Evolution in information on crustal geothermal parameters due to application of advanced experimental basis

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Abstract. New experimental basis was developed and implemented to provide improvement in geothermal data reliability and extension of the geothermal data application in geophysics. A continuous thermal core logging technology was developed (2015) and applied (2015-2018) on 27 300 cores from 31 wells. Correlations between thermal and other rock properties, established from integration of thermal and standard logging data, allowed to improve standard logging data quality and estimate thermal properties from standard logging data. New optical scanning instruments provide profiling thermal properties to characterize formation heterogeneity continuously with spatial resolution up to 0.2 mm. International recommendations on rock thermal property measurements were developed. The approaches were developed to improve techniques of thermal property integration in modern hydrodynamic simulators. Techniques were elaborated to determine firstly rock matrix thermal properties and provide fast thermal property measurements on rock cuttings. Rock fracturing characterization became possible from thermal core profiling. Vast data on thermal property at elevated temperatures were obtained with the special instruments. New investigations of vertical variations in heat flow performed with the new technologies confirmed our previous data on heat flow increase with a depth by 45-120 % that requires serious corrections of the previous results and reconstruction of geothermal maps often.

1. INTRODUCTION

The results of our geothermic measurements in scientific deep boreholes and other shut-in wells, suggestions on evolution of methodology and techniques of experimental investigations of the basic geothermic parameters, and necessity to register vertical variations in heat flow along boreholes have changed very much in knowledge on the crustal thermal regime and geothermic parameters including the formation thermal properties ([7], [13], Chekhonin et al., 2013). New approaches to the geothermic measurements and developed advanced experimental basis for geothermic experiments developed recently are described in the paper below. Integration of all these components in routine geothermic experiments are necessary to exclude losses in important information on the geothermic parameters in fundamental geophysical research as well as in exploration, prospecting and production of fields of geothermal energy and hydrocarbon resources.
2. RESULTS IN THERMAL PETROPHYSICS

A new technology of continuous thermal core logging was developed in 2015 and implemented widely in fundamental and applied experimental geophysics (2015-2018). The technology is based on application of the optical scanning technique for continuous non-destructive non-contact profiling of thermal properties (thermal conductivity (TC), thermal diffusivity, volumetric heat capacity (VHC), and thermal anisotropy coefficient) on full-size core samples that provides unique information for geothermal and hydrocarbon reservoirs [8], [9]. More than 27,300 core samples from 28 wells from 17 hydrocarbon reservoirs were studied in 2015-2017 using continuous profiling on all core samples along every well. High-resolution (~1 mm) profiles of TC and VHC were recorded along every core sample. TC tensor component perpendicular and parallel to the bedding plane, thermal anisotropy coefficient, thermal rock heterogeneity coefficient and VHC were determined for every core sample. The numerous measurements demonstrate that TC varies essentially (by dozens percent and often by many dozens percent) within every core sample for practically all rock types that restricts strongly application of traditional techniques for comprehensive characterization of the rock thermal properties (Chekhonin et al. 2013). The thermal anisotropy coefficient is significant especially for gneisses and shales (up to 3) and has a strong zonality along every well that is caused by structural and textural peculiarities of rocks [11], [15]. The approach was suggested (and tested successfully using measurements with pyrolysis technique) to transform TC profiles into detailed continuous profiles of total organic carbon along every well with a spatial resolution of ~1 mm. The correlations established from continuous thermal core profiling for numerous wells allowed us to transform the profiles of TC and thermal anisotropy coefficient into profiles of rock density, sonic P- and S-velocities, Young modulus and Poisson’s coefficient with average spatial resolution of ~10 cm (Popov E. et al., 2016; [3]. A way was suggested and tested to characterize acoustic anisotropy from the thermal anisotropy coefficient data. Our measuring technique and experimental thermal data are being used today for investigations of formation thermal regimes and formation thermal properties in basic and applied geothermics and in oil/gas science and industry for basin and petroleum system modeling, development and optimization of thermal methods of EOR, analysis of reservoir heterogeneity and anisotropy, in geochemistry and geomechanics also [3]. As a result, thermal petrophysics becomes an important scientific and practical direction for investigations and development of geothermal and hydrocarbon fields. The correlations between the rock thermal properties and the data of standard petrophysical well logging established from investigations of numerous reservoirs provide determination of the rock thermal properties from the standard petrophysical logging data when core samples are absent. The new technique provide high efficiency in investigations of geothermal reservoirs.

