ORIGINAL RESEARCH ARTICLE

DOI: https://doi.org/10.18599/grs.2018.4.396-403

The study of the relationship between thermal conductivity and porosity, permeability, humidity of sedimentary rocks of the West Siberian Plate

A.D. Duchkov, D.E. Ayunov, S.V. Rodyakin, P.A. Yan*

Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences, Novosibirsk, Russian Federation

Abstract. The determination of correlation between thermal conductivity and structural parameters (porosity, permeability, humidity) of sedimentary rocks is a very urgent task. This article analyzes and compares the results of measurements of these parameters for ~300 samples of Mesozoic sandstones and siltstones from the core of 18 wells drilled in the north-eastern and southern regions of the West Siberian plate. The thermal conductivity of all samples was measured in the dry state and some (90 samples) – after saturation with water. Porosity and permeability are determined for 280 and 230 samples, respectively. The obtained data are used to establish linear correlation connections between thermal conductivity, porosity and permeability. The most interesting are rather stable dependences of thermal conductivity of dry and water-saturated samples between themselves and with porosity. The established correlation dependences are interesting in practical terms. Some of them can be used to approximate the thermal conductivity of water-saturated rocks by measurements of dry rocks or even only by the porosity value. The relationship between the thermal conductivity of sedimentary rocks and porosity can be used for rapid assessment of porosity of rocks on advanced measurements of thermal conductivity of a full-size core. It is obvious that the revealed correlation connections require further clarification.

Keyword: West Siberian plate, Mesozoic sandstones and siltstones, thermal conductivity, porosity, permeability, humidity, correlation dependence

Recommended citation: Duchkov A.D., Ayunov D.E., Rodyakin, S.V., Yan P.A. (2018). The study of the relationship between thermal conductivity and porosity, permeability, humidity of sedimentary rocks of the West Siberian Plate. *Georesursy = Georesources,* 20(4), Part 2, pp. 396-403. DOI: https://doi.org/10.18599/grs.2018.4.396-403

Introduction

The thermal conductivity coefficient (hereinafter thermal conductivity, λ) quantitatively characterizes the process of heat transfer in the material (rock). This parameter (as well as other thermal properties – thermal diffusivity, heat capacity) is necessary when estimating heat flow and depth temperatures, when performing thermo-hydrodynamic and basin modeling, and calculating heat exchange processes in rocks. It should be noted that, until now, all information on the thermal conductivity of rocks is based on the study of core samples in laboratory conditions, as it is not yet possible to develop reliable equipment for measuring thermal properties of rocks directly in wells (Novikov et al., 2008).

The results of measurements of thermal conductivity of rocks of the sedimentary cover of the West Siberian Plate, obtained from studying the heat flow, are summarized and analyzed in a number of monographs (Kurchikov, Stavitskii, 1987; Teplovoe pole nedr Sibiri..., 1987; Balobaev, 1991, Lipaev et al., 2001). Analysis of the results showed that the thermal conductivity of sedimentary rocks is determined by the composition of the mineral skeleton, porosity (ϕ) and permeability (k) of the rock, as well as the type of fluid that fills the pores (air, water, oil). Thus, the thermal conductivity of water-saturated samples (λ_w) usually significantly exceeds the thermal conductivity of the same, but dry samples (λ_s), which is explained by the multiple difference in thermal conductivity of water and air (0.6 and 0.025 W/m/K, respectively). To estimate λ_w, it is necessary to saturate the dry samples with water and repeat the measurements, i.e. significantly complicate the experiments. In this regard, a very urgent task is to determine the correlation dependences between λ_s and λ_w, as well as between λ_s, λ_w and structural parameters (porosity and permeability) of rocks, which would allow to evaluate, even if roughly, the missing data. Accumulated during the study of heat flow information on the thermal conductivity of sedimentary rocks of the West Siberian Plate is largely

*Corresponding author: Albert D. Duchkov
E-mail: duchkovad@ipgg.sbras.ru

unsuitable for establishing correlations due to problems with the selection of samples collections and differences in equipment and measurement techniques.

The situation noticeably changed after high-performance instruments were created and widely used in the Russian Federation that allow rapid measurements of thermal properties of rocks: Thermal Comparator, TK (Kalinin et al., 1983) and especially Scanning Thermal Measuring Meter, ITS (Popov et al., 1983; Nikitin et al., 2016). These devices are equally metrologically provided (use one set of standards). Approximately the same for these devices and the depth of penetration of the heat signal into the rock (about 10 mm). All this allows us to reasonably compare the results obtained by these devices. The use of this equipment led, in a relatively short time, to a significant increase in the amount of experimental data (including in Western Siberia). The most detailed studies of the thermal properties of sedimentary rocks of the West Siberian Plate were carried out in 1995-2008 by the team of Yu.A. Popov. First of all, it is necessary to note the study of hundreds of samples of sandstones, aleurolites, basalts from the full-sized core of ultra-deep Tyumen well (SG-6) and En-Yakhinskaya well (SG-7) (Popov, et al., 1996; Popov et al., 2008). These works made it possible to form a general idea of the change in the thermal conductivity of rocks in almost the entire section (from Cretaceous to Triassic deposits) of the sedimentary cover of the West Siberian Plate. In the same period, studies were carried out to study the relationship between the thermal conductivity of sedimentary rocks and other physical properties on a specially selected collection of samples from the core of the Middle-Ob region wells (Popov et al., 2003). The collection consisted of 143 samples of sandstones and aleurolites of the Cretaceous and Jurassic age from a depth of 1360-3000 m. The porosity of the samples varied from 9.6 to 30.4%, and the permeability was 0.01-200 mD. All measurements of thermal conductivity were performed on the device ITS. The authors (Popov et al., 2003) studied dry and water-saturated standard samples with a diameter of 2.5 cm and a length of 3 cm, cut from a full-sized core along and across the layering. Accordingly, the authors obtained the values of thermal conductivity along ($\lambda_{\|}$) and across ($\lambda_{\perp}$) lamination and showed that the average values of $\lambda_{\|}$ were greater than $\lambda_{\perp}$ by about 20%. The authors trust the $\lambda_{\|}$ values more, since this component is less affected by the deconsolidation caused by decompression. The thermal conductivity of dry samples varied from 1 to 2.76 W/m/K, and water-saturated from 1.3 to 3.4 W/m/K. Analysis of the results allowed us to reveal fairly close linear and exponential dependencies connecting the thermal conductivity of samples with their porosity and permeability. For example, one can give two regression equations:

