ – density; Q – sources distribution in the medium.

In practical modeling the problem is subdivided into two parts: stationary and non-stationary.

5. MODELING THE STATIONARY THERMAL FIELD

5.1. Homogeneous medium

For stationary heat sources of limited size and simple form the analytical expressions for temperature and HF calculation may be formed on the basis of the known in potential theory expressions, that describe the distribution of the attraction potential and gravity field, produced by these bodies, at an arbitrary point. In this case, the boundary condition of zero temperature at the Earth's surface is satisfied by defining an apparent mirror sources of opposite polarity in the upper half-space. The modeling programs use the expression obtained in such a way to calculate the HF and temperature from a rectangular parallelepiped and a horizontal cylindrical body with a multiangular cross-sections (Kutas et al, 1989). An analysis of such expressions shows that with large horizontal dimensions of 3-D sources the temperature and flow values coincide with those obtained from the solution of A.N. Tikhonov for an infinite layer.

5.2. Inhomogeneous Medium

For the domain of the inhomogeneous medium with the coordinates: x=0,L_x; y=0,L_y; z=0,H in the 3-D version the stationary-temperature distribution can be obtained by solving the thermal conductivity equation:

$$div[\lambda(x,y,z)\ grad\, T(x,y,z)] = -Q(x,y,z) \quad (2)$$

with the boundary conditions

$$\lambda(x,y,z)\frac{\partial T}{\partial z}\Big|_{z=H} = q_H(x,y);\quad T(x,y,z)\big|_{z=0} = 0;$$
$$\frac{\partial T}{\partial x}\Big|_{x=0,Lx} = 0;\quad \frac{\partial T}{\partial y}\Big|_{y=0,Ly} = 0, \quad (3)$$

where q_H – is the distribution of HF coming to the study-medium bottom from the interior; Q – is the stationary heat sources distribution in the medium.

In the 2-D version the problem is reduced to the equation

$$div\,\lambda(x,z) grad\, T(x,z) = -Q(x,z) \quad (4)$$

with the boundary conditions:

$$\lambda(x,z)\frac{\partial T}{\partial z}\Big|_{z=H} = q(x);\quad \frac{\partial T}{\partial x}\Big|_{x=0,L} = 0;\quad T(x,0) = T_0. \quad (5)$$

At the lower limit of the domain z=H the HF q_H is given that comes to heterogeneous medium influencing the temperature distribution. It is usually superposed on the M-discontinuity, sometimes it may be situated in the Earths crust or mantle. The HF coming from depth is distorted by inhomogeneity in the distribution of the thermal conductivity coefficient and radiogenic heat sources.

In the computer program (Majcin and Tsvyashchenko, 1994) the finite-difference method is used to solve the problem (2–5). The systems of algebraic equations that are constructed within the framework of this method are solved by the upper relaxation method (Samarsky and Nikolaev, 1978). The calculation experiment method was used to determine the optimal parameters of a calculation scheme that provide the acceleration of the iteration process convergence. The reliability and accuracy of the temperature and HF calculation by the network method has been examined by comparing the obtained values with the results of analytical solutions of similar problems.

The software (Majcin and Tsvyashchenko, 1994) consists of a package of programs that realize the preparation of the network coverings of the cross-sections and the thermal field and HF calculation. A distinctive feature of the algorithms realized in the programs is the use of the "shooting ray" procedure to automate the construction of the network coverings of the modeled cross-sections (Tsvyashchenko, 2000; Tsvyashchenko et al, 2000).

The effectiveness and friendshipness of the thermal field modeling technology (Majcin and Tsvyashchenko, 1994) notably expanded by the supplement of the software with a set of auxiliary program modules and other program products (Tsvyashchenko et al, 2000). Firstly, a multifunctional automated system of projecting (ACAD) is used to form the electronic scheme of the model cross-section by use of geologic-geophysical data. Secondly, an additional procedure has been written in a special programming language mounted in this system to automate the process of constructing tracing rays with any necessary step. Thirdly, an auxiliary program has been also worked out which, according to the data of the solution of the modeling programs by the main computer modules of the software (information in the files of solution results), forms files of the results of calculation in the formats of the known package of the scientific graphics. This enables a sufficiently construction of HF diagrams, thermal sections and the model geometry if necessary.

The elaborated technology of the solution of a stationary geothermal problem for heterogeneous media enables the solution of the following problems:

1. Modeling HF and temperature distribution resulting from the uneven radiogenic heat sources distribution in the Earth's crust when no HF exists at the lower limit. The solution of this problem enables us to determine the crustal HF value at the surface and the distribution of temperatures produced by arbitrarily distributed heat sources in the Earth's crust with heterogeneous thermal conductivity. This data may be used to determine the value of the mantle HF and to separate its non-stationary anomalies.

2. Modeling HF and temperature distribution in a medium with inhomogeneous thermal conductivity when HF is given at lower boundary. Such a problem may arise when the thermal field of the heterogeneous lithosphere is modeled within ancient regions where the active tectonomagmatic processes have finished long ago and the thermal field is stationary. In the tectonically active regions with non-stationary field this problem provides modeling of the stationary component, which enables us to separate the non-stationary component later.

