FLUID-THERMAL REGIME IN THE CRUST-SUPERDEEP DRILLING DATA

Leonid Borevsky[1], Svet Milanovsky[2] and Leonid Yakovlev[3]

[1]Hydrogeoecological R&D Company, 15-th Parkovaya 10A, Moscow, 105203, Russia
[2]Institute of Planetary Geophysics of RAS, Bolshaya Gruzinskaya 10, Moscow, 123810, Russia
[3]Geological Institute of RAS, Pyzhevsky per. 7, 109017, Moscow, Russia

ABSTRACT

Versatile study in Kola (Baltic Shield) and Saatly (Trans-Caucasus) superdeep boreholes is presented. In both cases, hydrogeological conditions essentially determine thermal field in the upper part of the Earth's crust. In the Kola region, meteoric water circulation lead to intensive current cooling of the uppermost zone. In the deeper zone, hydrogenic dilation of ancient metamorphic rocks drastically changed their physical properties that manifested itself in the calculated heat flow density in depth. In the Saatly region, recently-discovered metamorphic downward flow of fluids mainly controls the temperature field down to 8-10 km. The flow is coupled with recent formation of permeable zones, which control intensity and directions of heat transfer in the studied part of the crust.

Key words: heat flow, hydrogenic dilation of rocks, metamorphic infiltration of fluids.

INTRODUCTION

Heat flow density (Q) is a fundamental parameter that characterizes the Earth's thermal energy state. Reliable estimates of heat flow density are critical because its value reflects both thermal heterogeneities at depth and subsurface effects that redistribute the heat flow. Deep and superdeep drilling are among the most effective methods of crustal thermal studies now used around the world.

The greater the depth of thermal investigations in boreholes, the more reliable are the estimates of the deep heat flow. Geothermal studies conducted in a superdeep borehole avoid perturbations of the geothermal gradient typical of shallow holes produced by paleoclimatic variations, active hydrogeological regimes or crustal erosion.

With increasing depth, however, problems of different kinds arise. One must consider high P-T conditions and their effects on thermophysical properties of rocks, and the influence of the physic-chemical state of rocks, their hydraulic properties and microfracturing on the thermal regime of the deep crust. Besides, fluid-rock interattion can give its own contribution to the heat and mass transfer in the crust. Geological and geophysical studies in the superdeep borehole help resolve these problems.

RESULTS OF RESEARCH IN THE KOLA SUPERDEEP HOLE

Geological settings. The Pechenga-Varzug Proterozoic volcanogenic belt extending in a nearly east-west direction across the Kola peninsula. The Precambrian terrains in the Pechenga ore province are grouped into 3 major complexes, the Archaean (AR_1) complex that forms the basement. the Tundra complex (AR_1-PR_1) that fills a pre-rift trough, and the Pechenga (PR_1) complex that gives rise to a linear rift-related structure.

The Kola hole *(SG-3)* drilled into the Baltic shield crystalline basement has provided a unique possibility for studying thermophysical properties of rocks, the geothermal gradient, thevertical component of heat flow density and heat production, for both Proterozoic and Archaean sections of the Pechenga greenstone structure. Because the Pechenga greenstone belt is structurally and compositionally isolated within the Archaean granite-gneisses, and the Archaean and Pechenga rocks are inhomogeneous in terms of thermal properties, detailed studies in a superdeep borehole are particularly helpful.

The following events are recognizable in the geological history of the Pechenga belt (Kremenetsky and Ovchinnikov, 1986): (1) a pre-rift event that produced an intercontinental depression on consolidated Archean basement (over **2.3** Ga), (2) a rift event including initial activation of the basement accompanied by andesitic-basaltic volcanism and the formation of shallow marine basins (2.2-2.1 Ga) and second activation of the basement accompanied by picritic-basaltic volcanism and accumulation of thick tuffaceous-terrigenous units (1.9-1.8 Ga), and (3) a post-rift event involving reverse fault dislocation (1.8-1.6 Ga).

At the first stage of the Pechenga paleorift evolution andesite-basalt lavas covered the rift floor composed of the Archean basement with a weathered crust. A sharp temperature increase resulted in the repeated heating of the basement rocks under epidote-amphibolite facies conditions. The partially closed system conditions for the metamorphism accounted for cracking of the upper part of the basement. The andesite-basalt lavas and associated marine sediments, after their consolidation, were metamorphosed in low-temperature greenschist facies.

The second stage of the Pechenga paleorift extension is characterized by intense picrite-basalt lava outflows (up to 2 km in thickness) which fully covered the first stage greenstone units. A rapid temperature increase and pressure led to progressive epidote-amphibolite facies metamorphism of the latter, involving cracking of the rocks and the formation of solution opening in them (a density decrease by hydrofracture! typical of hydrodynamically closed systems. The overlying picrite-basalt lavas with associated terrigenous sediments later underwent greenschist faciesmetamorphism.