$$\lambda_w/\lambda_s = 0,87 + 0,04\cdot\phi\ (R^2=0,75,\ N=143), \quad (1)$$

$$\lambda_w/\lambda_s = 0,95 + 0,03\cdot\phi\ (R^2 = 0,72), \quad (2)$$

which are obtained in (Popov et al., 2003; Popov et al., 2008), respectively. In these formulas (and subsequent ones), R^2 is a parameter characterizing the degree of reliability of the linear approximation; N is the number of measured samples; ϕ is in %.

We have obtained new data on the thermal conductivity of two collections of samples of sedimentary rocks of the same composition and age from cores of wells drilled in the northeast and southern regions of the West Siberian Plate. These collections are divided not only by geography, but also by the type of instrument used to measure thermal conductivity. In both cases, the thermal conductivity was measured on standard cores cut from a full-sized core perpendicular to its axis (parallel to lamination) and having a diameter and height of about 3.7-3.8 mm. This report discusses the results of these studies.

Collection 1 – samples from the core of the wells of the north-eastern part of the West Siberian plate

Collection 1 overview

Collection 1 includes 129 samples of Cretaceous and Jurassic sandstones and siltstones from cores of seven wells (Medvezhya-31, Suzunskaya-4, Gorchinskaya-1, Yuzhno-Noskovskaya-318, Deryabinskaya-9, Vostok-1, 3), drilled mainly in the North-East West-Siberian plate. The location of the wells and the primary results of the measurements are indicated in the work (Duchkov et al., 2013). The collection covers part of the section from 1,800 to 4,200 m. For measurements of λ, a "Thermal Comparator" (Kalinin et al., 1983) was used, the sensor of which was located at the ends of standard cores, regardless of the location of the layers in the core. First, the thermal conductivity of all samples was measured in the air-dry state (λ_s). Then, a part of the collection (90 samples) was saturated with water according to the standard method and the λ_w values were measured. For 93 and 53 samples measured by the ϕ and the k, respectively. The porosity of the rocks in the samples varies from 1 to 29% (mostly from 4 to 15%), and the permeability – from <0.001 to 440 mD (one sample – 1117 mD). In general, the thermal conductivity of dry samples varies from 0.6 to 2.6 W/m/K. According to the histogram (Fig. 1), the average value of λ_s is 1.8-2 W/m/K.

After saturation with water, the thermal conductivity of samples increases on average by 20-40% and varies from 1.6 to 3.2 W/m/K. The average value of λ_w is 2.6-2.8 W/m/K (the ratio of λ_w/λ_s varies from 1.1 to 2.1). Saturation of rocks with water leads not only to an increase in their thermal conductivity, but also to a relative leveling of its values along the section. The

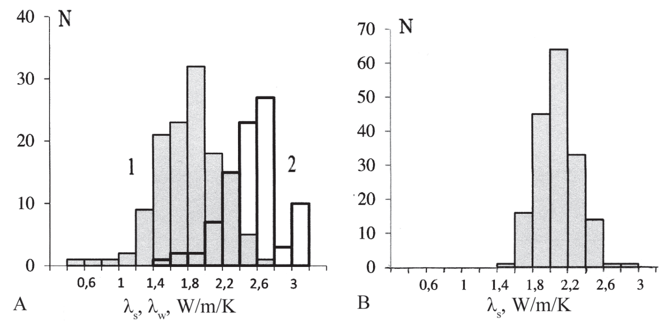

Fig. 1. Histograms of thermal conductivity values of Mesozoic sandstones and aleurolites from the core of the northeastern (Collection 1, A) and southern (Collection 2, B) parts of the West Siberian Plate: A1 – dry samples (N = 129), A2 – saturated samples (N = 93), B – dry samples (N = 175). N is the number of samples

Cretaceous and Jurassic formations are virtually identical in thermal conductivity.

The obtained results were used to search for correlations between the measured parameters λ_s, λ_w, λ_w/λ_s, ϕ and k.

A direct comparison of λ_s and λ_w shows the presence of a fairly close positive correlation dependence between them (Fig. 2):

$$\lambda_w = 1{,}52 + 0{,}56\ \lambda_s\ (R^2 = 0{,}51,\ N = 90). \qquad (3)$$

Some statistical data characterizing dependence (1) are given in the caption inscription to Figure 2. The scatter of the points of the correlation field is associated with the effect on thermal conductivity, in addition to porosity and fluid type, unaccounted changes in the mineral composition and structural and textural features of the rock.

