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CORRELATION OF HEAT FLOW WITH TECTONICS (CONVECTIVE CELLS) AND HYDROGEOLOGICAL FIELDS

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The paper considers the main factors that can lead to the heterogeneous thermal field of the lithosphere, and is based on experimental temperature measurements on 200 structures in the Soviet Union. Heat flow calculations were made, based on the method of determining heat conductivity of rock strata in natural conditions from seismic wave velocities. The peculiarities of the distribution of abyssal heat flow in the Precaucasus may be explained by the existence of a hexagonal convective cell in the upper mantle. The local and regional variation of the convective heat flow and its quantitative correlation with the structure of the upper layers of the crust reveal the influence of underground waters in the thermal field. A correction has been applied to the calculated heat flow for areas affected by ground water movements. Analysis of the vertical distribution of temperature and heat flow show that the thermal field in the outer layers of the Earth is stratified, and the following boundaries can be identified: atmospheric, neutral (boundary with constant yearly temperatures), hydrogeothermal and mantle-convective.

CORRELAÇÃO DE FLUXO TÉRMICO COM TECTÔNICA (CÉLULAS CONVECTIVAS) E CAMPOS HIDROGEOLÓGICOS – Este trabalho estuda os principais fatores que atuam na formação de um campo térmico heterogêneo na litosfera, baseado em medidas de temperaturas em 200 estruturas da União Soviética. O fluxo térmico foi calculado a partir da condutividade térmica das camadas rochosas em condições naturais, determinada através da velocidade das ondas sísmicas. As peculiaridades da distribuição do fluxo térmico abissal no Precaucaso, podem ser explicadas pela existência de uma célula convectiva hexagonal no manto superior. As variações locais e regionais da componente do fluxo térmico devido à convecção, e sua correlação quantitativa com as estruturas das camadas superiores da crosta, revelam a influência de águas subterrâneas nos campos térmicos. Foram feitas correções para as medidas de fluxo térmico nas áreas afetadas por movimentos de água subterrânea. A análise da distribuição vertical da temperatura e do fluxo de calor mostra que o campo térmico das camadas externas da Terra é estratificado e podem-se identificar os seguintes limites: atmosférico, neutro (limite com temperaturas anuais constantes), hidrogeotermais e células convectivas do manto.

METHODS OF HEAT FLOW DETERMINATION

The main source of information used during the study of the heterogeneous thermal field of the regions under investigation, were experimental measurements of temperature (T) in more than 500 deep boreholes which had a steady temperature regime. The temperature measurements have been made by the scientific workers of Kazan University with the help of the electronic distant research station EDIS- KSU (Neprimerov et al., 1983) which was developed by the chair of radioelectronics and repeatedly modernized. The station combines the high metrological parameters – precision (0.05°C), quick-acting, sensitivity – with mobility, reliability and minimum operation expenses. In its present version, it contains an abyssal instrument consisting of a sensitivity element (micro-

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thermoresistor of the Karmanov design) and a measuring transformer, a coupling channel (unprotected cable of the diameter of 3 mm) and a recorder. The station feeds on direct current, U = 12 v.

The temperature was measured in boreholes by section points, in 1-5 m. The boreholes stood idle for a long time (not less than a year) after boring or exploitation. The mean depth of the temperature measurements was 1700 m, the maximum depth was 4750 m. The geothermal gradients (Γ) were determined by temperature curves, by layers according to the generally accepted methods (Neprimerov et al., 1983).

The statistical estimates of the experimental data on geothermal gradient and seismic wave velocity (V) have shown (Eliseeva & Neprimerov, 1983) the validity of the theoretical description of heat transfer phenomena in rocks by means of the expression:

$$\lambda = \frac{1}{3} c\rho\tau V^2 \qquad (1)$$

where λ = thermal conductivity, c = heat capacity, ρ = density, τ = relaxation time of phonons (Reissland, 1975). Accurate graphs of dependence

$$\frac{\lambda}{q} = \frac{1}{\Gamma} = f(V^2) \qquad (2)$$

with correlation coefficients K = 0.6 – 0.99 and determination index R^2 = 0.64 – 0.84 have been obtained for terrigenous and carbonate rocks, Fig. 1.

The application of equation (1) to heterogeneous rocks has also been proved theoretically on condition that the porous medium under consideration is quasi-isotropic and quasi-elastic. In this case the expression (1) takes the form:

for low porosity (m), < 10-14%

$$\lambda = a V_s^2 \left(1 - b \frac{V_s^2}{V_l^2}\right) \qquad (3)$$

where

$$a = \frac{1}{3} c \rho_s \tau \frac{1}{1-m} \left(\frac{1+\delta_s}{1-\delta_s}\right)\left(\frac{1-\delta}{1+\delta}\right), \qquad (4)$$

$$b = \frac{m \rho_s}{3(1-m)\rho_l} \left(\frac{1+\delta_s}{1-\delta_s}\right), \qquad (5)$$

for high porosity, > 14%

$$\lambda = \frac{a}{b} V_l^2 \left(1 - \frac{1}{b} \frac{V_l^2}{V_s^2}\right) \qquad (6)$$

where δ is the Poisson's coefficient and the indices "s" and "*l*" correspond to solid and liquid phases respectively.