This evolution of the Pechenga paleorift is supported by relicts of low-temperature minerals among the superimposed high-temperature radiologically dated minerals as well as by geochemical and hydrophysical zonation (Kozlovsky, 1984). The subsequent evolution of the Lower Proterozoic rift-related structure led to overlapping of subsided basement blocks by products of andesitic-basaltic volcanism and their complete isolation, followed, after a break, by overlapping of the andesitic-basaltic extrusive rocks by picritic-basaltic sheets and complete isolation of the extrusives. As a result, the region under review underwent three diachronous metamorphic events: a pre-rift event (amphibolite and granulite facies in the Archean basement rocks)) and two syn-rift events (early and late). The early syn-rift metamorphism brought about low-temperature alteration of the subsided Archean basement and Lower Proterozoic andesite-basalts, whereas the late syn-rift metamorphic event involved the whole succession to produce the zoning now observed: greenschist facies at the top **(0-4.5 km)** and epidote-amphibolite, facies at the bottom (4.5.-10 **km)**. A feature **of** the syn-rift metamorphism is its development under system conditions produced by the subsidence of the Proterozoic andesite-basalt sequence into the Archean basement and overlapping of the sequence by a great thickness (2 km) of picrites and basalts. A temperature increase in the closed system resulted in an increase in fluid pressure by the autoclave-effect principle, inducing dehydration of **high-H_2O** minerals (actinolite, chlorite, etc.) in the initial greenschists with release of free water and the formation of deep low-density rock zones. At the Kola borehole the latter correspond to water-influx and low-seismic-velocity zones.

Hydrogeological and geothermal study in ***SG-3.*** Hydrogeological studies in the SG-3 hole showed that its zonation can be divided into 4 parts (Borevsky et al., 1984), **as** follows (Pig. **1**). I. Permeable zone, associated with exogenous issuring. Meteoric water with low salinity in fractures **(0-800m)**. **II**. Zone of joint (free and chemically bounded) waters, mainly chemically bounded, where free waters occurs only in a narrow fault zones and veins (800- 4500m). III. Zone of regional tectonic foliation and hydraulic disaggregation of rocks, with free high saline waters belonging to metamorphic fluid with primary marine origin (4500-9200m). IV. Zone of joint waters, mainly chemically bounded with vein-type reservoir for free water **(>9200m)**. Zones III and IV are associated with riftogenic evolution of the Pechenga Greenstone Belt. Fractures were formed during dehydration processes in the mentioned closed system.

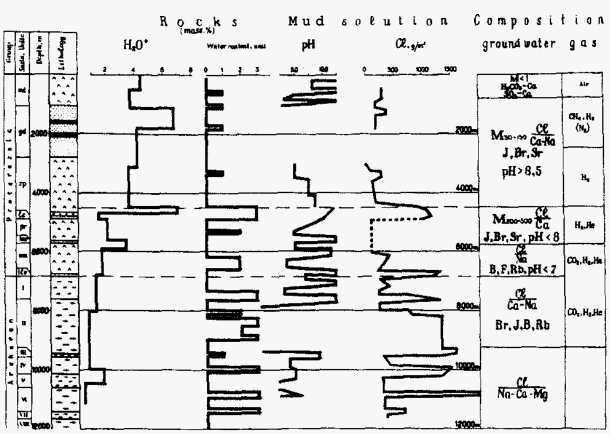
According to Borevsky et al. (1984) underground waters of the Proterozoic complex in the Kola hole section have **a** chloride-calcium-sodium composition pith elevated iodine, bromine and strontium contents (mineralization- 200-300 kg m^{-3}) in the zone of low density rocks (Fig. 1). This observation, along with the isotopic composition of the hydroxyl group ~~of the~~ newly-formed muscovite (δD = -30 $^{0}/_{00}$ **and** $\delta^{18}O$ = +9 $^{0}/_{00}$), points to a relation of the underground waters with the metamorphically generated fluids. The upper part of the Archaean basement is characterized by very light meteoric waters (δD = -100$^{0}/_{00}$), the lower part contains heavier (δD from -20 to **- 40** $^{0}/_{00}$) marine or meteoric-marine waters.

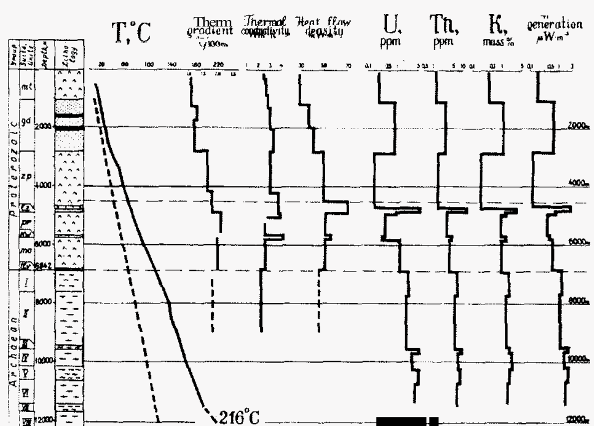
Geothermal data from the Kola hole is shown in Figure **2** and is summarized in Table 1.

The equilibrium geothermal gradient was found from a thermogram where the standstill period was 1.5 year. The absolute error in determining the gradient, depending on the measuringenvironment and instrument resolution, is on average 1 K/km.

