Thermal instability of the fluid column in boreholes

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ABSTRACT

For better understanding of temperature state in the shallow subsurface, temperature-depth logs can be completed by high-resolution long-run temperature-time monitoring(s) at selected depth(s). Observational evidence proved that even when a borehole is in relatively “fully” stabilized conditions, temperature data may exhibit certain unrest resembling irregular oscillations in the order of thousandths or even first hundredths of degree. We demonstrate the results of several monitoring experiments performed in widely different geological settings: (i) incidental observations from Kamchatka and Finland, (ii) repeated systematic studies performed in a well stabilized test hole in Prague (Czech Rep.), and (iii) results in rather complicated hydrogeological conditions in a deep Yaxcopoil hole (Chicxulub impact structure, Mexico). In all cases temperature time series displayed intermittent, non-periodic oscillations of temperature with sharp gradients and large fluctuations over all observed time scales. The spectral analysis revealed a high level of stochasticity in the measured signal. Calculated spectra showed “band-pass” behavior without any definite peaks, which might characterize periodicity. Local growth of the second moment technique revealed the presence of distinct temperature forming processes. It can be concluded that a fluid in a borehole subjected to a thermal gradient is stable as far as the gradient remains below certain critical value. It can be demonstrated that at higher Rayleigh numbers the periodic character of oscillations characteristic for “quiescent” regime is superseded by stochastic features. In the specific case of the Yaxcopoil hole, the time series above and below a specific “cold-wave” (characterized by low temperature gradients between 20 to 50 mK/m) contain a clear low frequency component produced by tidal forcing , which dominates over the high frequency domain (periods from 10-15 min to 1 min), which exhibit a scaling behavior. This pattern conspicuously changes in the center part of the cold-wave anomaly (where local temperature gradient exceeds 200 mK/m), where tidal forcing is present, but composes only ~3% of the signal.

Key words: temperature monitoring, borehole convection, recurrence quantification analysis, histograms cumulation technique, tidal forcing

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Temperature variation at different depth in borehole Kun-1 (Kunashir Island, Russia)

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ABSTRACT

Temperature monitoring in the Kun-1 borehole (Kunashir Island, Russian Far East) was started in September 2006. The main goal of this research is the investigation of short-term underground temperature instability in the Kuril-Kamchatka seismoactive zone. Borehole Kun-1 was drilled to a depth of 300 m in year 2000 for water level observation and earthquake prediction. Borehole penetrates volcano-sedimentary rocks of high permeability (tuffs) to a depth of 270 m; below this depth, it passes through marine sedimentary rocks (argillites, sandstones). Temperature profile was measured in September 2007 to a depth of 240 m. Thermal diffusivity of rocks was determined by analysis of diurnal temperature wave attenuation and phase shift with depth (0.6 10^{-6} m^2/c). Measured geothermal heat flow (108-150 mW/m^2) confirms a high value of heat flow in the Kuril Islands arc system. Temperature was monitored by 16-channel logger in the air (1.7 m above surface), soil (0.07, 0.37, 1.07 m) and borehole (20, 40, 60, 80, 100, 120, 140, 160, 180, 200, 220, 240 m) with thirty minutes reading interval. Two-days monitoring with two minutes reading interval was also performed in September 2007.

The experiment reveals temperature changes in a wide interval of timescales (from a few minutes to some months) with amplitude from thousandths to first of degrees. Two distinct kinds of temperature changes may be singled out: the quasi-regular temperature oscillation and non-regular temperature sudden changes. We suppose existing of at least four temperature forming processes which are responsible for such changes. i) Seasonal and diurnal temperature waves locate in the upper 20 and 1 m correspondingly. ii) Tidal diurnal and semi-diurnal waves with amplitudes from 0.001 to 0.006 K (proportionally to the temperature gradient). iii) Stochastic temperature changes with amplitude from 0.01 to 0.1 K caused by free intra-hole convection and probably by convection in the behind casing space and porous media. Existing of two reservoirs of convection explains random switching between different temperature oscillation regimes. At a depth of 63 m these two regimes are characterized by standard deviations 0.017± 0.002K and 0.010± 0.002K. Duration of each state lies between 0.5 and 2 month. iv) Sudden temperature changes had observed twice during the period 09.2007- 08.2008. Temperature increase of about 3K (at 240 m), 0.9 K (at 200 m) and 0.2 K (at 220 and 120 m) precedes the earthquake with M=5.8 had occurred on October 7, 2007 90 km to the Southeast from the station. After the earthquake temperature-time series displayed a partial relaxation of temperatures. The second temperature increase of about 0.1-0.2 K observed in July 13-28 2008 at all depths and precedes the earthquake with M=5.3 (August 14, 2008, 130 km to the East from the station). We hypothesized that sudden high-amplitude temperature changes reflects a complex pattern of behind casing water exchange between different water layers initiated by changes in the tectonic regime.