Empirical dependences (2) for high porosity

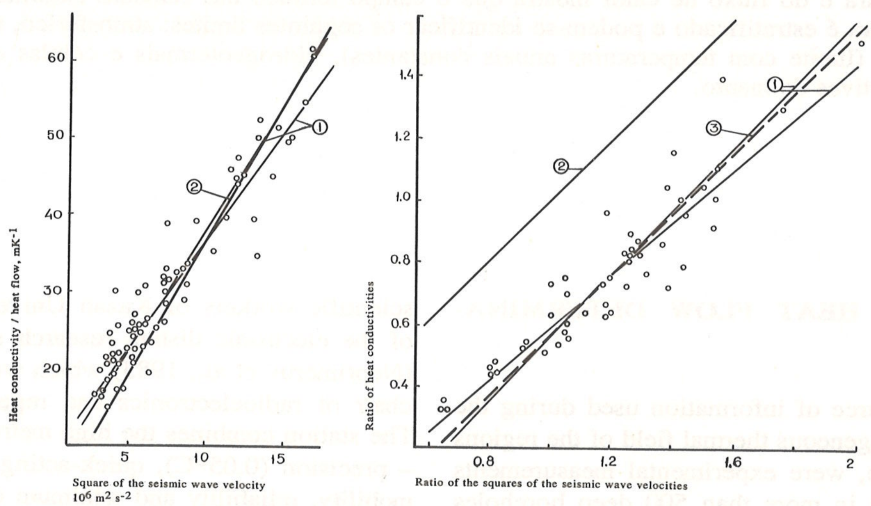

Figure 1. Correlation of heat and elastic properties of rocks in natural conditions: a) clay stratum N, b) ratio $(\lambda_1/\lambda_2) = (\Gamma_2/\Gamma_1) = f(V_1^2/V_2^2)$ for carbonate formations P_1-C_2 ks and C_1-D_3. 1. regression lines; 2. theoretical curves (equation 1); 3. theoretical curve taking into account the moving fluid (equation 9).

sandstones have not been established. This is in good agreement with the theoretical equation (6) (V_l = constant; dependence $\lambda = f(V_s)$ is weak).

Within zones of convective heat and mass transfer the following expression is valid:

$$q = q_{aB} \pm q_{cv} \qquad (7)$$

where q_{aB} is the abyssal heat flow, q_{cv} is the convective component of the heat flow, and the signs "+" and "–" correspond to the ascending and descending underground water movements respectively. If we take into account the equation

$$q_{cv} = c_l \rho_l w \Delta H \Gamma \tan \alpha \qquad (8)$$

where w is the filtration rate of fluids, ΔH is the strata thickness, tan α is the tangent of the inclination angle of the strata (Kruglikov, 1963) then expression (7) takes the form:

$$\frac{q_{aB}}{\Gamma} = \frac{1}{3} c \rho \tau V^2 \pm c_l \rho_l w \Delta H \tan \alpha \qquad (9)$$

or

$$\frac{1}{\Gamma} = a' V^2 \pm b' \qquad (10)$$

For the top permeable horizons the experimental regression lines have a form identical to equation (10) (e.g. the curve 3 on Fig. 1).

The calculation of λ using equation (1), on the basis of the established empirical dependence of heat conductivity on the seismic wave velocity, is proposed. Heat conductivity data for some of the rock strata are shown in Table 1. Laboratory-determined values for the parameters c, ρ and τ of equation (1) have been used (Neprimerov et al., 1983, Eliseeva & Neprimerov, 1983).

The precision of the method was determined by summing the errors of each value of calculation from equation (1). It results ± 25 per cent. However, the experimental indirect (through temperature) testing of the method in 11 boreholes has shown that the mean square error is 2°C, i.e. less than 5 per cent (Neprimerov et al., 1983; Christoforova & Neprimerov, 1985).

The suggested computational method for λ using equation (1) makes it possible to calculate the heat flow of the strata in a vertical section as well as to determine the abyssal heat flow and calculate the convective components of the heat flow.

The calculation method consists of the following stages. In a stratigraphic section the thicknesses of rocks are singled out, whose geothermal gradient values (from temperature curves) as well as seismic wave velocities (from the data of the seismic logging survey) are known. From equation (1) it is possible to calculate the heat conductivity for every layer, and by using the Fourier equation the heat flow can also be determined.

In all upper permeable horizons, q as a rule is somewhat less than q_{aB}. At some depth down the

Table 1. The variation of heat conductivity (λ) of main rock complexes in the Volga-Ural and Precaucasus regions.