The new technology for investigations of the rock thermal properties (thermal conductivity, thermal diffusivity, volumetric heat capacity, thermal anisotropy coefficient) of geothermal and hydrocarbon reservoirs was developed to provide numerous express high-precision measurements of the rock thermal properties on rock cuttings recovered from wells just during noncore drilling [10]. The technique provides the information on detailed variations of rock thermal properties along wells drilled without core recovery. The new technology of preparation of numerous synthetic samples consisting of core cuttings or non-consolidated rocks and special material-filler was developed, studied and tested. The approach for numerous non-contact high precision measurements of effective thermal conductivity, thermal diffusivity and volumetric heat capacity of synthetic samples was suggested, tested and applied. The theoretical models of effective thermal conductivity of heterogeneous media allowing to solve an inverse problem were suggested and modified that allows us to transform the results of effective thermal property measurements on synthetic samples into the data of rock cuttings thermal conductivity and volumetric heat capacity. The special enhanced optical scanning instrument was developed that provides the fast non-contact non-destructive high precision measurements of rock cutting thermal properties just in field conditions during the well drilling. More than 160 synthetic samples were fabricated to adjust and test the technology. Natural and industrial
materials (technical optical glasses (TF-1, K-8, LK-5, KV), several types of marble, granite and sedimentary rocks) with the thermal conductivity within a range from 0.7 to 4.5 W/(m·K) were used for fabrications of the synthetic samples during the technology testing and adjustment. A following workflow for synthetic sample preparation was developed: (1) preparation of material cuttings using a ball mill, and (2) fabrication of synthetic samples with a press machine. After that the synthetic samples are being studied for their effective thermal properties using high precision measurements with the optical scanner.

A new optical scanning instrument was developed to provide non-contact non-destructive measurements of thermal conductivity, thermal diffusivity and volumetric heat capacity of consolidated rock and other solids with a flexible spatial resolution (from 0.1 mm) and variable minimum thickness and width of rock samples under investigations. The instrument allows to determine the TC and VHC values and to record continuous profiles of these thermal properties for heterogeneous solids along the scanning line simultaneously in one experiment. The principal TC components of anisotropic solids can be determined if angles between a scanning direction and principal TC axes are known. Directions of the principal TC axes can be established from several measurements. Principal peculiarities of the new instrument include possibilities (1) to change mutual configuration of the heating spot and fields of view of infrared sensors just before every experiment, (2) to vary heating spot dimensions and the scanning velocity, (3) to vary a spatial resolution of thermal heterogeneity recording, thickness and width of the solid zone that is studied in the experiment, (4) to adjust the measuring regime parameters according to solid dimensions, thermal properties, and maximum heating temperature allowed. Non-contact principle of the measurements and possibilities to adjust the measuring regime parameters comprehensively for every experiment provide a measurement result uncertainty not more than 3% for TC and 5% for VHC (at confidential level of 0.95).

Methodology of rock fracturing characterization was developed and implemented. The methodology is based on measurements of the thermal conductivity tensor components of dry rock samples and repeated measurements of the thermal conductivity tensor components after water-saturation of the rock samples. Fracturing degree and orientation of fracturing are characterized from processing and interpretation of the data inferred from these two experiments.