3. Determination of the distorting effect of structures or blocks differing from the environment in thermal conductivity in a homogeneous or heterogeneous HF coming from below.

6. MODELING NON-STATIONARY THERMAL FIELD

In the absence of stationary heat sources the problem consists in solving a non-stationary equation of thermal conductivity

$$div\lambda(x,y,z)gradT(x,y,z,t)= \\ =c(x,y,z)\rho(x,y,z)\frac{\partial T}{\partial t}(x,y,z,t) \qquad (6)$$

with present boundary and initial conditions:

$$T(x,y,z,0)=0; \\ T(x,y,0,t)=0; \lim T(x,y,z,t)|\xrightarrow[x,y,z=\infty]{} 0. \qquad (7)$$

6.1. Homogeneous Medium

In such a version with λ, ς, ρ = *const* the problem has an analytical solution for some kinds of sources of regular geometrical form situated in a homogeneous half-space (Kutas at al, 1989). These solutions are used at the first stage of the fitting technology when an optimization block is included which is used to select non-stationary heat source parameters for the homogeneous half-space. Let us describe briefly the main components of the method of automated fitting of non-stationary HF anomalies (Kutas et al 1989).

Criteria of the observed and modeled field approximation. The software for fitting is based on the optimization of the sum of squares differences between the measured and modeled field components. To realize the possibility of the automated fitting of several fields and linear transformations of the type of sliding window

$$\delta U_i = \sum_{j=-n}^{n} c_j U^{i+j}, \quad j=-n,\ldots,0,\ldots,n, \qquad (8)$$

where δU_i – is the transformant value at he *i-th* point; $\{c_j\}_1^s$ – is subset of weighting multiples values of the transformation sliding window operator; *s=2n+1* – is the number of values of the field components *U* used to calculate the transformant at the flowing point. In the elaborated algorithms and programs the quality index F is used in the following from:

$$F = \sum_{m=1}^{M}\alpha_m \sum_{i=1}^{N_m}\frac{a_{im}}{U_m^{cp}}\left\{\sum_{j=n_m}^{n_m} c_{Jm}\left[U_{R,m}^{i+j} - U_{T,m}^{i+j}\left(x^m\right)\right]\right\}^2. \qquad (9)$$

Here

$$U_m^{cp} = \sum_{i=1}^{N_m} U_m^i \Big/ N_m; \quad U_{T,m}^i = \sum_{j=1}^{K_m} U_{j,m}^i + A^m x^i + B^m y^i + C^m z^i + D^m$$

$x^m = \left(x_1^m, x_2^m, \ldots, x_{P_m}^m\right)$; M, m – are the amount and number of the field components used in fitting; α_m – is the weighting multiplier of the component contributions to the *F* values; N_m – number of points where the components is given; a_{im} – is the weight of the *i-th* point; $U_{R,m}^i, U_{T,m}^i$ – are the measured and modeled values of the components; $U_{j,m}^i$ – contribution of the *j-th* approximating cell; K_m – is the number of cells; P_m – is the total number of the parameters;

A_m, B_m, C_m, D_m – are the coefficients of the linear background of the component *m*.

Optimization procedure. The automated computer fitting of the parameters of a specific approximating construction is realized by minimizing the objective function (9) using a special optimization procedure including some modifications of the gradient methods of optimization (steepest descent methods with normalizing the descent direction and a procedure of the acceleration of convergence, gradient and conjugate gradient methods) as well the optimization procedure based on a known algorithm of the singular matrix decomposition (SVD).

The approximating construction includes two types of cells corresponding with two types of heat sources: cooling and short-time acting. The first realized with cooling of heated substance carried out from the interior and the second one with thermal energy emission (absorption) in limited volume accompanying different physical-chemical and geodynamic processes.

The elaborated software and algorithms is supplemented with some programs of graphic visualization of the fitting results (of the observed and fitted fields, as well as configuration of the fitted objects) on the monitor screen and acquisition of hard copies of graphics presentations on the printer.

In the cause of a homogeneous medium, after fitting he heat source parameters and determining non-stationary temperatures and heat flow the data are given to the block of summing the stationary and non-stationary fields and then they are transformed for graphical presentation.

6.1. Heterogeneous Medium

For heterogeneous media (when a priori geologic-geophysical information is available) the results of the automated fitting are summed with those of the solution of the stationary problem and are based as the first approximation to solve the problem by network methods. In the following the problem is solved by numerical methods using a separate program to calculate the non-stationary thermal field of the heterogeneous media. In the 2-D case we solve the equation

$$div(x,z)\ grad\ T(x,z,t) = \\ = C(x,z)\ \rho(x,z)\ \frac{\partial T(x,z,t)}{\partial t} \qquad (10)$$

$$T(x,z,0) = const;$$

$$T(x,0,t) = const; \quad \lim T(x,z,t)\Big|_{x,z,t\to\infty} \longrightarrow const\ . \qquad (11)$$

The technology of the presentation of a model, the structure of the files of the input and output information, the succession of the operation is similar to those used in solving a stationary problem. But the non-stationary field calculation program is supplemented with a procedure of calculating the field by a time network with the step given a priori. The length of the time step and the number of step are given in the control file. After comparing the calculated flows with the observed ones a conclusion is made of whether the accepted model corresponds with the real medium. The great differences between the field values may result from notable discrepancies between the real medium and the accepted model whose parameters have been recovered by optimization methods. The discrepancy of the media in solving the problems by the automated fitting method and network methods may result in a notable discrepancy of the results of calculation. In such cases, one can match the observed and the modeled thermal field with necessary accuracy using the network methods and varying the heat source parameters. Note once more that the use of the network method to interpret the non-stationary anomalies has a sense when reliable information of non-stationary medium parameters is available. Such information on the Earth's crust is presently available along deep seismic sounding profiles.