Lithological – stratigraphic rock mass	Rock type	The calculated λ ($Wm^{-1} K^{-1}$) from seismic wave velocity: mean	minimum	maximum	Laboratory measurements
Volga-Ural					
P_1-C_2 ks	carbonate	2.3	1.6	2.9	1.99-2.2*
C_2 vr	c/lau	1.8	1.1	2.7	1.8*
C_1 sp-ok	carbonate	2.9	2.4	3.4	2.41-2.72*
C_1-D_3	carbonate	2.9	1.6	4.0	2.1 -2.53*
basement	gneiss	2.9-3.1	-	-	2.64-3.12*
Precaucasus					
N_1 mkp	c/lau	1.36	0.93	1.55	1.33**

* – Dyakonov & Jakovlev, 1969

** – Matvienco & Sergienco, 1976

section (called the hydrogeothermal boundary), the heat flow does not change, and is equal to q, as determined in the thick strata of clays. This value of the heat flow was taken for q_{aB}, and hence the q_{cv} values were calculated from equation (7).

The typical results of vertical distribution of temperature, gradient, seismic wave velocities, conductivity and heat flows can be seen in Fig. 2 for the Volga-Ural anteclise. Fig. 3 shows the variation of q_{aB} in the regions studied.

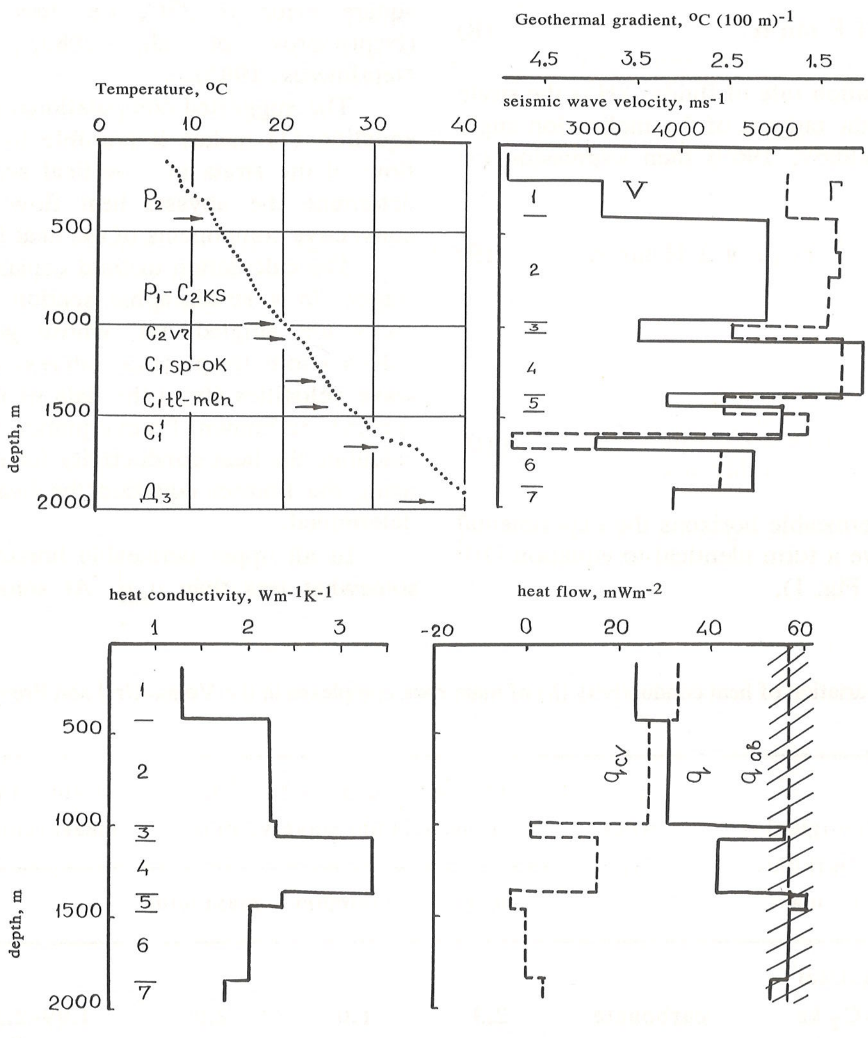

Figure 2. The distribution of the geothermal parameters in the borehole Jzhevskaja N 164. The shading area – interval of the error of heat flow calculation, $\pm$ 5 mWm^{-2}. Figures in graph are the lithological section: 1. sandstones, clays and partings; 2. limestones, dolomites and partings; 3. clays and partings; 4. dolomites, limestones; 5. sandstones, clay partings and outers; 6. limestones, dolomites and partings; 7. argillites, sandstones and partings.