As already noted, the thermal conductivity of sedimentary rocks is largely determined by their porosity (ϕ). There is an inverse linear relationship between these parameters. The regression equation obtained by measuring the λ_s and ϕ samples from

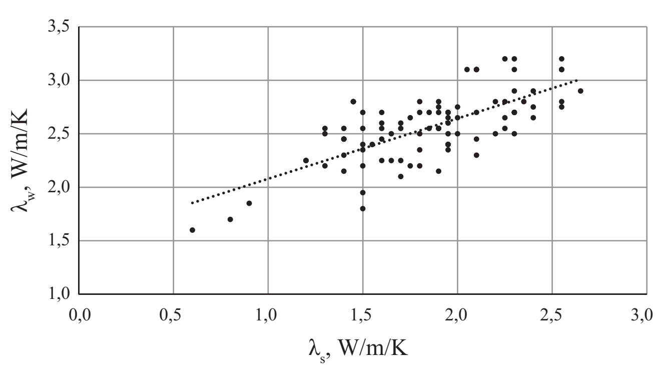

Fig. 2. Collection 1. Linear correlation between the measured values of λs and λw. The linear regression equation (line): $\lambda_w = 1.52 + 0.56\ \lambda_s$ ($R^2 = 0.51$, N = 90). The standard deviation of individual values of λ_w from the regression line is 0.26 W/m/K. Hereinafter, R^2 is a parameter characterizing the degree of reliability of linear approximation; N is the number of samples

Collection 1 has the form:

$$\lambda_s = 2{,}43 - 0{,}05\ \phi\ (R^2 = 0{,}54,\ N = 93). \qquad (4)$$

Most ϕ measurements were performed on samples with a porosity in the range of 5-15%. This interval ϕ is characterized by the largest scatter of measured values of λ_s (the standard deviation of individual values of λ_s from the regression line is 0.35 W/m/K). When interpreting the relationship of thermal conductivity with ϕ, it should be borne in mind that λ responds to changes in total porosity (the total volume of all pores). When measuring porosity, open porosity is usually recorded on samples, depending on the volume of communicating pores.

The correlation between the values of λ_w and ϕ is much weaker, since in this case the contrast of thermal conductivity of the rock matrix and the filling fluid is much less than in dry rocks:

$$\lambda_w = 2{,}95 - 0{,}03\ \phi\ (R^2 = 0{,}34,\ N = 54). \qquad (5)$$

Formulas (3-5) can be used for a rough estimate of λ_s by the values of ϕ, and as well for the thermal conductivity of water-saturated samples by the values of λ_s or even just ϕ. This is necessary in cases where thermal conductivity measurements cannot be performed due to the lack of equipment or suitable core samples. Using the formula (4), we can estimate the average thermal conductivity of the mineral skeleton (matrix) of the samples (λ_m), setting ϕ = 0. In the rocks of our collection λ_m is 2.5 W/m/K.

In the works (Popov et al., 2003; Popov et al., 2008), it was suggested to use the ratio λ_w/λ_s for studying correlation relationships. Figure 3 shows the correlation between this parameter and ϕ according to our data. The regression equation is:

$$\lambda_w/\lambda_s = 1{,}04 + 0{,}03\cdot\phi\ (R^2 = 0{,}69,\ N = 54). \qquad (6)$$

Obviously, this correlation dependence is the most reliable of those given earlier (parameter R^2 has a maximum value), and it also corresponds well to equations (1) and (2) obtained from studying collections of rocks from other regions of the West Siberian Plate.

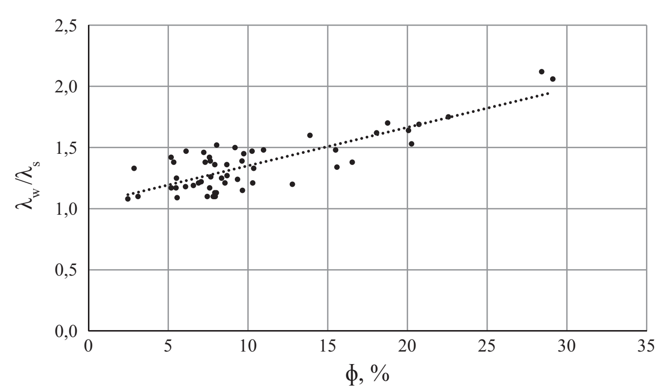

Fig. 3. Collection 1. Linear correlation between the values of the ratio of thermal conductivity of water-saturated and dry samples (λ_w/λ_s) and their porosity. The linear regression equation: $\lambda_w = 1.04 + 0.03\ \phi$ ($R^2 = 0.69$; N = 54)

The dependence can be used to estimate the thermal conductivity of water-saturated sedimentary rocks by the values of λ_s and ϕ.