7. MODEL CALCULATIONS

The elaborated modeling technology has been rather widely approbated on model problems. Numerous results of model calculations made by use of algorithms and program of the automated fitting of non-stationary heat sources are given in (Kutas at al, 1989). The model examples of used to approbate the proposed technology were constructed with considering the structure tectonic elements most frequently found in nature. Let us consider briefly upon some model problem.

Gaben-shaped structure. Fig 1 show a theoretical model of Earth crust, that include a homogeneous graben filled with sediments. The thermal conductivity of rocks composing the graben, is almost by two time lower than that of rocks which enclose it. In the HF field the graben is mapped with HF decreased by 6-8 mWm^{-2}. Here, against the background of the general decrease of the flow values, a local increase of the flow values by 2-3 mWm^{-2} is marked over central graben part. The graben limits on the Earth's surface are mapped in the HF field by acute-angle local anomalies with intensity to 15 mWm^{-2}. This character of the HF behavior over the graben results from the refraction of heat flow, i.e. its propagation over the line of the least thermal resistance. The character of such refraction has been studied in detail on model examples.

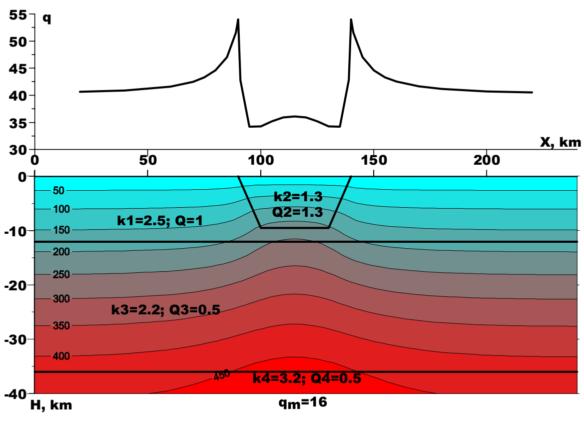

Figure 1. A thermal model for a graben in the crust. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, Wm^{-1}K^{-1}; Q – heat generation, mkWm^{-3}; 100….500-temperature, ºC.

Fig. 2. show a schematic stationary geothermal model of the Earth's crust of a complicate graben-shaped structure (Dnieper-Donetsk depression). Note that in each specific case the real model of the studied depression, get up with invoking the geologic-geophysical information, may differ from that given in the figure. Over the graben notable HF variations are marked that are first of all due to the HF refraction which envelopes the low thermal conductivity medium (high thermal resistance). For the same reason, the HF of the central part of the graben is notably lower. If the graben is filled with rocks of thermal conductivity higher

than that of the environment a reverse picture will be seen. Here it is also armful to note that HF variation is more notably influenced by thermal conductivity variation rather than those of heat generation. The calculations show that the thermal conductivity change by two times with a stable heat generations causes more notable HF variations than in the case of the jump of the heat generation by two times with a stable thermal conductivity. Hence, it may be concluded that the HF distribution is very notably influenced by the thermal conductivity of the near-surface crustal blocks. This factor exceeds by several times the effect of the heat generation change in blocks.

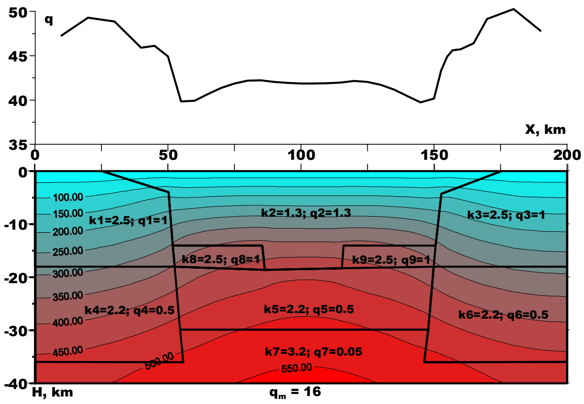

Figure 2. A thermal model for a schematic Dnepr-Donetsk depression. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, $Wm^{-1}K^{-1}$; Q – heat generation, $mkWm^{-3}$; 100….500-temperature, °C.

A trapezium with steep side faces (fig. 3). The model consists of three horizontal interbeds whose thermal conductivity increases with depth, while its heat generation decreases.