According to assessments made by Milanovsky et al. (1994), the maximum temperature disturbance in the borehole due to drilling effects is -1 °C for 1.7 year-period, whish would provide ~1-2% error in the estimates of the equilibrium gradient. This error is less than the accidental error in estimates of the gradient during thermal logging.

To calculate the heat flow and to extrapolate temperatures to **a** depth from the bottom of the borehole to the Moho discontinuity (12,064 **- 40,000** m) the measured thermal conductivity (Lubimova et al., 1985: Popov et al., 1986) **was** adjusted for P-T conditions in the crust. Thermodynamic conditions in the upper layer of the crust in the Pechenga area are characterized by a slow temperature increase, therefore the effects of both pressure P and temperature T on the thermal conductivity of rocks in the section were considered. Temperature correction was calculated by a common ratio which characterizes the dependence of the phonon thermal conductivity component on temperature. The data on corrected heat flow summarized in Table 1, to **a** first approximation, are consistent with the above considerations on in situ thermal conductivity corrected for pressure and temperature conditions. More detailed studies of the borehole SG-3 should be aimed at verifying the in ***situ*** conductivity. One of the problems is determining corrections





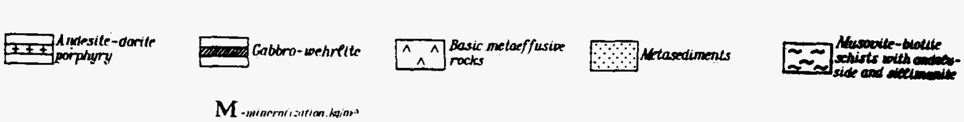


Figure 1. Hydrogeological characteristics of the Kola borehole.

Figure 2. Geothermal parameters of the Kola borehole.

Table 1. Summarized geothermal data from the Kola superdeep borehole

Depth, m	Mean vertical temperature gradient, °C/100m	Mean thermal conductivity of rocks, λ, $Wm^{-1}K^{-1}$	Average heat flow density, Q, mWm^{-2}	Q with correction for P-T conditions, Kola borehole.
0-1200	1.1	2.7	29.7	-
1200-1600	1.25	2.95	36.9	-
1600-2000	1.2	3.1	31.2	-
2000-2805	1.2	3.3-3.4	39.6-40.8	39
2805-4500	1.65	3.0±0.2	49.5±3	-
4500-4900	1.8	3.7-3.8 (λ max-4.0)	66.6-68.4 (Qmax - 72)	-
4900-5642	2.1	2.5-2.6	52.5-54.6	50.3
5642-5717	1.75	3-3 5	52.5-61.2	-
5717-6400	2.1	2.5-2.6	52.5-54.6	49.2
6400-6800	2.35	2.5	58.7	51.7
6800-7200	2.0	2.22	44.4	-
7270-9456	1.7	2.4	45.6	-

in thermal conductivity for rock moisture. The task is to define the porosity (fracturing) of rocks in **situ,** since cores extracted onto the surface undergo artificial fracturing by technogenic effects in addition to their natural porosity (fracturing).

Discussion of geothermal **data.** Geothermal studies that were carried out in the Pechenga province prior to the Kola borehole gave an uncorrected heat flow value of 38 mW m^{-2} or 42 mW m^{-2} after a correction for the thermal effects of glaciation. Our deep geothermal study permits verifying the heat flow density in the wellbore to *9* km depth. The results of the heat flow analysis is discussed below.

Table 1 and Figure 2 give the mean values of geothermal gradient, thermal conductivity, U, Th, K, heat generation and vertical component of heat flow for *SG-3* as inferred from (Krivtsov, 1991; Lubimova et al., 1985; Milanovsky et al., 1994). The geothermal gradient increase with depth is accompanied by an increase in the vertical component of heat flow . The heat flow at *3* km depth is almost twice the estimate of heat flow at the Pechenga structure prior to drilling the Kola borehole. Lack of information on the deep heat flow which is unaffected by near surface factors may explain why the predicted temperature at 10 km depth is rather low (120 °C instead of the measured value of 200 °C), (Lubimova, 1968). The observation of a gradient increase with depth requires consideration of factors other than erosion and paleo-glaciation effects. Matertian Suite (mt) rocks that are exposed at the surface are little-metamorphosed (the greenschist facies prehnite-pumpellyite zone). This observation implies weak erosion for the Pechenga complex which, according to geological evidence, is most likely to have been stripped of only **2.5 - 3.0 km of** overburden. Since the process occurred over a long period of time (hundreds of millions of years) the erosion correction to the geothermal gradient is negligible.