It is known that between porosity and permeability of sedimentary rocks there is a correlation. Accordingly, there should be a correlation relationship between thermal conductivity and permeability. This was confirmed in (Popov et al., 2003), in which the values of λ_w/λ_s and k were compared for 60 rock samples from the core of the Middle-Ob region wells and an exponential increase of λ_w/λ_s from 1.3 to 2.3 was found as permeability from 0.03 to 100 mD (the correlation equation is not given in this work). We verified the existence of correlations between λ_s, λ_w, λ_w/λ_s, and k using the data we have. Previously it was stated that the permeability of 93 samples from Collection 1 basically varied from <0.001 to 440 mD. More than half of the samples are poorly permeable rocks (k <0.001), which must be excluded during the correlation. Due to the significant range of changes in permeability, the logarithm (lg k) is normally used to represent it. As a result, the equation for the inverse linear correlation between λs and k for 53 samples has the form similar to (4):

$$\lambda_s = 1{,}8 - 0{,}21 \cdot \mathrm{lgk}\ (R^2 = 0{,}37,\ N = 53), \qquad (7)$$

where the dimension k is in mD. With an increase in permeability (and porosity) in the rock, the amount of air that conducts heat poorly increases, and, accordingly, the effective thermal conductivity of the sample decreases.

For a smaller amount of data (26 samples in total), the correlation between the thermal conductivity of water-saturated rocks (λ_w, λ_w/λ_s) and their permeability was considered. The corresponding regression equations are:

$$\lambda_w = 2{,}58 - 0{,}15 \cdot \mathrm{lgk}\ (R^2 = 0{,}29,\ N = 26)\ \mathrm{K}, \qquad (8)$$

$$\lambda_w/\lambda_s = 1{,}44 + 0{,}13 \cdot \mathrm{lgk}\ (R^2 = 0{,}41,\ N = 25)\ \mathrm{K}. \qquad (9)$$

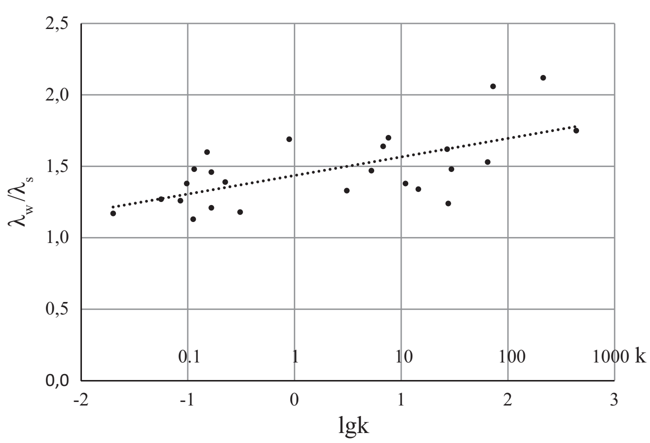

Fig. 4. Collection 1. Linear inverse correlation between the measured values of thermal conductivity of samples (λ_w/λ_s) and their permeability (k in mD; lgk). Regression equation: $\lambda_w/\lambda_s = 1.44 + 0.13 \cdot \mathrm{lgk}$ ($R^2 = 0.41$; $N = 25$)

The most stable last correlation is shown in Fig. 4. It follows from equation (9) that, according to our data, λ_w/λ_s increases from 1.2 to 1.9 as k increases from 0.03 to 100 mD, i.e. noticeably slower than according to the work (Popov et al., 2003).

It was noted above that the correlation equations (3, 5, 6) can be used to approximate the thermal conductivity of water-saturated samples of sedimentary rocks by the values of λ_s and ϕ. As an example, such calculations were performed by us for samples from the Vostok wells, the results of measurements and calculations are shown in Table 1 (Duchkov et al. 2014). First, the calculated values of λ_w^* by λ_s (Eq. (3)). Then, parameter ϕ determines the values of λ_w^{**} (Eq. (5)). And, finally, the λ_w^{***} values are calculated from λ_s and ϕ (Eq. (6)).

A comparison of the experimental and calculated values of λ_w shows that the difference between them for individual samples can be significant. And this is not surprising, since the regression equation allows us to estimate only the average of several λ_w, corresponding to one particular value of λ_s or ϕ, or their combination. However, the average calculated values of λ_w for all samples differ from the experimental average by no more than 3-5%. It is clear that the estimated results for samples of rocks not included in our collection may be somewhat worse. But in any case, when conducting geothermal studies (for example, studying heat flow, calculating deep temperatures), it is more expedient to use the calculated values of λ_w (they will be much closer to the truth) than the thermal conductivity of dry samples. This is especially true for sedimentary rocks with high porosity.

	Sampling depth, m	ϕ, %	Thermal conductivity, W/m/K				
			λ_s	λ_w	λ_w^*	λ_w^{**}	λ_w^{***}
1	2058	28,33	0,6	1,6	1,8	2	1,3
2	2067	29,12	0,9	1,85	2,0	2	1,9
3	2072	28,42	0,8	1,7	2,0	2	1,6
4	2127	12,79	1,5	1,8	2,4	2,5	2,2
5	2299	13,89	1,5	2,4	2,4	2,5	2,3
6	2317	18,76	1,5	2,55	2,4	2,3	2,5
7	2472	7,6	2,1	2,45	2,7	2,7	2,7
8	2520	20,73	1,3	2,2	2,2	2,3	2,3
9	2528	20,07	1,4	2,3	2,3	2,3	2,4
10	2617	20,26	1,6	2,45	2,4	2,3	2,8
11	2679	18,07	1,6	2,6	2,4	2,4	2,7
12	2744	22,57	1,4	2,45	2,3	2,2	2,6
13	2806	16,54	1,85	2,55	2,6	2,4	3,0
14	3067	15,58	1,9	2,55	2,6	2,4	3,0
15	3184	15,5	2,1	3,1	2,7	2,5	3,3
Average				2,33	2,35	2,32	2,44