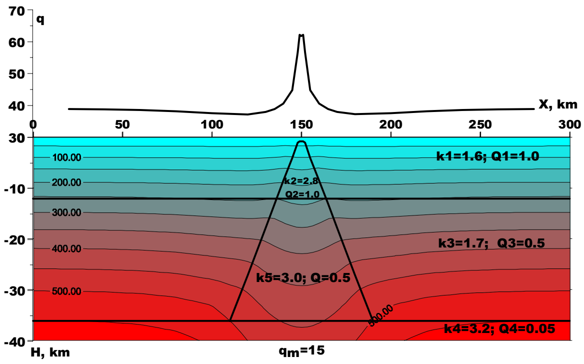

Figure 3. A thermal model for a “trapezium” type block in the crust. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, $Wm^{-1}K^{-1}$; Q – heat generation, $mkWm^{-3}$; 100….500-temperature, °C.

Two upper interbeds are practically to the surface picked by a trapezium-shaped body. In the model of fig. 3 the thermal conductivity in the upper and lower trapezium fragments is nearby by two times higher than in horizontal interbeds, while the heat generation remains the same. This model forms a spike-shaped (rather narrow compared to the trapezium base) local HF anomaly with more than 20 mWm^{-2} intensity. Due to the thermal conductivity increase by two times the anomaly intensity in the upper part of the trapezium model increases by 10 mWm^{-2} with preserving the form of the anomaly itself.

Stock-type structure (fig. 4). Unlike the previous model example, the stock model is featured by notably longer horizontal dimensions (over 20 km) in the upper part of the structure. The stock is formed by the lowest fourth interbed of the model and pierces all three upper interbeds. The stock amplitude is 35 km and the intensity of the local HF anomaly caused by it approaches 15 mWm^{-2}. In the anomaly center a local HF decrease occurs over the stock.

Heterogeneous diapir (fig. 5). The model is a structure expanding toward the surface, and the thermal conductivity and heat generation values decrease horizontally from the periphery to the center.

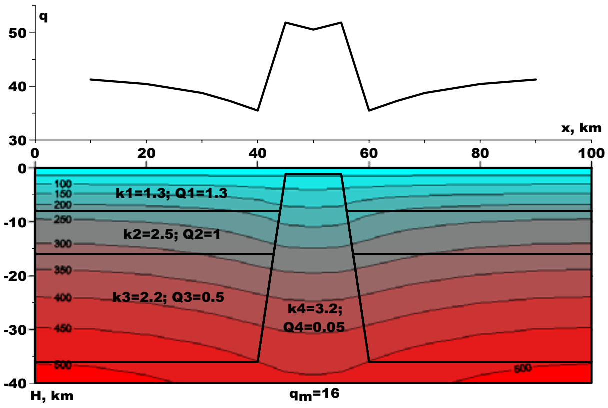

Figure 4. A thermal model for a stock in the crust. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, $Wm^{-1}K^{-1}$; Q – heat generation, $mkWm^{-3}$; 100….500-temperature, °C.

The diapir from the depth of 36 km pierces up to the surface two overlying interbeds of the structural model. The diapir dimensions at the depth of the base are 50 km and 150 km at the surface. Low HF of more than 10 mWm^{-2} maps the central 100 km part of the diapir. The diapir contacts with the uppermost interbed at the surface are clearly marked by positive spike-shaped local anomalies of more than 5 mWm^{-2} intensity.

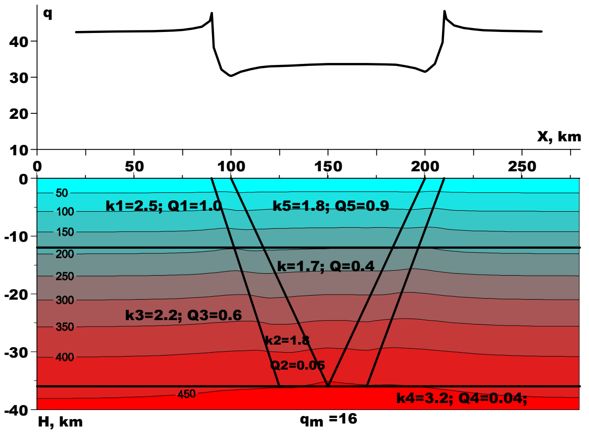

Figure 5. A thermal model for a heterogeneous diapir in the crust. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, $Wm^{-1}K^{-1}$; Q – heat generation, $mkWm^{-3}$; 100….500-temperature, °C.

“Wave” type structure (fig. 6). The model is a three-layer medium at whose surface (in the upper interbed) two wave-shaped depressions with 10 km depth at the central points are situated. The thermal conductivity values of the rocks filling the depressions are by two times lower than those of

rocks in which the depressions are situated, while their heat generation values are, contrarily, by 1.5 times higher. In the HF field at the surface the depression are mapped by low HF values (to 10 mWm^{-2}). The contacts of the depressions with rocks enclosing them are marked at the surface by three positive spike-shaped anomalies of the intensity to 10 mWm^{-2}. The central anomaly peak is by approximately 1.5 times more intensive than the side peaks (the influence of the low thermal conductivity environment is feet).