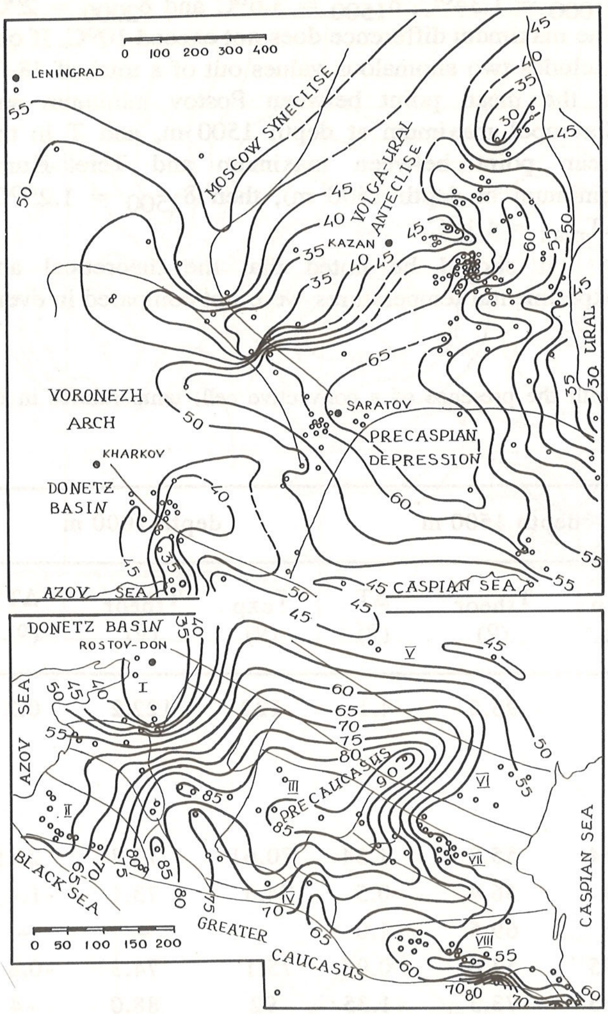

Figure 3. Abyssal heat flow maps, mWm^{-2}. ° localities of heat flow measurements. Thin lines are the boundaries of the main structural-tectonic elements: I. Rostov outcrop; II. West Kuban foredeep; III. Stavropol arch; IV. Mineral Water outcrop; V. Russian platform eastern part; VI. Karpinsky swell; VII. Terek Kuma uplits zones; VIII. Terek-Sunzha zone.

HEAT FLOW AND CONVECTIVE CELLS

The experimental study of the thermal field of the Precaucasus region (250 boreholes have been measured) has indicated its complex structure. In terms of T and q_{aB} isolines (Fig. 3) one regional maximum at the centre and six relative minimums can be singled out (Neprimerov et al., 1983). The Rostov outcrop, West-Kuban foredeep, Mineral Water outcrop, Terek-Sunzha zone, Terek- Kuma uplifts zone and Russian platform eastern part all have notably lower values of T and q_{aB}.

The analysis of the form and size of the anomalies of the T, q-field helped to make an assumption of the existence of a hexagonal convective cell in the upper mantle. The assumption was based on the experiments and ideas of G. Benar and R. Rayleigh (Jaluria, 1983; Coulomb, 1973), on the formation of regular convective cells of hexagonal form in which the hot fluid ascends at the centre and cold fluid descends along the walls, as well as on the ideas of Hess (1974) about the existence of convective flows in the mantle.

The mechanism of the functioning convective cell in the mantle explains: a) The observable relation of the heat and geodynamic fields, i.e. neotectonic uplifts in the region of the Stavropol arch and downthrow of marginal areas. The established empirical dependence of heat flow on the velocity of the neotectonic vertical movements of the crust has a high correlation ratio K = 0.85. b) The sharp temperature changes obtained by extrapolation of the T-field to depth (e.g. about 2000 °C at depth 70 km). c) The histogram of the distribution of the heat flow for the Precaucasus region. Three extremums are clearly fixed in the histogram – in the area of minimum, mean (background) and maximum values q_{aB}, whereas for geothermally stable regions histogram of q_{aB} has the form of the normal distribution (e.g. for the Volga-Ural region).

The depth to the roof of the cell was chosen to be 70 km due to the following considerations:

Firstly, this is the depth at which the vertical and horizontal components of the heat flow become equal. The minimum vertical heat flow in the Precaucasus is equal to 30 mW m^{-2}. The horizontal q was determined from the horizontal geothermal gradient using equation (18) on the assumption that $\lambda_{vert} = \lambda_{hor}$. At a depth of about 70 km q_{hor} is equal to 30 mW m^{-2}.

Secondly, a sharp temperature change is known to exist at depth marking the transition from continent to ocean, and which is caused by the height change at the continent-ocean, the mean height change being $\Delta H_m = 3.8$ km. On the other hand the mean values of heat flow in the oceans exceeds that on the continents. A system of the Fourier equations for the continent-ocean transfer has been set up on assumption that at the base of the lithosphere there must be a levelling of temperatures because of thermal convection:

$$q_{con} = \frac{T_x - T_o}{H_x} \lambda_{con}$$

$$q_{oc} = \frac{T_x - T_{o.f.}}{H_x - \Delta H_m} \lambda_{oc} \qquad (11)$$

where T_o is the constant yearly temperature and $T_{o.f.}$ the ocean floor temperatures. It has been obtained:

with $\lambda_{con} = \lambda_{oc} = \lambda = 3$ Wm^{-1} K^{-1}, $H_x = 71$ km, $T_x = 1335$ °C, with $\lambda = 2.5$ Wm^{-1} K^{-1}, $H_x = 69$ km, $T_x = 1540$°C.