The rock matrix thermal conductivity and volumetric heat capacity values are required in numerous thermo-hydrodynamic simulators for modeling heat and mass transfer processes in reservoirs. Two techniques were developed to determine the rock matrix thermal conductivity and volumetric heat capacity. Technique 1 allows us to determine the matrix thermal properties from the measurements on core plugs with different porosity values using the optical scanning instruments when rock anisotropy and heterogeneity are accounted for carefully. The lithologically homogeneous rock collections should be prepared and studied. The regression equations “rock matrix thermal conductivity vs porosity” and “rock matrix volumetric heat capacity vs porosity” allow us to determine the rock matrix thermal properties with high reliability. Technique 2 for determination of the rock matrix thermal properties is based on application of the continuous thermal core logging technology when the continuous thermal property profiles are processed jointly with standard petrophysical logging data. In this case continuous distributions of the rock matrix thermal conductivity and volumetric heat capacity along wells are recorded that provides detailed accounting for reservoir heterogeneity.

The geometric mean model of effective thermal conductivity [6] applied widely in geothermics for rock thermal conductivity characterization was modified to provide more correct results of thermal conductivity estimations for porous and fractured rocks. The model modification is based on determination of the Assad’s correction coefficients [1] integrated in the geometric mean model for different types of dry and fluid saturated rocks from our thermal conductivity measurements on more than 8 000 core samples.

3. RESULTS OF HEAT FLOW DETERMINATION
Our geothermic measurements within the deep continental drilling programs in the former USSR (1985-1991) and later in Russia, within the ICDP (1996-2014) as well as our new geothermic experiments (2018) have provided vast experimental data (on temperature, thermal gradient, rock thermal properties, and heat flow) to define the thermal characteristics of the crust. A principal advantage of the scientific boreholes was that they permitted repeated temperature logging over long time intervals (often several years) after drilling or fluid injection ceased. Thus we were able to determine fully equilibrated thermal gradients, and study spatial and temporal variations in temperature and temperature gradient within individual rock formations. Scientific boreholes are usually cored, helping scientists in measuring thermal conductivity along large continuous sections of the borehole. The advanced optical scanning technique with reliable metrology has been used to measure the rock thermal properties on many thousands of core samples (Popov Yu. et al., 2016). As a result, deep and super-deep scientific boreholes prove invaluable in the determination of vertical heat flow distribution, one that can usually not be studied in commercial boreholes.

The measurements in the scientific boreholes demonstrated that temperature gradient recovery up to equilibrium occurs essentially faster than it was assumed earlier. The rate of temperature gradient recovery was found to be different for different formation layers [13]. For some parts of a given formation the temperature gradient may reach equilibrium practically upon completion of drilling or fluid injection. This allows us to determine relatively robust equilibrium temperature gradient values from temperature measurements performed in boreholes even immediately upon completion of drilling. On the other hand an accurate estimation of formation recovery time profile along a borehole – and this implies several temperature measurements over time – can provide valuable information about the distribution of reservoir properties just from the temperature logging data.

In most cases a correlation between temperature gradient and thermal conductivity determined for short depth intervals along the borehole does not follow the Fourier Law for steady-state conductive heat transfer. In other words it can be shown that vertical variations in temperature gradient do not correspond to the vertical variations in thermal conductivity. This implies that heat transfer in a formation of significant depths (more than 2-4 km) may not be in steady state and/or not purely conductive as routinely assumed.

The detailed thermal conductivity data obtained from continuous thermal core logging or from the thermal property measurements with core sampling 1-2 m using the advanced optical scanning instruments (Popov Yu. et al., 2016) allow us to determine a conductive component of the heat flow within every 10-100 m interval along every borehole under investigation. Thermal conductivity anisotropy was estimated and accounted for in all cases for determination of necessary components of rock thermal conductivity as well as for heat flow calculations in anisotropic formations [11]. Water-saturation of rock samples at vacuum and special instruments developed for the thermal property measurements under elevated pressure and temperature were used to provide corresponding formation conditions and to account for a decompressional effect that affects the rock thermal conductivity and rock anisotropy significantly sometimes (Chekhonin et al., 2013). More than 30 000 core samples were studied for the rock thermal properties totally to record vertical variations in the heat flow and to determine terrestrial heat flow values during our geothermic experiments in Russia and abroad.