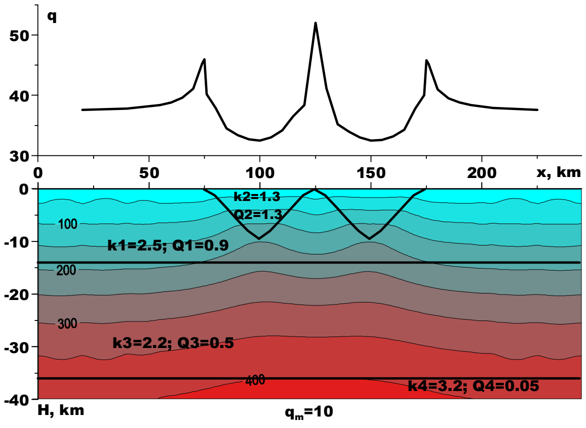

Figure 6. A thermal model for a "wave" type block in the crust. q – heat flow, q_m – mantle heat flow, mWm^{-2}; k – thermal conductivity, Wm^{-1}K^{-1}; Q – heat generation, mkWm^{-3}; 100….500-temperature, ºC.

The above model examples and the results of numerous calculations made on other structural models provide a great amount of information for the formation of the ideas of the character of the behavior of the thermal field anomalies over the tectonic elements of different structure as well as the influence of thermophysical parameters of the environment (thermal conductivity and heat generation) on the anomaly values.

8. MODELING GEOLOGICAL ENVIRONMENT

Figs. 7, 8 and 9 show the geothermal cross-sections of the crust along the transect EUROBRIDGE 95-96 and Geotraverse VI. The first profile crosses the Baltic Synclase, Western-Lithuanian granulitic belt, Eastern Lithuanian mobile belt, Belarus-Baltic granulitic belt, Belarus Massif and Osnitsk-Mikashevichi Igneous Belt. The second profile intersects the Volyn, Novograd-Volyn, Vinytsa, Podolian and Kirovograd blocks of the Ukrainian Shield. Tectonic setting and heat flow of these features are described in detail elsewhere (Lithosphere…, 1988; UROBRIDGE…1999; Kutas et al. 1999; Starostenko et al., 2002)

The western East European Craton is characterized by the low heat flow, with its values ranging between 20 and 50 mWm^{-2}. The reduced heat flow of 20-35 mWm^{-2} is a prominent feature of the Western Lithuanian and Belarus-Baltic granulitic belts, Belarus Massif and Osnitsk-Mikashevichi Igneous Belt. The increased heat flow (<40 mWm^{-2}) is observed over the western Ukrainian Shield, and Kirovograd block. The Baltic Synclase is marked by high heat flow (up to 85 mWm^{-2}).

The geothermal models are based on: 1) experimental data on generation of radiogenic heat and conductivity of rocks with different composition, age and origin from the upper Earth's crust; 2) geochemical information on the composition rocks of the different origin and condition of their formation as well as the content of radioactive elements in them; 3) geophysical evidence for the distribution of velocity, density and other physical properties in the Earth's crust; 4) geological information; 5) heat flow measurements corrected for climate changes and topography. The data are reported in (Lithosphere…, 1988; Lebedev et al.,1993; 2001; EUROBRIDGE…,1999; Kutas et al. 1999)

Boundary conditions are the values of the mantle heat flow on the base of the lithosphere and the constant temperature on the roof of the lithosphere. In formulating and solving a problem the assumption was made that the lithosphere is rigid and heat transfer is by conduction. The problem was solved by a fitting method using the heat conduction equations presented in Carslaw and Jaeger (1959).

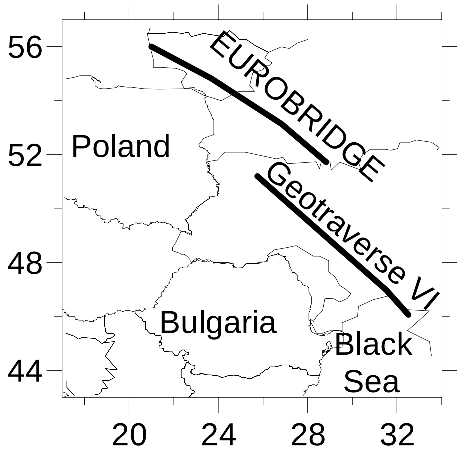

Figure 7. Geotransects disposition scheme

Several models have been constructed combining different values for heat generation, conductivity and boundary conditions. Estimating the heat generation at a site of heat flow measurement and a mean value for different types of rocks within tectonic blocs has been made. The pattern of temperature and heat flows is governed by the distribution of radiogenic heat and heterogeneities of thermal properties. The models show that the thermal field is stationary over all tectonic features except from the Baltic Synclase.

Of all tectonic units the Ukrainian Shield is studied best where measurements of heat generation and heat flow have been performed simultaneously in many borehole. In the uppermost crust (a depth of 300-400 m) generation is in a range of 2-4.and 0.2-0.4 mkWm^{-3} for migmatite, granite and basic granulite respectively. As a regional model cannot reveal local variations in heat generation with depth, mean values of generation for blocks have been used in calculating. The mantle heat flow ranges form 17-22 mWm^{-2} within the shield. Heat flow anomalies are produced mostly by different composition and formation of rocks in the crust.