For the Precaucasus region a three-dimensional stationary problem of heat conductivity was solved:

$$\frac{\partial}{\partial x_1}\left(\lambda \frac{\partial T}{\partial x_1}\right) + \frac{\partial}{\partial x_2}\left(\lambda \frac{\partial T}{\partial x_2}\right) + \frac{\partial}{\partial x_3}\left(\lambda \frac{\partial T}{\partial x_3}\right) = 0 \quad (12)$$

$\delta_{1000} = 1.34$°C, $\delta_{1500} = 3.6$°C and $\delta_{2000} = 2$°C. The maximum difference does not exceed 10°C. If one excludes two anomalous values out of a total of 48 (T in the mean point between Postov minimum and Stavropol maximum at depth 1500 m, and T in the mean point between maximum and Terek-Kuma minimum at depth 1500 m), then $\delta_{1500} = 1.25$°C, $\Delta T_{max} = 4.1$°C.

It should be noted that the theoretical and experimental temperatures were not compared in every

Table 2. The comparison of the experimental and theoretical (with the presence of a convective cell) temperatures in the Precaucasus.

Region	depth 1000 m			depth 1500 m			depth 2000 m		
	T_{exp}* (°)	T_{theor}** (°)	ΔT (°)	T_{exp} (°)	T_{theor} (°)	ΔT (°)	T_{exp} (°)	T_{theor} (°)	ΔT (°)
minima:	71	67.7	-3.37	97.6	93.5	-4.1	122	122.2	0.2
Stavropol									
Rostov	39.56	41.9	2.34	54.34	55.8	1.34	70.61	72.8	2.19
West-Kuban	42.5	42.7	0.2	55.9	56.4	0.5	74.5	73.1	-1.4
Mineral Water	53.64	54.5	0.86	68.5	69.5	1.0	-	-	-
Terek - Sunzha	42.5	42.7	0.2	56.95	57.0	0.05	75.1	74.3	-0.8
Terek - Kuma	52.5	52.0	-0.5	74.65	73.3	-1.35	92	88.0	-4
Eastern-Russian	40	40.2	0.2	52.9	53.9	1.0	70.5	70.5	0

* – The mean temperature in the area of the given extremum

** – At the point of the extremum

As a lower boundary condition we used the temperature distribution corresponding to the convective cell with one ascending and six descending branches: the radius of the cell is 300 km, $q_{as} = 90$ mW m^{-2}, $q_{des} = 40$ mWm^{-2}, $T_{max} = 2600$°C, $T_{min} = 650$°C, T_{mean} (background) = 1340°C. The problem was solved by the electronic computer ES-1033 by the finite difference method.

The difference in heat conductivity of the basement and sedimentary strata was taken into account: $H_B = 3.7$ km, $\lambda_B = 3$ Wm^{-1} K^{-1}, $\lambda_{s.s.} = 1.5$ Wm^{-1} K^{-1}.

There are considerable similarities between the theoretical temperature field and the experimentally measured one (Fig. 4a, b and Table 2) at depths of 1000 m, 1500 m, 2000 m with mean square errors

separate point (i.e. borehole). A great number of factors affect the temperature distribution under natural conditions. A comparison in every separate point would lead in some cases to anomalously high errors for it is very difficult to take into account all the factors, for example, lithological, structural-tectonic, and so on. Therefore we compared mean T_{exp} and T_{theor} for the singled out zones of the maximum, minimum, intermediate and also background regions.

Thus, the experimental data do not contradict the assumption of the existence of convective cell in the upper mantle with the parameters mentioned.

It should be stressed that $\Delta T = T_{max}-T_{min}$ can be lower if the roof of the cell is the inclined plane. For example, with $\Delta H = H_{max}-H_{min} = 30$ km (H_{max} and H_{min} are maximum and minimum depths to the roof of the cell) $T_{max}-T_{min} = 2200-900 = 1300$°C.