Key words: borehole, temperature variation, monitoring, Kunashir Island.

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Surface temperature reconstruction from borehole data and oak's ring width chronology in Kunashir Island, Russia

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ABSTRACT

Borehole temperature reconstruction and oak's ring width index series in Kunashir (the southernmost island in the Kuril chain) were integrated in order to reconstruct surface temperature variations in the last four centuries.
Temperature measurements in the Kun-1 borehole, located near Yuzhno-Kurilsk about 200 m from the Pacific coast, was performed in 2007 to the depth of 240 m. Thermal diffusivity of rocks (tuffs) was determined by analysis of diurnal temperature wave attenuation and phase shift with depth (0.6 10^{-6} m^2/s). Prior to paleoclimatic interpretation the temperature-depth profile was topographically corrected and the local anomaly, induced by water flow, was eliminated. The ground surface temperature (GST) reconstruction reveals a cold period with mean annual temperature equal to 3˚C from AD1600 to the second half of 19th century, which coincides with the Little Ice Age. The subsequent warming resulted in the increase of mean annual temperature up to more than 6˚C by the end of 20th century.
Tree-ring samples were collected from 20 oak trees (*Quercus crispula*) in the forest located 37 km south of Yuzhno-Kurilsk and within 1 km of the Pacific Ocean. The BRL chronology was developed from the raw ring width series using ARSTAN detrending procedure (Jackoby et al., 2004). The reconstruction shows a strong annual and multidecadal variability with the predominance of periods 30-50 years long, having spectral properties similar to the Pacific Decadal Oscillation (PDO), which largely controls temperature and precipitation in the region. Unlike the geothermal reconstruction BRL chronology does not demonstrate any century-long trends. However both reconstructions reproduce the cooling in 1970s-early 1990s.
Integration of the two paleoclimatic proxies is based on the assumption that the soil temperature strongly influences both borehole temperature and ring width variability but in a different frequency domain. The procedure of integration of the two proxies included: i) smoothing of the BRL chronology by a running windows of unequal length progressively increasing while moving toward the past in order to construct the curve BRL_R, operating in the same frequency domain that does the GST-reconstruction; ii) calibration of BRL chronology in terms of surface temperature using GST reconstruction in the interval of their maximum coherence with a simultaneous correction of the efficient thermal diffusivity, which determines the time scale of GST curve (as result of this procedure the value of thermal diffusivity had increased up to 0.7 10^{-6} m^2/s); iii) smoothing of the BRL chronology by a running windows of a constant length in order to eliminate the high frequency variability and preserve the multidecadal variations (BRL_{LF}); iv) construction of integrated surface temperature curve ($GST_{INT}=GST+k(BRL_{LF} - BRL_R)$, where k is a sensitivity coefficient.
The integrated curve of surface temperature retains both centennial and multidecadal temperature variations, and the amplitudes of these variations are commensurable (Standard Deviations are 0.68˚C and 0.53˚C correspondingly. According to our reconstruction the peaks of surface temperature in Kunashir were centered near 1600, 1638, 1677, 1722, 1770, 1801, 1827, 1850, 1884, 1925, during 1954-1973 and since the year 2001, and they broadly correspond to the "cool" PDO phases.

Key words: borehole temperatures, tree-rings, ground surface temperature, paleoclimate reconstruction.

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Geothermal applications in mine refrigeration engineering in South Africa

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ABSTRACT

An increasingly important application of geothermal studies is in the field of mine ventilation and refrigeration engineering. As mining operations approach greater depths, prediction of the heat load on underground workings becomes more important not only for worker safety and hygiene but also for mine feasibility planning. The primary source of heat loads on mines is natural heat from the surrounding rock. It is therefore important to have access to accurate data pertaining to virgin rock strata temperatures and thermophysical properties (thermal conductivity, density, specific heat capacity and thermal diffusivity) of rock adjacent to mine workings. Although accumulation of such data is relatively routine, it can be difficult to acquire sufficient data for mine planning purposes. In addition, innovation is required in certain experiments such as determining the thermal properties of waste material that is re-introduced into mine workings (backfill). The problem is particularly important in South Africa where gold mines are approaching depths of 4 km, platinum mines depths of 2 km and many other mines depths greater than 1 km. In some of these mines the virgin strata temperature exceeds 70 °C. In this paper, we present case studies comparing the virgin rock temperature data and rock property data from different mining areas in South Africa as well as detailed measurements on backfill from a deep gold mine, and their implications for deep mining.