The low heat flows above the granulitic belts are associated with the low heat generation in rocks of granulitic metamorphism (mainly mafic granulite) and reflect the basic composition of the crust. The radiogenic heat is 0.1-0.7 mkWm^{-3} for granulite, gneiss, calciphyre and enderbite. It varies from 0.6-0.8 to 5-7 mkWm^{-3} and more for granite. However, the increased heat generation in granite is not always accompanied by an increase in the heat flow. For example, the heat generation of Osnitsk granite is 1-2 mkWm^{-3} while the heat flow rarely exceeds 35 mWm^{-2}. It follows that the granitic layer is thin and during its origin redistribution of radioactive elements in the crust has only occurred without the change of their amount. Gneiss and shale are usually characterized by relatively reduced heat generation. The increased heat generation of the Kirovograd granite sufficiently affects on the heat flow. Based on heat flow, the thickness of granite in the Kirovograd block is assumed to be 7-9 km. A number of heat flow local anomalies are related to variation in conductivity of rocks and to movement of underground waters.

The mantle heat flow of the Baltic Syneclise increases to 30-35 mWm^{-2}. In this tectonic feature the vast anomaly of heat flow with small horizontal gradients cannot be caused by the specific distribution of radioactive elements or conductivity variations. As inferred from thermal modeling its source (an intrusion or asthenolith) is situated in the upper mantle or middle crust.

CONCLUSIONS

A set of software has been developed to solve stationary and transient thermal problems. It sufficiently accelerates calculating procedure, increases informative capability of models and allows us to decide more confidently between various alternative hypotheses describing geothermal processes The variations in heat flow along the profiles studied are due mainly to the different distribution of temperature in the crustal blocks. Beneath the Baltic Synclase the temperature changes between 200 and 900ºC while below the Ukrainian Shield it varies from 50 to 600ºC.