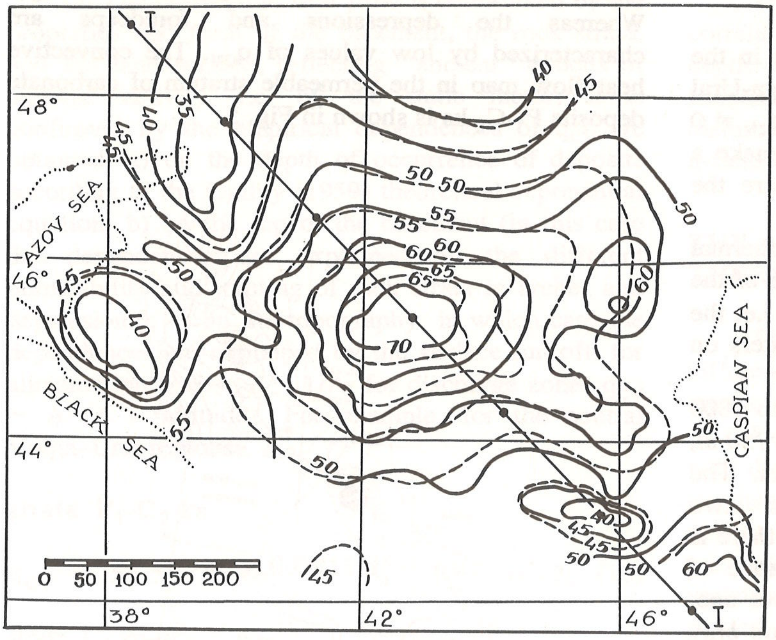

Figure 4a. Temperature distribution with the presence of a convective cell in the upper mantle. Theoretical (dashed lines) and experimental (continuous lines) schemes of isotherms at the depth of 1000 m.

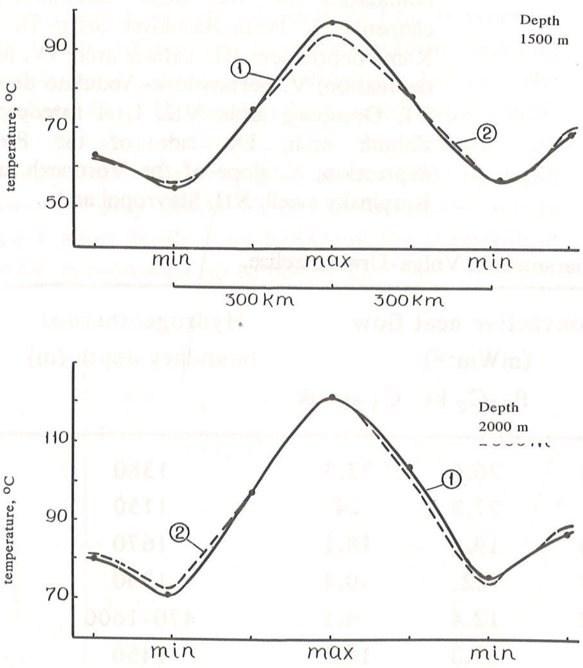

Figure 4b. Experimental (1) and theoretical (2) (with the presence of a convective cell in the upper mantle) distributions of temperatures at 1500 and 2000 meters depth along profile I-I: Donetz Basin – Stavropol Arch-Caspian Sea. Points in graphs are mean values T_{exp} in the area of the given extremum, where theoretical temperatures have been calculated.

CONVECTIVE HEAT FLOW

The investigation of the spatial changes in the convective component of heat flow in the Volga-Ural and Precaucasus regions (about 700 values of $q_{cv} \neq 0$ have been obtained) has made it possible to make a number of conclusions, and the main ones are the following:

1. The main character of the hydrogeothermal regime of the region is the depth of occurrence of the boundary separating the zone where $q_{cv} \neq 0$, i.e. the influence zone of the moving underground waters on the T, q-field.

In the regions studied it changes from 0 to 1800 m. The mean value in the Precaucasus region is 750 m, and in the Volga-Ural region it is 1350 m. The hydrogeothermal boundary H_{ht} separates two hydrogeological regimes – the top one, where there is vertical water filtration (as a rule it is the zone of penetration of infiltration waters) and the lower one, where the motion of underground waters occurs only along inclined horizons. The calculations of q_{cv} from equation (8) have shown that the effect of the inclined filtration on the thermal field is 2-3 orders smaller than with vertical filtration with equal rate, cm/year. With the inclination angles of the horizons which occur in the regions studied the effect is small. It is within the error of determination of q.

The mean values of the depths of occurrence of hydrogeothermal boundary and of convective heat flow by separate structural-tectonic elements are shown in Table 3.

2. The convective heat flow in the permeable horizons along the section decreases with depth to zero, Fig. 7. A structural-tectonic factor plays a decisive role in the regional variation of q_{cv}. The arches and uplifts are notable for higher values of q_{cv}. Whereas the depressions and foredeeps are characterized by low values of q_{cv}. The convective heat flow map in the permeable stratum of carbonate deposits P_1-C_2 ks is shown in Fig. 5.