Key words: heat flow, mining, South Africa.

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Instruments for studying the thermal properties of rock at elevated pressure and temperature

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ABSTRACT

The principal objectives of the research are (1) to provide reliable data on the thermal properties (TP) of rock and the variations at simultaneous influence of elevated temperature (T) and pressure (P), and to use these results (2) to develop a database on TP variations for different rock types.

Two instruments for studying the thermal conductivity (TC), thermal diffusivity (TD), and volumetric heat capacity (VHC) of rock at simultaneous influence of elevated pressure and temperature have been elaborated. The first instrument is designed for thermal property measurements at elevated temperature, pore, and overburden pressure. The second instrument provides measurements at elevated temperature, pore, and two components (axial and side confining) of overburden pressure. Both instruments are designed for measurements at temperature and pressure variations up to 250 degC and 200 MPa, respectively. Line-source method is used for rock TP measurements. The principal advantage of the line-source method realization is a possibility of simultaneous measurements of TC and TD tensor components during one PT cycle.

The measurement method and designed instruments have been metrologically tested on a set of six reference samples with TC and TD values within ranges of respectively 0.71…10.7 $W \cdot m^{-1} \cdot K^{-1}$ and $(0.557…5.42) \cdot 10^{-6}\ m^2 \cdot s^{-1}$ at normal conditions as well as at elevated temperature, pressure, and at simultaneously increased PT conditions. According to the test results, total error of TC, TD, and VHC measurements does not exceed 4, 7, and 8%, respectively.

In total, 121 crystalline and sedimentary rock samples from Ural super-deep well (Russia), Yen-Yakhinskaya superdeep well, Voronezhskaya deep well (Russia), and the territory of Germany have been studied at elevated temperature (up to 200 degC), pore (up to 80 MPa for sedimentary rocks), and overburden pressure (up to 200 MPa). Analysis of the measurement results have allowed us to establish a strong correlation between slope angle of TC (P,T) curves and TC values at normal PT conditions. This fact makes it possible to (1) develop a technique for prediction of TC variations at elevated PT conditions on the basis of data obtained at normal conditions and to (2) take into account correction factors during heat flow density estimations.

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Key words: thermal properties, temperature, and pressure.

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Sensitivity study of the empirical theoretical model of the thermal conductivity of rock

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ABSTRACT

Experimental testing of the empirical Lichtenecker's theoretical model (*the geometrical mean model*, 1928), for estimations of effective thermal conductivity (TC) of two component inhomogeneous media, demonstrates that the model gives significant errors (by dozens of percents) for either dry or fluid-saturated rocks in most cases. The experiments have been performed on more than 1,400 samples of porous sedimentary rocks (sandstone, siltstone, shale, dolomite, and limestone) from sedimentary basins in Russia and Mexico.

It was established that the modified Lichtenecker-Rother's theoretical model $\lambda_{eff} = \lambda_M^{1-f\Phi} \cdot \lambda_f^{f\Phi}$ (1), where λ_M is matrix TC, λ_f is TC of fluid in pores, Φ is porosity, and *f* is a correction factor, can provide much more reliable and satisfactory data if the correction factor "*f*" is determined from the previous experiments of a studied rock type.

Values of factor "*f*" were not studied and determined earlier. Numerous experimental high-precision data on λ_{eff} obtained from the direct measurements of the thermal conductivity of the rock, with the optical scanning instruments, allowed us to determine "*f*" values for different rock types from formula (1), when λ_M , λ_f and Φ are known. Typically λ_M values can be determined from regression equations of correlations between rock TC for dry samples and porosity.

It was established that the uncertainty in factor "*f*" is significant for porosity range 0…5% and practically unacceptable for all rock types studied. Within porosity range 5…15%, the uncertainty in factor "*f*" decreases and for porosity values larger than 15%, "*f*" values are stable.

The sensitivity study completed for the Lichtenecker-Rother's model allowed us to determine the requirements of all input parameters (λ_M, λ_f and Φ) taking into account the necessary range of porosity, rock types, and type of fluids in pores. To study variability in λ_{eff} caused by uncertainties in factor "*f*" values, we estimated relative variability δf in factor "*f*" estimation from formula (1) caused by relative uncertainties $\delta\lambda_M$ (error in matrix TC determination), $\delta\lambda_{eff}$ (error in rock's TC measurements), $\delta\Phi$ (error in porosity determination) in parameters λ_M, λ_{eff} and Φ.