Table 1. Measured and calculated by the formulas (3, 5, 6) values of thermal conductivity of samples of water-saturated rocks from Mesozoic sediments exposed by the Vostok-1 (samples No. 1-6, 10-12) and Vostok-3 (samples No. 7-9, 3-15) wells; λ_s, λ_w, ϕ – measured values of thermal conductivity and porosity; λ_w, λ_w** and λ_w*** are the values of thermal conductivity calculated by the formulas (3, 5, 6), respectively*

Collection 2 – samples from the cores from the wells located in the southern part of the West Siberian plate

Collection 2 Overview

Collection 2 includes 175 samples of sandstones and aleurolites of Jurassic age selected from cores of 10 wells (Biazinskaya-1, Kasmanskaya-1,2; Nadezhdinskaya-1, Optimistic-1, Pogranichnaya-2, Rakitinskaya-4,5,7; Uzasskaya-1), drilled in the southern part of the plate (Novosibirsk region). The collection contains samples from the Tyumen (J_{1-2}) and Vasyugan (J_3) suites, approximately in equal proportions (96 and 79 samples) from depths of 2430-2780 m. Thus, the studied collections significantly differ not only in the number of samples taken, but also according to the size of the sampling interval (Collection 1 – 2400 m interval, 129 samples were selected; Collection 2 – 350 m interval, 175 samples were selected). As before, standard cores were studied – cylinders cut from a full-sized core perpendicular to its axis (parallel to lamination) and having a height and diameter of about 37-38 mm. In the course of the research, the thermal conductivity of only dry cores was measured, and their porosity and permeability were determined. It was found that ϕ varies from 0.54 to 19.3%, k – from <0.001 to 120 mD. An ITS device was used to measure thermal conductivity (Popov et al., 1983). Scanning took place along the axis of the standard core. At the same time, the position of the scanning line relative to the stratification of the core was not specifically tracked (as in the study of Collection 1).

The thermal conductivity of dry cores varies from 1.4 to 2.9 W/m/K, the average value of λ_s is 2.1 W/m/K. The samples taken from the Tyumen (J_{1-2}) and Vasyugan (J_3) suites are almost identical in thermal conductivity: 1.70-2.63 and 1.45-2.57 W/m/K, respectively. According to the histogram (Fig. 1), the bulk of the samples from Collection 2 has a thermal conductivity of 2.0-2.2 W/m/K, i.e. about 0.2 W/m/K higher than the main group of samples Collection 1. Thus, it should be stated that, in terms of average thermal conductivity, dry samples of the same type and same age rocks gathered in two collections representing different, fairly distant parts of West Siberian plates differ by about 10%. It can be assumed that this difference is associated with the use of different thermal conductivity meters (TK and ITS) in the study of Collections 1 and 2. However, the data presented in the work (Popov et al., 2003) do not seem to confirm this assumption. According to these data, dry sandstones and aleurolites from the upper Jurassic and lower Cretaceous of the Middle-Ob region are characterized (measured on ITS) with an average thermal conductivity of about 1.7-1.8 W/m/K different from our estimates. In this regard, it is possible that the described variations in the mean values of λ are associated with changes in the mineral composition and structural features of the rocks in the sections of different regions. This problem requires a special, more detailed, consideration. From the identified differences, we can conclude that the data obtained from several collections of samples should be interpreted separately and only then be solved the question of combining them. Below we will show it on the example of data for the Collection 2.

Correlations between λ_s and ϕ, k

When studying the samples of Collection 2, only the values of λ_s, ϕ, and k were measured. When comparing 170 pairs of λ_s, ϕ values, a correlation dependence is obtained, the regression equation of which has the form:

$$\lambda_s = 2{,}47 - 0{,}04 \cdot \phi \ (R^2 = 0{,}43;\ N = 170). \qquad (10)$$

Comparison of equations (4) and (10) shows that they are completely identical. This allows one to add the measurement results of λ_s, ϕ for both collections and to obtain the correlation dependence of the sum of the data (Fig. 5). The regression equation for the total dependence is:

$$\lambda_s = 2{,}49 - 0{,}05 \cdot \phi \ (R^2 = 0{,}5;\ N = 263). \qquad (11)$$

Thus, despite the differences in the sampling sites of Mesozoic sandstones and aleurolites of the West Siberian Plate and their quantity, identical correlation dependences between the measured values of λ_s and ϕ were obtained (equations (4, 10, 11)). It would be interesting to check the stability of this dependence on the collections of other samples.

From equation (11) it follows that the thermal conductivity of the mineral skeleton λ_m (λ_s value at $\phi = 0$) of samples from Collections 1 and 2 is the same and is 2.5 W/m/K (Fig. 5). At the same time, judging by the work (Popov et al., 2003), rocks similar to the type and age from Middle-Ob region should differ significantly in the composition of the mineral skeleton, since their average λ_m is 3.2-3.6 W/m/K, i.e. much higher than our values.