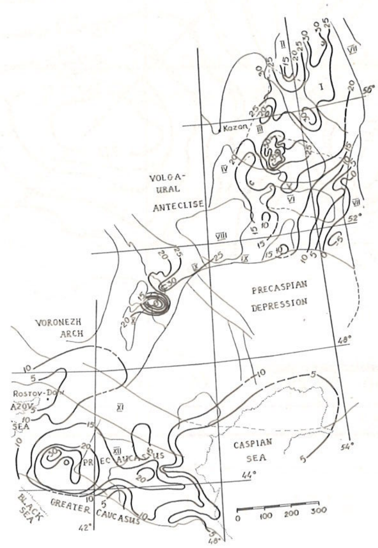

Figure 5. Convective heat flow map, mWm^{-2}. Volga-Ural anteclise - P_1-C_2 ks, Ural foredeep – P_2, Precaucasus – N_2-N_1 tch. Thin lines are the boundaries of the main structural-tectonic elements: I. Perm-Bashkiria arch; II. Upper-Kama depression; III. Tataria arch; IV. Melekess depression; V. Sernovodsk-Abdulino depression; VI. Orenburg arch; VII. Ural foredeep; VIII. Zhiguli arch; IX. side of the Precaspian depression; X. slope of the Voronezh arch; XI. Karpinsky swell; XII. Stavropol arch.

Table 3. Mean hydrothermal parameters. Volga-Ural anteclise.

Region	Convective heat flow (mWm^{-2}) P_2	P_1-C_2 ks	C_1 sp-ok	Hydrogeothermal boundary depth (m)
Perm-Bashkiria arch	33.3	26.6	22.3	1380
Tataria arch	45	27.8	24	1150
Orenburg arch	34.3	19.6	18.1	1670
Side of the Precaspian depression	33.7	22	-0.4	1300
Slope of the Voronezh arch	33.2	12.4	4.1	470-1600
Upper-Kama depression	26	19.3	16.5	1450
Melekess depression	15.4	17.8	17	1350
Sernovodsk-Abdulino depression	8.2	10.7	5.8	1370
Ural foredeep	0.2			0
Precaspian depression	4.7			0-350
Mean value	28.4	23.7	18.2	1350

3. The convective heat flow is determined by the properties and form of the basement, the rock strata, and the land surface, reflecting "ancient" epochs of tectonic activity, i.e. by the static factor. It is confirmed by the empirical dependences of q_{cv} we obtained: a) on the depth of occurrence of deposits according to the Ogilvy (1959) theoretical exponential equation; b) on the top of the basement (in this case the dependences are explained by the different permeability and jointing of rock strata in arches and depressions); c) on the topography, in which case the dependences are explained by the surface run off: for alimentation zone $q_{cv} \sim 1/A$, for discharge zones $q_{cv} \sim A$ (A – altitude). For example, for the central Volga–Ural regions:

strata P_1-C_2 ks

$$q_{cv} = 58.5 - 16.4e^{0.0011H}, \quad R^2 = 0.72; \quad (13)$$

strata C_1 sp-ok

$$q_{cv} = -0.0036\, H_B + 29.7, \quad K = 0.61; \quad (14)$$

discharge zone of the Tataria arch: $q_{cv} = 0.09A+16$ where H, H_B, A in metres.

4. It has been established that the depth of occurrence of the hydrogeothermal boundary correlates well with temperature distribution in the sedimentary strata. It can be seen in Fig. 6 where a line of mean values of T (mean within separate structural-tectonic elements) closely follow the variation line H_{ht}. In places where infiltration waters penetrate to greater depth, the temperatures are anomalously low. For example, at the 1000 m depth mark they are only 20-25°C, but in the places where their penetration depth is up to 500 m the temperature at the 1000 m increases up to 68-80°C.

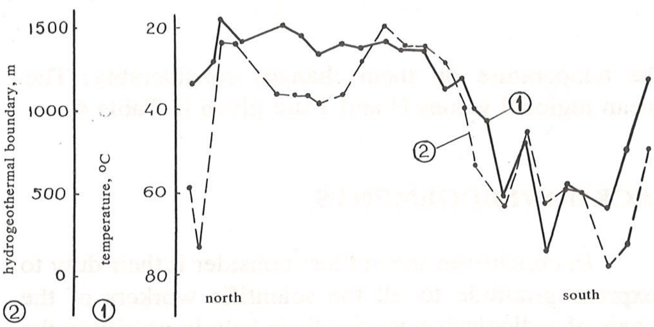

Figure 6. The effect of the hydrogeological factor on the thermal field of the sedimentary strata. Points are the values T and H_{ht} along profile: Pechora syneclise – South Caspian basin.

The results obtained not only prove the close correlation of the rock temperature with penetration depth of infiltration waters, but also confirm a more fundamental conclusion that the hydrogeological disturbance is one of the main factors that influence T, q-field in the upper layers of the Earth's crust.

THE MAIN REGULARITIES OF THE THERMAL FIELD OF THE EARTH

The analysis of heterogeneous thermal field of different regions has revealed some notable common regularities (Neprimerov et al., 1983).

Heterogeneity of the temperature field increases with depth, presumably as far as the asthenosphere in the mantle of the Earth. This regularity manifests itself most vividly in "predicted" graphs (Fig. 7), the principle of their construction is rather simple: a variation interval (ΔT) and mean temperature values plotted at fixed depth. The greatest heterogeneity of the T-field of the sedimentary strata is at the depth of the layer of constant yearly temperatures.