Now consider a correction for glaciation. Assume that the present-day surface temperature To = 0°C, the last, Ostashkovsk, glaciation episode occurred 10 years ago (t1) and the duration of this glaciation episode (t_2-t_1) was 1.1×10^4 years. If the surface temperature during glaciation is taken as T_1, then the perturbation which must have been superimposed upon the geothermal gradient at depth z is (Lubimova, 1968):

$$\Delta\gamma=-T_1\left[\frac{1}{\sqrt{\kappa t_1}}\exp\left(-\frac{z}{2\sqrt{\kappa t_1}}\right)-\frac{1}{\sqrt{\kappa t_2}}\exp\left(-\frac{z}{2\sqrt{\kappa t_2}}\right)\right]$$

The mean thermal diffusivity for the Pechenga rocks is $\kappa = 1.10\cdot 10^{-6}\ m^2 s^{-1}$. The correction to an undisturbed geothermal gradient for glaciation computed by equation (1) for two values of surface temperature during glaciation: T_1 = **-4°C** and -6°C. The correction decreases rapidly with depth and drops to 5% at 700 - 800 m for a gradient of 11 °C/km. Taking into account the correction for glaciation, the heat flow density in the interval 0-1,000 m depth is estimated, on average, at **32** mW m^{-2} and the apparent increase of heat flow with depth is only marginally diminished.

A different explanation for the discrepancy between shallow and deeper heat flov values may be sought In the hydrologic conditions in the Pechenga province. As is known, thermal and filtration properties of rocks are substantially affected by their degree of fracturing. In the upper part of the crust at the Kola borehole site hydrogeologists (Borevsky et al., 1984) have revealed a *800* m thick zone of regional fracturing.

Consider the filtration effect on the geothermal regime of the zone of exogenic fractures. Heat generation effects for the upper 5 km of crust are neglected in first approximation (Kremenetsky et al., 1989) and if the velocity of vertical groundwater filtration is denoted as v_z, then the value of this velocity is:

$$v_z=\frac{\ln(Q_2/Q_1)\lambda}{\rho_0 c(z_2-z_1)}$$

where Q_1 and Q_2 are heat flows at depth z_1 and z_2, ρ_0 - water density. Substituting for λ = 2.1 $Wm^{-1}K^{-1}$, z_1 = 200 m, z_2 = 1,200 m, Q_1 = 30 mWm^{-2}, Q_2 = 37 mWm^{-2} in the equation, we get the average Darcy velocity v_z = 0.43 cm per year. The true filtration velocity is $v = v_z/n$, where n is fracture porosity of rocks.

From geothermal evidence, the thickness of the zone of exogenic fractures is **1,000** to **1,200 m,** somewhat greater than the thickness inferred from hydrogeological data. Below this zone the number of fractures decrease. Nevertheless, hydrogeological sampling at the Kola borehole demonstrated that water influxes also occur at great depth (Fig. 1, 2) This is probably due to sandstone interlayers widely spread in the lowermost parts of the fourth, sedimentary, Zhdanov Suite (gd). Unfortunately, no hydrogeological sampling was undertaken in the **2,000 -** 3,000 m interval, but geothermal data from **2,** *000* to **2,750** m depth show an increase in the heat flow values from **37-38** mWm^{-2}

to **42-43** mWm^{-2}, and to **48-50** mWm^{-2} at the contact with the third, volcanogenic, Zapolyarny Suite (Zp).

On the other hand, suppose that groundwater with a constant regional run-off level are migrating relative to fractured rocks at a rate v_z similar to modern vertical motions w_z. The heat flow distortion in stationary approximation can be obtained by the expression (Kutas, **1978**)

$$\varphi = 1 \pm \frac{V_z c \rho_0}{\lambda}$$

whore φ shows to what extent the total heat flow in the filtration zone with thickness Δz and filtration velocity v_z, differs from the measured conductive heat in the medium where thermal conductivity of rocks is λ. From Somov and Rakhimova **(1983)**, the velocity of modern vertical crustal motions at the Kola borehole is **0.4** - 0.5 cm per year and a similar value of the vertical water filtration velocity is inferred from geothermal **data**

A value of **49,5±3** mW m^{-2} found for massive diabases of the Zapolyarny Suite (2,805-4,500 m) is probably the best choice for the deep heat flow density for the Pechenga structure as rock units at these depths are not subjected to the above discussed hydrologic effects. Moreover, this intervel is above the fractured zone of regional dislocation metamorphism where groundwater convection may distort the temperature field. The existence of fractures in the rock units at greater depth also hampers estimating the effective thermal conductivity.

Figure **2** and Table 1 demonstrate the true distribution of U, Th and K heat generation versus their average values calculated for each unit. The mean heat generation value for the Proterozoic **(PR1)** and Archean (AR) rocks is $0.41 \cdot 10^{-6}$ Wm^{-3} and $1.47 \cdot 10^{-6}$ Wm^{-3} respectively. The contribution of the Pechenga complex to the total heat flow is **2.8** mWm^{-2}, that of the Archean complex, to 11.5 **km** depth, is **6.86** mWm^{-2}. The overall radiogenic crustal contribution to 11.5 km depth is **9.7** mWm^{-2}.

The distribution of the radioactive elements is, to a large extent, affected by greisenization and retrograde metamorphism. These processes are responsible for the formation of schistose and highly fractured zones **as** well a5 water influx **zones** at the Kola borehole mainly below 6,000 m.