Significant vertical variations in the conductive component of the heat flow were established for all boreholes under study. Continental heat flow density values established from our experiments in scientific deep and super-deep boreholes exceed significantly (by 23-147 %) previous experimental estimates for shallow boreholes (see the Table below).

**Table.** Our experimental data on heat flow density from the measurements in scientific continental boreholes.
The terrestrial heat flow density within the Moscow synclise (the East European platform) was determined earlier as 25-50 mW/m² [5]. Our new experimental determinations of vertical variations in the heat flow in the Moscow synclise within the depth intervals of 2500-4000 m demonstrated that a conductive component of heat flow ranges from 52 to 77 mW/m², that is significantly (up to 60%) larger than most of the previous heat flow estimations in the region. Our experimental investigations were performed for two new wells – the parametric North Molokovo well (3313 m in depth, Khrestzovsko-Molokovskiy megaswell) and the parametric Vysokovo well (2670 m, South-Eastern flange of the synclise). Thermal conductivity was measured on 136 cores for the North Molokovo well and 93 cores for the Vysokovo well that corresponds to down parts of the wells. The optical scanning technology was used for rock thermal conductivity measurements on water-saturated cores (Popov Yu. et al., 2016). Temperature gradient increase with a depth was established for both wells. Rock thermal conductivity anisotropy was found to be essential (up to 1.5). The artificial fracturing of cores appearing after core recovery was considered as a basic reason of rock thermal anisotropy and was accounted for the in-situ rock thermal conductivity determination. Significant vertical variations and general increase in the heat flow with a depth were established for both wells. The maximum values of the heat flow are 64-77 mW/m² for the North Molokovo well and 52-64 mW/m² for the the Vysokovo well that corresponds to down parts of the wells. According to our experimental data for the Vorotilovo deep well [12] with correction on flow refraction effect, terrestrial heat flow density was estimated as 60-70 mW/m².

Our recent (2018) geothermal measurements in southeastern part of the European platform (Russia) were performed using a wide set of advanced measuring geothermal technique: continuous thermal core logging technology, instruments for thermal property measurements at formation conditions,
combination of thermal property measurements on full-size cores and core plugs, water-saturation of core samples at vacuum, accounting for multi-side rock formation heterogeneity and micro- and macro anisotropy. Several temperature logging measurements in shut-in well were performed that demonstrated thermal equilibrium of the well and surrounding formation. New experimental heat flow data demonstrated again essential vertical variations in heat flow when new heat flow estimates exceed previous experimental data by 80-95%.

These heat flow estimates produced by experimental data mostly from deep and super-deep boreholes can significantly change our understanding of the nature of the thermal regime in the crust. Our estimates demonstrate that the correct determination of terrestrial heat flow requires application of advanced measuring techniques, boreholes of sufficient depths, detailed information on the vertical distribution of thermal conductivity and temperature gradient, thermal equilibrium of the rock formation under study and information about the spatial and temporal variations in the temperature gradient, whether those variations are induced by advective heat transport, or time-dependent transient signals.

According to Emmermann and Lauterjung [4], evaluation of the geothermal data from the KTB pilot hole provided also the highly unexpected result that the thermal gradient (21 K/km) and vertical heat flow (55 mW/m²) met the predicted values only in the upper 1000 m. Both parameters then increased rapidly to about 1500 m, after which almost constant gradients of 28 K/km and heat flow values of 85 mW/m² prevailed.

The data presented in our table above allow us to agree with a conclusion by Emmermann and Lauterjung [4] that “values of geothermal gradient and heat flow from shallow drill holes in crystalline terranes tend to be systematically too low”.

The information and data described above allow us to conclude that the essential differences between previous and new experimental data on formation thermal properties and heat flow values (resulting in possible essential uncertainties in temperature predictions for depths below well bottoms) are serious reasons to reconsider previous estimates of geothermal resources (including geothermal resources maps) often.

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