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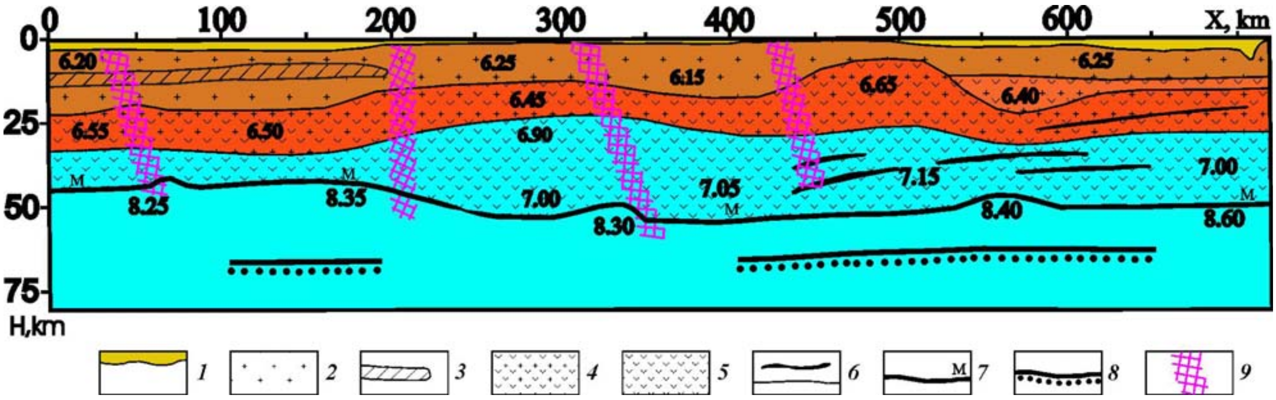
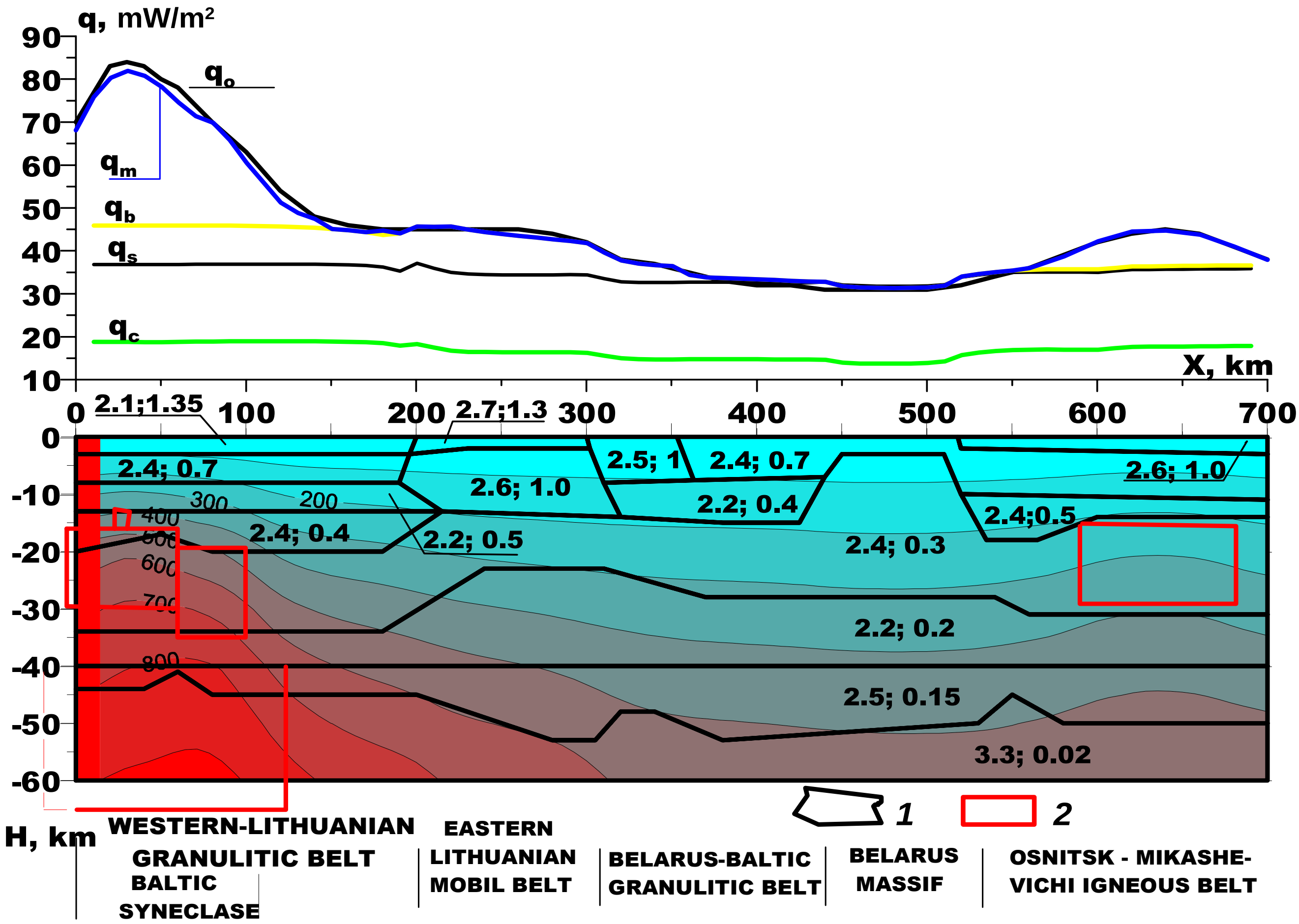
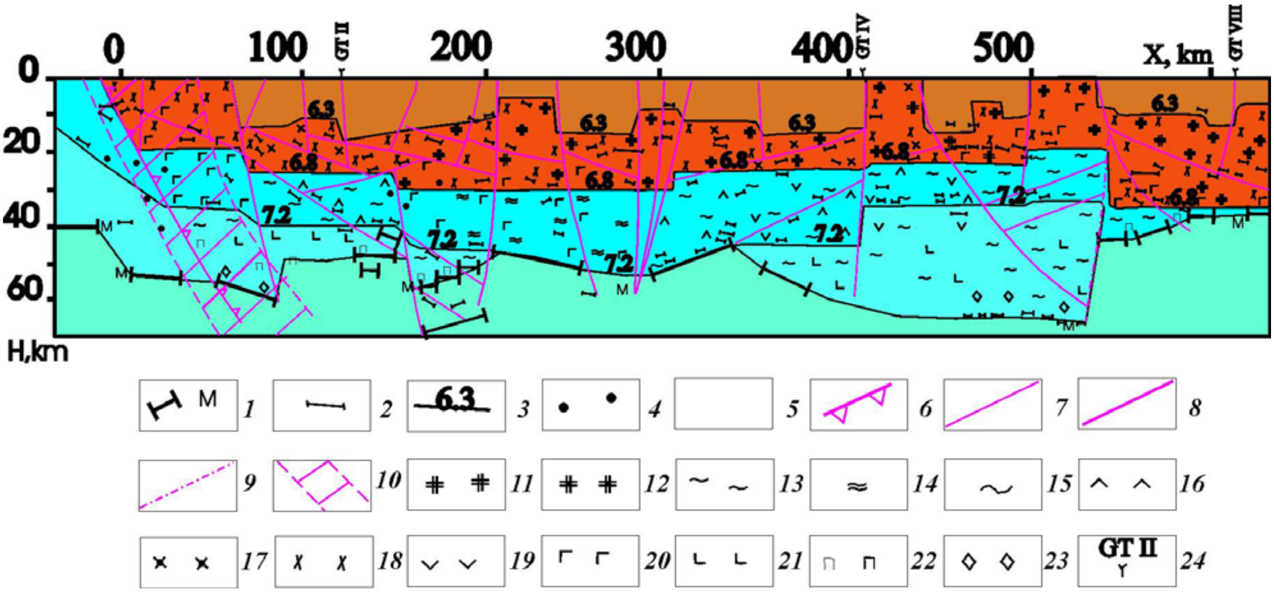


a.)