The distribution of the Th/U ratio in the Proterozoic metabasic rocks indicates that the highest scatter of the values is common to the Mayarvin Suite, which, in this case, is ascribed to the mobility of uranium that under low temperature and free water conditions can change valency from **4** to **6** (in this particular case uranium is predominantly subtracted!. Note that the region of dislocation metamorphism with sharp Th/U variations is consistent in depth with sharp geothermal gradient variations and thus can be treated **as** evidence of weak fluid convection in fracture-porosity natural environments (Lubimova et al., **1985)**. From the estimates made by these authors, the permeability of fractured rocks required for **such** convection is $1 \cdot 10^{-12}$ m^2 in small zones (150-200 m) and $\sim(2-5) \cdot 10^{-14}$ m^2 at **6-7** km depth.

RESULTS OF RESEARCH IN THE SAATLY HOLE

Downward fluid flow in the Saatly region

In the central part of Kura depression the Saatly superdeep hole was drilled **to** the depth of **8,3** kilometers (Fig. **3)**. The hole recovered Neogenic **molassic** sequence, Upper Cretaceous limestones and layer of Mesozoic volcanites, mainly basalts, subjected to a greenstone

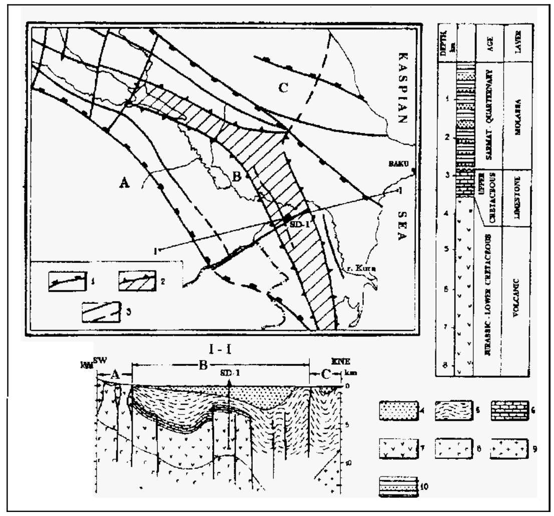


Figure **3**. Saatly superdeep hole and geological structure of the Eastern Trans-Caucasus.
A - Lesser Caucasus, B - Kura depression, C - Greater Caucasus; 1 - the largest faults, **2** - Saatly tectonic elevation, 3 - large faults, **4** - post-Neocene molassa, 5 - Paleocene - Neocene molassa, **6** - carbonate layer, **7** - volcanic rocks. 8 - mafic basement of the Kura basin, **9** - felsic rocks, 10 - molassa in the Saatly superdeep hole (SD-1).

metamorphism in conditions of zeolithic to greenshist facies. Versatile research of the Saatly hole showed that a downward flux of elisional waters into the volcanic layer takes place in the near-hole space.

First of all, the flux manifested itself in a contrasting cooling of the Earth's crust near the hole and in increase of the conductive heat flow density from **25** mW/m^2 at depth of **4** km to ***50*** mW/m^2 at depth **of** 7 km **(Fig.** 4). In the course of drilling, inflow of ground water into the hole from the molassa aquifers occurred, whereas in basaltic layer that inflow gave way to an intensive absorption of the drill liquid fromthe hole into fractured zones. At the depth of **8,3** kilometers the absorption exceeded the feasible limits, and drilling was interrupted.

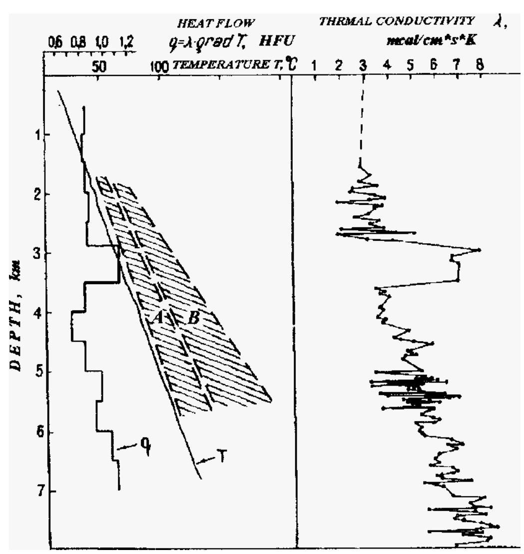


Figure **4**. Geothermal data from the Saatly superdeep hole. A - temperature in the Saatly tectonic elevation, B - temperature outside the Saatly elevation.

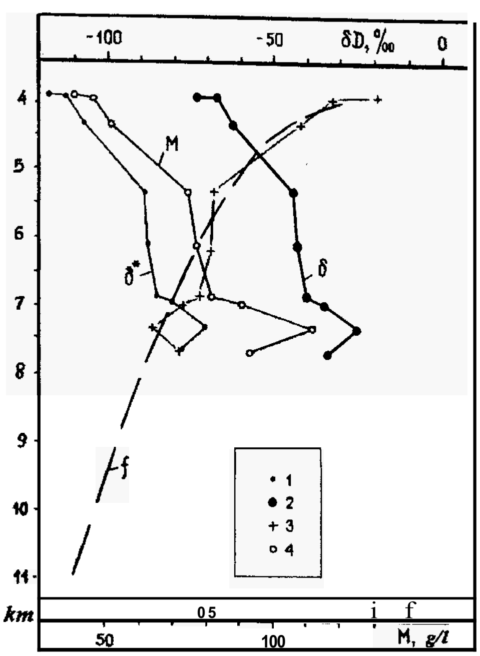
Table 2. Hydration reactions for basic rocks and their volumetric effects