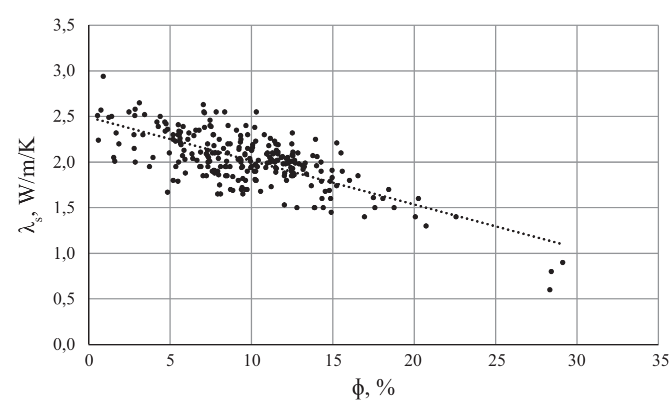

Fig. 5. Linear inverse correlation dependence between the measured values of thermal conductivity (λ_s) and (ϕ) of all samples from Collections 1 and 2. Regression equation: $\lambda_s = 2.49 - 0.05\phi$ ($R^2 = 0.5$; $N = 263$)

As already noted, the permeability of rocks in the Collection 2 (173 samples) varies from <0.001 to 120 mD. After elimination of poorly permeable rocks (<0.001 mD), 109 samples remain in Collection 2, and the correlation relationship between λ_s and lgk and the corresponding regression equation are determined:

$$\lambda_s = 2 - 0{,}13\ \lg K_{пр}\ (R^2 = 0{,}17;\ N = 109). \quad (12)$$

Despite the greater number of samples measured, this correlation dependence is generally less reliable (R^2 = 0.17) than that obtained earlier in the study of Collection 1 (equation (7), R^2 = 0.37). A comparison of the correlation equations (formulas (7) and (12)) shows that the regression lines in both cases have approximately the same slope, but are shifted relative to each other by approximately 0.2 W/m/K. In this situation, combining these two collections is not reasonable.

Factors affecting the type of correlation relationship between λ_s and ϕ

All the obtained correlation dependences are characterized by a significant scatter of data. To clarify the causes of variation, the authors checked according to Collection 2 data the influence of a number of factors (permeability, the content of cement and quartz with λ = 7.7 W/m/K). This became possible, since all samples of the Collection 2 were subjected, among other things, to petrographic analysis.

To test the effect of the permeability factor, the samples were divided into three groups: "poorly permeable" (<0.001 mD), "medium permeable" (0.2-3 mD), and "high permeable" (>3 mD). For each group of samples, the presence of correlations between λ_s and ϕ was checked (Fig. 6).

It was established that a relatively small sets of "high-permeable" samples shows the maximum variation of porosity values for samples with close thermal conductivity and does not reveal a correlation link between λ_s and ϕ. The rest of the sets are characterized by fairly stable, having the same slope correlation

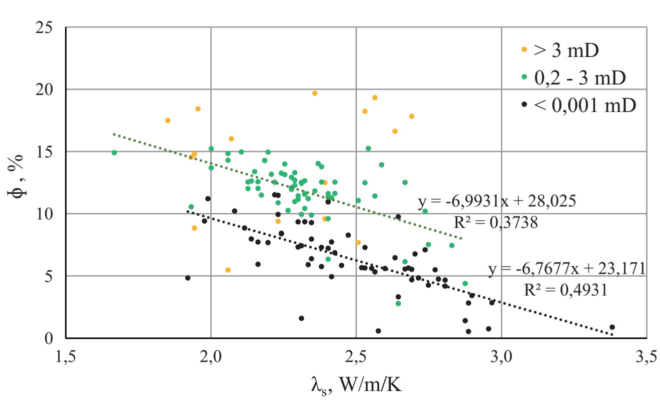

Fig. 6. Collection 2. Connections between porosity and thermal conductivity and linear trends for groups of "poorly permeable", "medium-permeable" and "high-permeable" samples

dependencies between the studied parameters. However, they are shifted relative to each other so that the porosity of "poorly permeable" samples is lower by 5% than ϕ "medium-permeable" samples with the same thermal conductivity.

The study of the effect of the cement content in samples (clay and carbonate) was carried out separately for the groups of "poorly permeable" and "mediumpermeable" samples. In each group, three sets of samples were considered on the cement content in the mineral skeleton: less than 10%, 10-30% and more than 30%. Again, the correlation dependences between λ_s and ϕ were constructed from these groups. In all sets of both samples groups, close correlation dependences between the studied parameters were found.

The study of the effect of quartz content in the samples was also conducted separately for the groups of "medium-permeable" and "poorly permeable" samples. According to the total content of quartz in the mineral skeleton, three sets were taken: less than 25%, 25-50% and more than 50%. On the correlation diagram, λ_s and ϕ, the samples showed no obvious differences. Thus, it can be stated that of the three different factors considered (permeability, cement and quartz content), it is permeability that has the main influence on the nature of the correlation dependence between λ_s and ϕ. When constructing such a relationship, it is desirable to remove from the samples the values of λ_s obtained for samples whose permeability exceeds 3 mD. It is likely that these conclusions are valid for the other correlation dependences considered in the article.