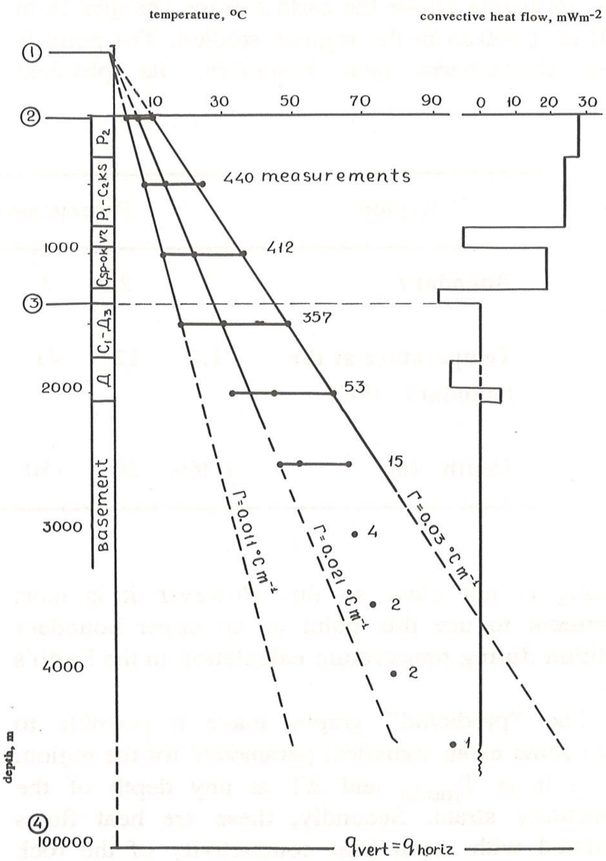

Figure 7. "Predicting" graph and summary hydrogeothermal section of Volga-Ural anteclise. The main boundaries of the thermal field: 1. atmospheric; 2. boundary with constant yearly temperatures; 3. hydrogeothermal; 4. mantle-convective.

The mean statistical behaviour of temperatures with depth in the region is described by the simple linear equations:

$$\frac{\partial T_{mean}}{\partial H} = \Gamma_{mean} = const,$$

$$\frac{\partial T_{min}}{\partial H} = \Gamma_{min} = const,$$

$$\frac{\partial T_{max}}{\partial H} = \Gamma_{max} = const \qquad (15)$$

For example, for the Volga-Ural regions: Γ_{mean} = 2.1°C (100 m)$^{-1}$, Γ_{min} = 1.05, Γ_{max} = 3.3; for Precaucasus: Γ_{mean} = 4, Γ_{min} = 2, Γ_{max} = 5.8.

It has been proved experimentally that this is valid for any region not depending on its geological, tectonic and geothermal structure, which allows one to speak about the similar nature of forces giving the heterogeneous T-field of the Earth crust in various regions.

The prolongation of the obtained lines (15) upwards gives a point where all the three straight lines cross. Its height above the earth surface changes from +170 to +460 m in the regions studied. The point is called atmospheric heat boundary. Its physical meaning is not clear so far. However it is most convenient to use this point as an upper boundary condition during temperature calculation in the Earth's crust.

The "predicted" graphs make it possible to obtain some mean statistical parameters for the region. Firstly, it is T_{mean} and ΔT at any depth of the sedimentary strata. Secondly, these are heat flows calculated with mean heat conductivity of the rock complex. Thus, for the Precaucasus q_{mean} = 54.4 mWm^{-2} (58.5), q_{min} = 18.6 (30), q_{max} = 91.5 (92). The brackets include heat flows calculated by the experimental Γ and V in every borehole. Thirdly, it is an increase of horizontal geothermal gradient defined by the equation

$$G = \frac{\partial}{\partial H} \left(\frac{\partial T_{hor}}{\partial L}\right) \qquad (16)$$

where L are line dimensions of the areas under study between minimum and maximum.

Summarising all the above statements, four main boundaries may be recognised for the Earth.

1. The atmospheric heat boundary.
2. The boundary of the layer of constant yearly temperatures. It is a layer where the direct influence of the day and yearly oscillations on the T-field of the Earth ends.
3. The hydrogeothermal boundary – a boundary layer, where the regional influence of the moving underground waters on the thermal field of the region ends.
4. The supposed mantle-convection heat boundary is the lithosphere boundary. Its depth is determined by the surface where the coincidence of the vertical and horizontal components of the heat flow is observed.

Each boundary is a very uneven surface. The values of the depth of occurrence of boundaries and the temperature on them changes considerably. The mean regional values H and T are given in Table 4.

Region	Precaucasus				Volga-Ural region			
Boundary	1	2	3	4	1	2	3	4
Temperature at the boundary (°C)	1.2	12	41	1340	-1.5	6	28	1400
Depth (m)	+260	20	750	70000	+450	20	1350	77000

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