No	Reaction	Metamorphic facies	Reference	T, °C / p, kbars	ΔV_{total} / ΔV^{matrix} cm^3	Δe_{total} / Δe^{matrix} %
	$CaAl_2Si_2O_8$ (anortite) + $2SiO_2$ (quartz) + $4H_2O$ (water) → $CaAl_2Si_4O_{12}*4H_2O$ (laumontite)	Zeolitic	Fyfe et al. 1959	50-200 / 1 - 4	+10,20 / +82,20	+5,2 / +66,7
	$5MgSiO_3$ (enstatite) + $CaAl_2Si_2O_8$ (anortite) + $5H_2O$ (water) - $2Ca_2Al_3O_{12}(OH)$ (epidote) + $Mg_5Al_2Si_3O_{10}(OH)_8$ (chlorite) + $4SiO_2$ (quartz)	From Zeolitic to Green-schist	Fyfe et al. 1978	50-400 / 1 - 7	-128,93 / -34.43	-19,7 / -6,1

Zones of the inflow and absorption of fluids were operatively detected by means of time-to-time registration of iodine and chlorine contents in the drill liquid circulating in the hole. The technique provided an another interesting result: in the pore water of volcanites, allotigenic iodine and chlorine present being alien for the composition of the host rocks (Yakovlev, 1992).

The altered rocks in the in the uppermost part of the volcanic layer were subjected to a relative enrichment with some elements (sodium, lithium, fluorine) in the course of their spilitization and propilitization under the influence of waters coming from the molassa (Kremenetsky et al., 1990).

Borevsky et al. (1986) and Yakovlev (1992) represented isotopic data, as follows. Firstly, isotopic composition of the bound water of metabasalts is in a good agreement with that of the molassa free water in view of fractionation of hydrogen and oxygen isotopes in *situ*. Secondly, total content of deuterium in the metavolcanites evenly increese with the depth (Fig. 5), that is a result of fractionation of



in the bound water of volcanites (1, symbol δ'), calculated deuterium content in the equilibrium free water (2, symbol δ), volumetric portion of the remaining free water (3, f) and water salinity (4, M) variations in depth in the Saatly hole.

hydrogen isotopes in the course of aqueous minerals formation along the path of descending fluid. At last, contents of ^{13}C in the vein carbonates from the volcanic layer oscillates near the zero in depth, that pointed out to the transfer of carbon from the overlaying marine limestones. Moreover, contents of ^{18}O agree with the isotopic composition of the solution which came from the sedimentary layer.

Calculation of the fluid flow velocity based on geothermal data (Yakovlev, 1992) yielded its average value in the basaltic layer of about 1 mm/yr. This result is in a good agreement with independent estimation obtained from geological data.

Summarized both calculated and empirical data (hydrogeological, geothermal, petrological, isotopic and geophysical ones) provided a principal hydrodynamical pattern of the Saatly near-hole space that shows the following:

1. As a whole, water heads in the permeable zones decrease in depth.

2. In the volcanic layer some zones of water manifestations were recovered, namely in the following intervals: 3540-4060m, 4820-5130m, 5950-6400m, 7100-7600m and 7900-8267m. Water influxes took place in the intervals upper parts, whereas the drill mud was being absorbed in their lower parts. The circumstance shows a descending infiltration of water coming to those zones from upper intervals and discharging from them to the deeper intervals.

3. The carbonate and volcanic layers are a single fractured system saturated with moving water moving through permeable zones of different origin, namely: laterally spreaded zones of lithogenic dilation and sequences od volcanoclastics and sub-vertical zones of tectonic fracturing. Therefore, the flux descending on the whole is locally drawn to the most permeable zones, *so* it has a cellular structure; loca! flow paths may have both lateral or even upward direction.

Recent manifestations of the downward fluxes in the Kura depression are plainly revealed by the regional hydrogeological data (Yakovlev, 1992). At the typical hydrodynamical cross-section (Fig. *6)* one can see a regional zone of elevated pore pressures. Beneath this zone heads of ground waters decrease with the depth. Hydrochemical anomalies mark places of the down discharge of fluids to the lower layers.

Therefore, very versatile data give independent evidences for reality of the discovered hydrodynamical disturbance in the deep interior of the Trans-Caucasus region.

We are coming now to its mechanisms and its coupling with another geological processes. This is interesting, in particular, from the viewpoint of interpretation of geothermal data.