Conclusion

In the course of the research, two collections of samples (a total of ~ 300 samples) of sedimentary rocks from core 17 wells drilled in the north-east and southern regions of the West Siberian Plate were studied. Two devices – Thermal comparator (Kalinin et al., 1983) and Scanning thermal conductivity meter (Popov et al. 1983) – have been used to measure the thermal conductivity of all samples in a dry state and some (90 samples) after saturation with water. Porosity and permeability are determined for 280 and 230 samples, respectively. Studies have shown, as should be expected, that the thermal conductivity of sedimentary rocks is determined primarily by the porosity and type of fluid (air, water) that saturates the pores. In our experiments, after saturation with water, the thermal conductivity of sedimentary rocks (average porosity 12-15%) increased on average by 20-40%. This shows how important it is to use the corresponding values of the thermal conductivity for different geothermal calculations, at least assessed by empirical correlation. The relevance of experimental research in the scouting for such connections between thermal conductivity and its determining factors is unquestionable. We used our data to establish relationships between λ_s and λ_w, ϕ, lgk; λ_w and ϕ, lgk; λ_w/λ_s and ϕ, lgk. All the resulting regression equations for convenience are summarized in Table 2 with the numbers of the regression equations preserved.

First of all, it is necessary to note the presence of stable (R^2 = 0.43-0.54) bonds λ_s with λ_w and ϕ. The same correlation dependences λ_s and ϕ (equations 4, 10, 11) for both collections and their sum were obtained, despite the different numbers of samples in the sets (93-263 samples) and the places of their selection. At the same time, it should be pointed out that in all studied samples, Mesozoic sedimentary rocks of the same type and age are presented. Therefore, an urgent task is to check the indicated relationships λ_s and ϕ on collections involving other sediments.

Significantly less in the considered collections of samples for which there are measured values of λ_w and ϕ. However, it is for them that the most stable connection (R^2 = 0.68) between λ_w/λ_s and ϕ was obtained. The corresponding regression equation (6) satisfactorily corresponds to the correlations (1 and 2) obtained earlier for other regions of the West Siberian Plate (Popov et al., 2003; Popov et al., 2008). In these works, the opinion is expressed that the correlations between λ_w/λ_s and ϕ are inherent in different types of rocks, which probably indicates their universal character for sedimentary rocks.

It was not possible to obtain stable correlations between thermal conductivity and permeability of samples. So, for 109 dry samples of Collection 2, a regression equation was obtained (equation 12), for which the degree of reliability of the linear approximation R^2 is only 0.17. The relationship between permeability and thermal conductivity of water-saturated rocks (equations 8, 9) is somewhat more stable, but they were obtained in just 26 samples.

Samp. coll.	Eq. no.	Parameters	Regression equations	R^2	N
	1	λ_w/λ_s, ϕ	$\lambda_w/\lambda_s = 0,87 + 0,04\cdot\phi$	0,75	143
	2	λ_w/λ_s, ϕ	$\lambda_w/\lambda_s = 0,95 + 0,03\cdot\phi$	0,85	-
1	3	λ_s, λ_w	$\lambda_w = 1,52 + 0,56\cdot\lambda_s$	0,51	90
1	4	λ_s, ϕ	$\lambda_s = 2,43 - 0,05\cdot\phi$	0,54	93
1	5	λ_w, ϕ	$\lambda_w = 2,95 - 0,03\cdot\phi$	0,34	54
1	6	λ_w/λ_s, ϕ	$\lambda_w/\lambda_s = 1,04 + 0,03\cdot\phi$	0,68	53
1	7	λ_s, lgk	$\lambda_s = 1,8 - 0,21\cdot lgk$	0,37	53
1	8	λ_w, lgk	$\lambda_w = 2,58 - 0,15\cdot lgk$	0,29	26
1	9	λ_w/λ_s, lgk	$\lambda_w/\lambda_s = 1,44 + 0,13\cdot lgk$	0,41	25
2	10	λ_s, ϕ	$\lambda_s = 2,47 - 0,04\cdot\phi$	0,43	170
1+2	11	λ_s, ϕ	$\lambda_s = 2,49 - 0,05\cdot\phi$	0,5	263
2	12	λ_s, lgk	$\lambda_s = 2 - 0,13\cdot lg\phi$	0,17	109

Table 2. Correlation dependences between thermal conductivity, porosity and permeability of samples of sedimentary rocks of the West Siberian Plate. Note: Regression equations (1 and 2) are given in (Popov et al., 2003; Popov et al., 2008), respectively. Equations (3-12) are obtained by the authors. R^2 is a parameter characterizing the degree of reliability of linear approximation; N is the number of samples; ϕ – in %

The considered correlation dependences are undoubtedly of practical interest. First, some of them (equations 3-6) can be used for an approximate estimate of λ_w from the measured values of thermal conductivity of dry rocks or only their porosity. The example given in the article (Table 1) showed that in this case one can get results that correspond to the measured ones.

A very important fact is the presence of correlations of thermal conductivity of dry sedimentary rocks with their porosity and permeability. Thus, the established relationship (equation 11) can be used to quickly estimate the porosity of rocks using previously measured λ_s values. Hence, using anticipatory measurements of λ_s of the core, it is possible to identify highly porous rock intervals, which can be further studied in more detail by traditional methods. To apply this technique, it will be necessary to measure the thermal conductivity of a full-sized core (better than air-dry) and, using the correlation links λ_s with ϕ, to estimate changes in the porosity of rocks with depth. Thermal conductivity of dry rocks is measured much easier and faster than porosity (and permeability), especially when using modern express equipment such as ITS.

It is obvious that the identified correlations, which are of great importance for the rapid assessment of the thermal and structural properties of sedimentary rocks, require further clarification. It is necessary to continue the work on increasing the volume of samples of measured parameters for different types of rocks and geological provinces, as well as analyzing and refining the correlation dependencies considered in the article.