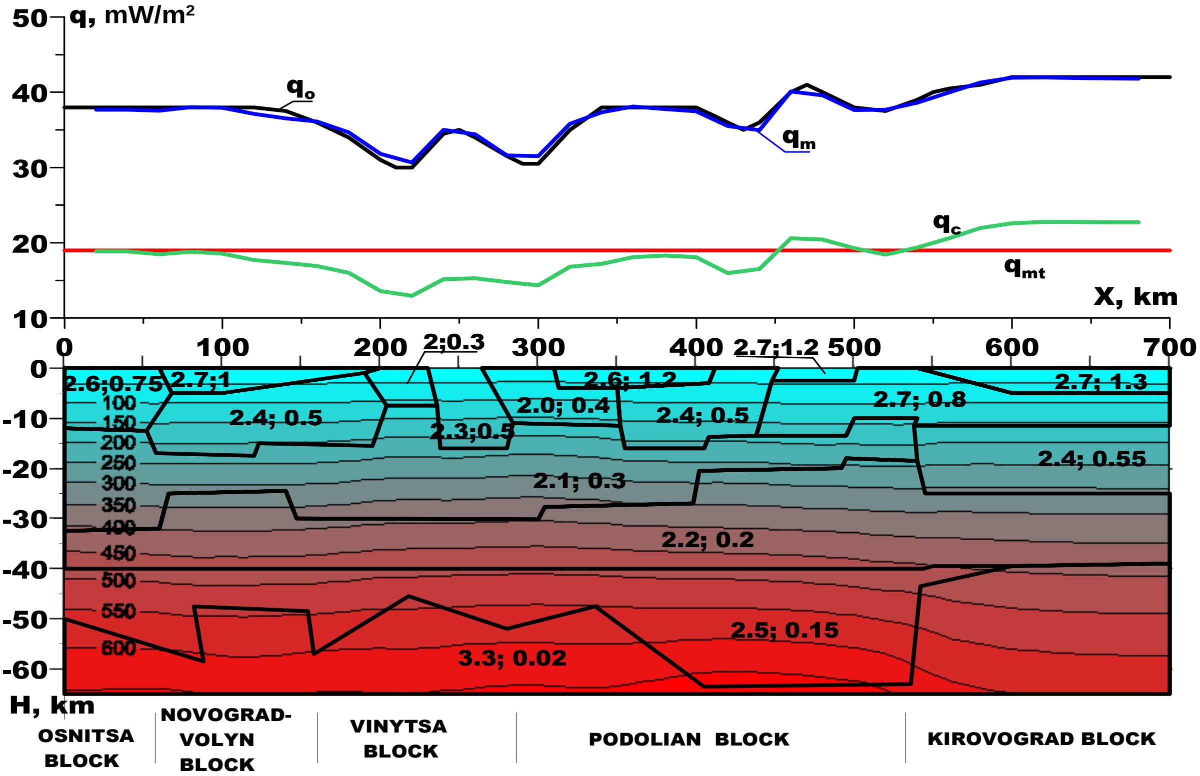


b.)

Figure 8. A lithosphere structure (a) and geothermal model (b) for the Earth's crust along the transect EUROBRIDGE 95-96.(a) *1* – sedimentary cover; *2* – upper crust; *3* – layer of the lowered velocity in the upper crust; *4* – middle crust; *5* – lower crust; *6* – seismic boundary elements, constructed upon refracted and reflected waves; *7* – Moho-discontinuity; *8* – boundaries in the lower lithosphere; *9* - deep-laid fractures: (b) Heat flow, mWm^{-2}. q_o – observed; q_m – modelled; q_b – regional background; q_s – stationary; q_c – crustal; 200….800- temperature, °C. The first number in each block is thermal conductivity ($Wm^{-1}K^{-1}$) and the second one is heat generation ($mkWm^{-3}$}; *1* – stationary thermal sources, *2* – transient thermal sources.



a)



b.)

Figure 9. A lithosphere structure (a) and geothermal model (b) for the Earth's crust along the Geotraverse VI. (a) ***1*** **- Moho-discontinuity;** ***2*** **– areas of the wave reflection;** ***3*** **– velocity izolines of P wave in km/s;** ***4*** **– points of diffraction;** ***5*** **– crust-and-mantle mixture;** ***6*** **– between megablock juncture zone Fenoscandia – Sarmatia;** ***7*** **– fracture of high rank;** ***8*** **between megablock fractures;** ***9*** **– Moho-discontinuity steps;** ***10*** **– anomaly seismic zone;** ***11*** **– charnockites;** ***12*** **– enderbites;** ***13*** **- biotite ;** ***14*** **– two-pyroxen gneiss and crystalline schist; 15 – basic granulite;** ***16*** **– basaltoides;** ***17*** **– granodiorites;** ***18*** **– diorites;** ***19*** **– amphibolites;** ***20*** **– gabbros;** ***21*** **– peridotites;** ***22*** **– pyroxenites;** ***23*** **– eclogites;** ***24*** **– geotransect intersection: (b) Heat flow, mWm^{-2}: q_o – observed; q_m – modelled; q_c – crustal; q_{mt} – mantle; 100….600-temperature, °C. The first number in each block is thermal conductivity (Wm^{-1}K^{-1}) and the second one is heat generation (mkWm^{-3}).**