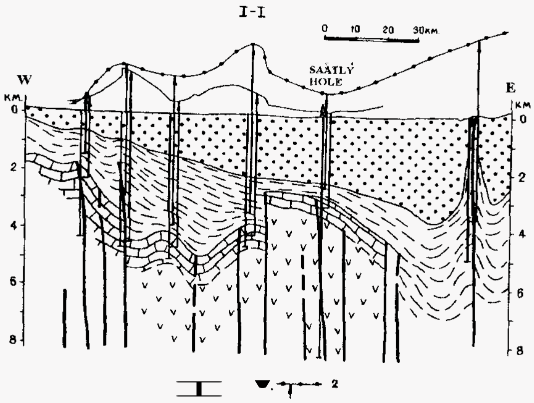


Figure 6. Hydrodynamical cross-section I-I. 1 - water heads in the Tertiary molassa, 2 - water heads in the Cretaceous rocks.

The down flow coupling with greenstone metamorphism of the basaltic layer

Formation of convective fluxes in basalts being hydrated has 2 duel nature. On the one hand, it is caused by creation of vacuum in the pore space of basalts resulting negative volumetric effects of hydration reactions like chloritization, epidotization, etc. On the other hand, the downward flux is a result of squeezing the water out of the sedimentary cover where catagenesis proceeds.

The effect of vacuum creation in the course of rocks hydration was illustrated by a set of schematic reactions being typical for PT-conditions of greenstone metamorphism of basalts (Yakovlev, 1992; Yakovlev and Borevsky, 1994b). Two of those reactions are represented in the Table 2.

One can see that formation of chlorite and epidote, the main products of greenstone metamorphism of basalts, proceeds with a volumetric effect of about -20%. Obviously, such marked deficiency of the water-rock system's volume caused by the heterophase reaction must be balanced in the open system by inflow of a mobile phase. That is the origin of the downward fluxes in the Trans-Caucasus region.

The mentioned cooling of the Earth's crust by the downward fluxes gains the negative chemical volumetric effect due to the thermal contraction of the medium.

Such coupling of chemical and thermal deformations with the hydrodynamical disturbance in the water-rock system was considered in (Yakovlev, Borevsky, 1994a; See also Yakovlev, 1995). Their estimation of this interrelation intensity showed pore pressure will change by 100-1000 when the volumetric effect of chemical reactions is only of the order of 0.1% or temperature changes only by some tens degrees. Note, that piezometric effect of the order of 100-1000 bars leads to destruction of low-permeable fragments of the rock matrix due to its hydrofracturing and/or destruction of grains near their contacts. Owing to this advection of fluids erases or speed up itself trying to embrace the total volume of initially monolithic blocks. Chemical and phase heterogeneity of matrix provides non-uniform hydration of minerels, with different signs of volumetric effects in separate zones (pores). Two above reactions (Table 2) are the evidence of this phenomena. All the processes reveal themselves in the very beginning of the alteration of igneous rocks.

The aqueous solution coming into the deep bowels of the basaltic layer is concentrated up to a state of brine resulting the water addition to mintrals. This inference follows from the analysis of deuterium content in metabasalts in the Saatly superdeep hole. The content increases with depth (Fig. 5) as a result of isotopic fractiation in the course of the rocks hydration. Yakovlev (1992) carried out calculation of the intensity of water absorption versus depth by the use of a formula much as the Role's equation for the liquid evaporating. the calculation showed that primary elisional waters with mineralization of about 40 g/l may be concentrated at the depth of 8-10 km up to a brine state with mineralization of 150-200 g/l.

Thus and so, mineral-forming secondary processes in the mafic rocks of large thickness appear as powerful regulators of the hydrodynamics as well as geochemistry and geothermal conditions of deep geospheres, since they are closely coupled with excitation of the metamorphic infiltration of fluids.

Global manifestations of the metamorphic infiltration of fluids

Metamorphic infiltration of fluids must erase in the initially dry rocks if the former get the P-T-conditions for greenstone metamorphism if an outer source of water take place, and a good hydraulic relationship between them was enabled. Adopting this criteria to the Trans-Caucasus region, Yakovlev (1992) showed that favorable preconditions for the metamorphic fluids infiltration took place from the end of Mesozoic to the Middle Eocene within the "Trans-Caucasus Basaltic Belt". The belt was extended toward Iran, Anatolian and Pont mountains as a thick volcanic cover.

The metamorphic infiltration of fluids is likely typical for the Earth's crust fragments where the sedimentary layer directly covers the basaltic basement. Such structure is typical for many crustal units as follows: depressions of orogenic belts (Kura depression, River Po basin, etc.), basins of marginal seas and other depressions of the ocean-continent transitional zone (Sea of Japan, Eastern-Kamchatka depressions, etc.), some continental rifts (Baikal Rift Zone, Upper Rhine graben, Mississippian rift, etc.), and also sedimentary basins of the ocean.

A remarkable phenomenon of the downward flux of seawater through the hole 504B (Deep Sea Drilling Project! near the Costa-Rica rift (Becker et al., 1983, etc.) seams to be a bright example of current manifestation of the metamorphic fluid infiltration. Resuming of the down flow some years after its primary impulse is the most notable circumstance, which may be explained by the pulsed character of seismic activity provoked by the down flux along faults (Yakovlev, 1992).

Thus, the processes considered have possibly of wide current and ancient manifestations in the Earth's crust. So, they must be taken into account in the study of the thermal and coupled processes in the lithosphere, both current and ancient ones.