Acknowledgments

The study was carried out according to the plan of basic research works of the Department of Geophysics, Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences, with financial support from the Russian Foundation for Basic Research grant No. 16-35-00211.

References

Balobaev V.T. (1991). Geotermiya merzloi zony litosfery severa Azii [Geothermy of the frozen zone of the lithosphere of the north of Asia]. Novosibirsk: Nauka, 194 p. (In Russ.)

Duchkov A.D., Sokolova L.S., Ayunov D.E., Zlobina O.N. (2013). Thermal conductivity of sediments in high-latitude West Siberia. *Russian Geology and Geophysics*, 54(12), pp. 1522-1528. https://doi.org/10.1016/j.rgg.2013.10.015 (In Russ.)

Duchkov A.D., Sokolova L.S., Rodyakin S.V., Chernysh P.S. (2014). Thermal conductivity of the sedimentary-cover rocks of the West Siberian Plate in relation to their humidity and porosity. *Russian Geology and Geophysics,* 55(5-6), pp. 784-792. https://doi.org/10.1016/j.rgg.2014.05.021 (In Russ.)

Kalinin A.N., Sokolova L.S., Duchkov A.D., Cherepanov V.Ya. (1983). Issledovaniya teplovogo komparatora primenitel'no k izmereniyam teploprovodnosti gornykh porod [Research of the thermal comparator in relation to measurements of thermal conductivity of rocks]. *Geologiya i geofizika = Geology and Geophysics*, 3, pp. 116-122. (In Russ.)

Kurchikov A.R., Stavitskii B.P. (1987). Geotermiya neftegazonosnykh oblastei Zapadnoi Sibiri [Geothermy of oil and gas regions of Western Siberia]. Moscow: Nedra, 134 p. (In Russ.)

Lipaev A.A., Gurevich V.M., Lipaev S.A. (2001). Teplovye svoistva gornykh porod neftyanykh mestorozhdenii Tatarstana [Thermal properties of rocks of oil fields of Tatarstan]. Kazan: KMO Publ., 205 p. (In Russ.)

Nikitin D.S., Khutorskoi M.D., Nikitin A.S. (2016). Beskontaktnye izmereniya teplofizicheskikh svoistv gornykh porod na ustanovke TS14 [Non-contact measurements of thermal-physical properties of rocks on TC14 device]. *Protsessy v geosredakh = Processes in GeoMedia*, 3(7), pp. 246-254. (In Russ.)

Novikov S.V., Popov Yu.A., Tertychnyi V.V. et al. (2008). Vozmozhnosti i problemy sovremennogo teplovogo karotazha [Opportunities and problems of modern thermal logging]. *Geologiya i razvedka = Geology and exploration*, 3, pp. 54-57. (In Russ.)

Popov Yu., Tertychnyi V., Romushkevich R. et al. (2003). Interrelations between thermal conductivity and other physical properties of rocks: experimental data. *Pure and applied geophysics,* 160, pp. 1137-1161. https://doi.org/10.1007/PL00012565

Popov Yu.A., Romushkevich R.A., Gorobtsov D.N. et al. (2008). Teplovye svoistva porod i teplovoi potok v raione bureniya sverkhglubokoi En-Yakhinskoi skvazhiny [Thermal properties of rocks and heat flow in the area of ultra-deep drilling in the En-Yakhinskaya well]. *Geologiya i razvedka = Geology and exploration*, 2, pp. 59-65. (In Russ.)

Popov Yu.A., Romushkevich R.A., Popov E.Yu. (1996). Thermophysical studies of rocks of the Tyumen ultradeep well section. V kn.: *Tyumenskaya sverkhglubokaya skvazhina (interval 0-7502 m). Rezul'taty bureniya i issledovaniya* [Book: Tyumen ultradeep well (interval 0-7502 m). Results of drilling and research]. *Sbornik dokl. Nauchnoe burenie v Rossii* [Coll. papers: Scientific drilling in Russia]. Is. 4. Perm: KamNIIKIGS, pp. 163-175. (In Russ.)

Popov Yu.A., Semenov V.G., Korostelev V.M. et al. (1983). Opredelenie teploprovodnosti gornykh porod s pomoshch'yu podvizhnogo istochnika tepla [Determination of thermal conductivity of rocks using a movable heat source]. *Izvestiya. Physics of the Earth,* 7, pp. 86-93. (In Russ.)

Teplovoe pole nedr Sibiri [Thermal field of Siberia depths] (1987). Ed. E.E. Fotiadi. Novosibirsk: Nauka, 195 p. (In Russ.)

About the Authors

Albert D. Duchkov – DSc (Geology and Mineralogy), Professor, Chief Researcher

Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences

3 Ak. Koptyug ave., Novosibirsk, 630090, Russian Federation

Dmitry E. Ayunov – PhD (Physics and Mathematics), Senior Researcher

Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences

3 Ak. Koptyug ave., Novosibirsk, 630090, Russian Federation

Sergey V. Rodyakin – Junior Researcher

Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences

3 Ak. Koptyug ave., Novosibirsk, 630090, Russian Federation

Petr A. Yan – PhD (Geology and Mineralogy), Head of laboratory

Trofimuk Institute of Petroleum Geology and Geophysics of Siberian Branch of Russian Academy of Sciences

3 Ak. Koptyug ave., Novosibirsk, 630090, Russian Federation

Manuscript received 04 July 2018;
Accepted 26 September 2018;
Published 30 November 2018