It was established that (1) uncertainty δf <10% at *f* =0.3…0.9 practically at any matrix TC of sedimentary rocks (2…7 $W \cdot m^{-1} \cdot K^{-1}$) with porosity Φ<20%, provides acceptable uncertainty (<10%) in effective TC estimation, (2) influence of uncertainty in matrix TC estimation on factor "*f*" determination essentially increases with the increase in effective TC, (3) uncertainty in matrix TC estimation should not exceed 25% at λ_{eff} >1.4 W/(m·K) corresponding to the most types of sedimentary rocks.

The research was carried out with the generous support of Schlumberger Oilfield Services, an international company in the oil and gas industry.

Key words: thermal conductivity, theoretical model.

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On the role of radiogenic heat production in geothermal studies

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ABSTRACT

Heat production due to radioactive decay of long-lived isotopes of U, Th and K (namely, ^{235}U, ^{238}U, ^{232}Th, and ^{40}K) in rock formations constituting the Earth's crust plays a key role in interpretation of heat flow data, particularly in continental regions. Radiogenic heat production in the crust typically contributes an estimated 40-60% of the heat flow in an area. Computations of thermal structure in the crust, assuming steady-state conditions, are made by considering heat flow data as the surface boundary condition, and models for distribution of radiogenic heat production and thermal conductivity with depth. These studies have strong implications for delineating the thermal structure of the lithosphere and assessing the stability of cratons. In addition to the classical heat flow studies, several new and inter-disciplinary applications have emerged during the past three decades, such as past climate change reconstructions from borehole temperature-depth data, modeling of coupled mass and heat transfer, thermal signatures of tectonic processes, thermal history of sedimentary basins, and exploration and assessment of geothermal energy potential, geo-engineering problems, and assessment of environmental radioactivity – all of which depend on good characterization of U, Th and K levels in various rock formations and radiogenic heat production estimates derived from them.

Estimates of radiogenic heat production are most commonly obtained from analysis of U, Th and K using gamma-ray spectrometry, which employs a NaI (Tl) or germanium detector and a multichannel analyzer. Low-level- counting facilities have been established by a few geothermal groups worldwide for characterization of heat production in crustal rocks in general, and the relatively radioelement-depleted middle-to-lower crust, in particular. In-situ gamma-ray spectrometer and detector assemblies employing large volume crystals have complemented the laboratory-based studies in areas abounding with fresh outcrops, resulting in a much faster coverage.

Gamma ray spectrometric studies carried out in a number of geological provinces in the Indian shield have led to important findings that are consistent with the heat flow data in the individual provinces. The datasets reveal, for example, (i) contrasting heat production characteristics between different sub-provinces of the south India Precambrian terrain, consistent with the differences in upper crustal composition, (ii) systematic upward enrichment of U and Th in a granite batholith, consistent with its metaluminous nature, (iii) localized, thin veneers of anomalous high heat production, (iv) the association of granulite facies rocks with the lowest heat production ever reported, and (v) the existence of a metasomatically enriched granulitic layer between the overlying amphibolite facies level and the underlying radioelement-depleted granulite facies level. These results are integrated with other geological and geophysical information to arrive at realistic crustal heat production models, which are then used for modeling the thermal structure of the continental lithosphere.

Key words: Radiogenic heat production, radioelemental analysis, heat flow, thermal structure, India

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Geostatistical approaches on the thermal conductivities of rocks

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ABSTRACT

The statistical information on thermal conductivity of rocks is important to design a geothermal heat pump system because thermal conductivity of the ground can provide reliable system design. We conducted geostatistical analysis on the measured thermal conductivities of 1,551 rock samples collected over the whole area of Korea. The sample spacing is generally 2 to 10 km distance but the distance is very irregular. Thermal conductivities were measured on core samples or fresh outcrops of rocks, if core samples were not available. The geology of Korea is complex and shows serious heterogeneity. The whole data of the samples were mainly divided into igneous, metamorphic and sedimentary rock types; granite and gneiss were selected to carry out geostatistical analysis. General statistics were calculated in order to define the characteristics and thermal conductivity ranges of several rock types. Stationary model was applied in semivariogram analysis and range, sill, and nuggets were calculated. Thermal conductivity distribution maps were constructed with Kriging interpolation method and several cross validation tests were performed to evaluate the generated maps. The thermal conductivity of granite ranges from 1.82 to 5.87 W/m-k, and that of gneiss ranges from 1.64 to 6.75 W/m-k. The averages of granite and gneiss are 3.32 W/m-k and 3.70 W/m-k respectively. The two histograms of these data show lognormal distributions and lognormal Kriging method is applied.

Key words: geostatistical, thermal conductivity, kriging, semivariogram, geothermal heat pump

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