CONCLUSION

The paper shows the importance of hydrogeological effects for understanding geothermal observation in superdeep holes. Deep fluids were established on depth more than 6 km. For Kola area subvertical meteoric water flow in the upper part of the crust is the main factor decreasing the heat flow density till 2 km.

For Saatly hole the cooling effect caused by hydration of dry basic rocks was observed. This effect manifested itself both in the sedimentary cover and especially in the depth interval 4-6,7 km, in the volcanic basement. Established process of metamorphic infiltration of fluids is important in many present geological situations for the interpretation of geothermal observations.

REFERENCES

Becker, K., Langseth, M.G. and Von Herzen, R.P. (1983) Deep crustal geothermal measurements, Hole 504B, Deep Sea Drilling Project Legs 69 and 70. *Init. Rep. of the DSDP*, Vol.69., pp.223-235.

Borevsky, L.Y., Vartanjan, G.S. and Kulikov, G.V. (1984). Hydrogeological essay. In: *The Kola superdeep borehole, E.* A. Kozlovsky (Ed!, pp. 240-254. (in Russian).

Borevsky, L. V. and Kremenetsky, A.A. (1985). Geological role of groundwaters in progressive metamorphism under open and closed systems conditions. In: *Groundwaters and the evolution of lithosphere,* Nauka, Moscow, pp. 8-11 (in Russian).

Borevsky, L.V., Polyakov V.A., and Yakovlev, L.Ye. (1986). Application of isotope methods to investigate hydrodynamics of superdeep aquifers (1986). In: *Methods of investigations and evaluation of deep horizons water deposits.* Moscow, VSEGINGEO, pp.51-58. (in Russian).

Fyfe, W.S., Turner, F.G. and Verhoogen, J. (1959). *Metamorphic reactions and metamorphic facies.* Baltimore. 321 pp.

Fyfe, W.S., Price, N.J. and Thompson, A.E. (1978). *Fluids in the Earth's Crust, Elsevier, Amsterdam.* 383 pp.

Kremenetsky, A.A., Lapidus, A.V. and Skryabin, V.Yu. (1990). *Geological-geochemical methods of deep prognosis of the ore deposits.* Nauka, Moscow. 223pp.

Kozlovsky, E.A. (Ed). (1984). *The Kola superdeep borehole,* Nedra, Moscow, 490pp. (in Russian).

Kremenetsky, A.A., Milanovsky, S.Yu. and Ovchinnikov, L.N. (1989). A heat generation model for continental crust based on deep drilling in the Baltic Shield. *Tectonophysics,* Vol. 159, pp 231-246.

Kremenetsky, A. A. and Ovchinnikov, L.N. (1986). *Geochemistry of deep rocks,* Nauka, Moscow, 262 pp. (in Russian!.

Krivtsov, A.I. (Ed). (1991). *Models and cross-sections of the Earth's crust.* Compiled by A.A.Kremenetsky. IMGRE, Moscow, 164 pp.

Kutas, R.I. (1978). *Heat flow field and a thermal model for the Earth's crust,* Naukova Dumka, Kiev, 147 pp. (in Russian).

Lubimova, E.K.(1868). *Thermal regime of the Earth and the Moon,* Nauka, Moscow, 280pp. (in Russian).

Lubimova, E. A., S. Yu. Milanovsky and Smirnova, E.Y. (1985). New data from heat flow studies at the Baltic Shield. In: *The history of heat filed of variable endogenic regime zones of Eastern Europe,* Nauka, Moscow, pp. 93-110. (in Russian).

Milanovsky, S.Yu., Kremenetsky, A.A. and Ovchinnikov, L.N. (1994). Geothermal studies of the crust in the Northern Baltic Shield: the Kola superdeep borehole. *J.G.R.* (submitted)

Popov, Yu.A., Boitchov, V.Ye., Berezin, V.V., Lanev, V.S., Semenov, V.G. and Konirev, V.S. (1986). Study of thermal conductivity of the rocks from the upper part of Pechenga Complex, *Dokl. Akad. Nauk USSR,* Vol. *289,* No 5, pp. 1083-1087. (in Russian).

Somov, V. I. and Rakhimova, I.Sh. (1983). *Present crustal motions of the Carpathian-Balkan region and adjacent structures,* 144 pp., (in Russian).

Yakovlev, L.Ye. (1995). Chemical hydrofracturing and secondary permeability in the Hot Dry Rock reservoir. *This issue.*

Yakovlev, L.Ye. (1992). Role of allometamorphism of the basaltic foundation of sedimentary basins in the' Earth's crust evolution. *Izvestiya Rossiyskoy Akademii nauk, seriya geologicheskaya,* No *9*, pp.41-60.

Yakovlev, L.Ye. and Borevsky, L.V. (1994a) Hydrodynamical response of water-rock system on chemical and thermal volumetric deformations. *Geokhimiya,* No 7, pp.1002-1011.

Yakovlev L.Ye. and Borevsky, L.Y. (1994b) Interaction of hydrodynamical, chemical and thermal processes in the earth crust. *Geokhimiya,* No 8.