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PRINCIPLES AND METHODS TO CONSTRUCT DETAILED MODELS OF COMPOSITE MODERN AND PALEOTEMPERATURE FIELDS

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The western Siberia's geotemperature field belongs to the category of composite fields, which is manifested by its significant changeability due to abrupt climatic changes in the late Quaternary. Deviation of geotemperature gradients reaches ±50%. The mathematical model of the geotemperature field has been constructed and on its base methods were developed for determination of deep heat flow and prediction of modern and paleotemperatures. The heat flow determinations were fulfilled for more than 300 deep boreholes. The parameter value varies from 44 to 80 mWm^{-1}, averaging 56 mWm^{-1}. Maps of deep heat flow distribution, maps of modern temperatures and maximum paleotemperatures at the base of western Siberia's sedimentary mantle have been constructed.

O campo de geotemperatura da Sibéria Ocidental pertence à categoria de campos compostos, que é manifestado por sua mudança significativa devida a variações climáticas no Quartenário Superior. Os desvios nos gradientes geotérmicos são de ordem de 50%. Foi construído o modelo matemático do campo geotérmico e com base neste, foram desenvolvidos métodos que permitem a determinação do fluxo térmico profundo e a previsão de paleo e atuais temperaturas. As determinações de fluxo térmico foram obtidas para mais de 300 poços profundos. O valor deste parâmetro varia de 44 a 80 mWm^{-2}. Foram construídos mapas da distribuição de fluxo de calor, de temperaturas atuais e de máximas paleotemperaturas na base do mante sedimentar da Sibéria Ocidental.

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INTRODUCTION

A study of the temperature field of the West Siberian Plate by traditional methods present a number of difficulties. First, the reliable temperature measurements were fulfilled for a little more than 100 areas. With so limited heat flow determinations its distribution over such a large and complex region cannot be established for certain. Second, a sharp variation of observed heat flow values on the depth has been found. The heat flow density increased from 20 mWm^{-2} at 0-200m depth to 40 mWm^{-2} and more at 1000-1500m depth in the south of the region. A quite opposite tendency have been found in the north of western Siberia. It is not clear which data should be taken into account and how to correlate the parameter values for different boreholes. The aim of the given article is to find out the reasons of the abrupt changeability of observed heat flow with depth and to develop the method of undistorted heat flow calculation, which would enable to take into account not only the temperature logs, but point temperature measurements as well; to give geologic interpretation of the data obtained.

TEMPERATURE FIELD CHANGEABILITY

A repeated abrupt climatic changes took place in the Quaternary period in the western Siberian territory, as in many other regions of the Northern Hemisphere. They resulted in formation of permafrost rock complexes and their further complete or partial degradation. The peculiarity of the western Siberia conditions lies in the fact that climatic changes in a relatively short period of time were accompanied by significant changes of permafrost rock thicknesses. The mathematical analysis showed that present geotemperature pattern of the region due to these effects is essentially transient. Deviation of the present geothermal gradients from the steady-state ones greatly varies both by area and section, reaching ±50% and more. Fig. 1 shows some estimations of geothermal gradient declination (△g) from the stationary temperature gradients (g) made with due account for the main peculiarities of the change of cryolithozone thickness during the Quaternary (Kurchikov and Stavitsky, 1987). The reliability of these estimations is testified by the above mentioned change of the heat flow density with depth. Another verification is provided by the plots in Fig. 2, where the curves of individual thermal gradient change are given separately for shale (solid lines) and sandy (broken lines) rocks for boreholes located in different regions of western Siberia. One can see that in many boreholes geothermal gradient increases with the depth, which would have meant in a steady-state field that the thermal conductivity of the same rocks decreases with depth. It contradicts the experimentally established fact that with the compaction of rocks the thermal conductivity increases. Corrections for changeability (Fig. 2b) eliminate this contradiction, all the curves become uniform.

Thus, the estimations show that the heat flow determinations performed by traditional methods give the values which differ to a various degree from the stationary ones, and therefore cannot be used in the geothermal and geologic interpretations without further investigations.

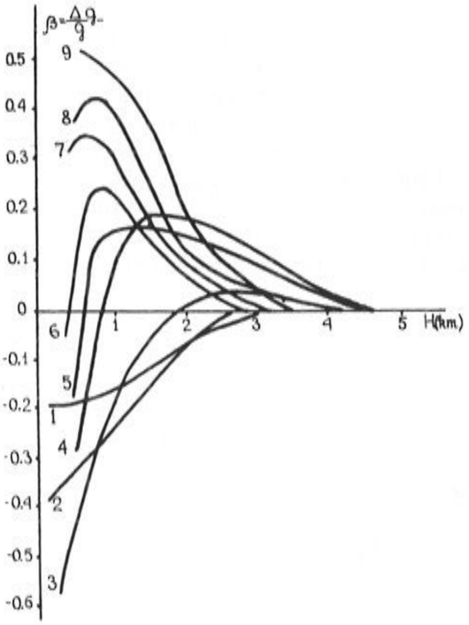

Figure 1 — Deviation of the present geothermal gradients from the normal ones: 1-56°N, 2-58°N, 3-60°N, 4-62°N, 5-64°N, 6-66°N, 7-68°N, 8-70°N, 9-72°N.

MODEL OF THE PRESENT GEOTEMPERATURE FIELD

The analysis of the processes and factors affecting the present geothermal field structure of the West Siberian basin showed that alongside with the distribution of the deep heat flow and nonequilibrium of the temperature field the most significant are also the distributions of rocks with different thermo-physical properties in the sedimentary mantle section and in plane. All the other factors are of the secondary or local significance and may be ignored when the main regularities of the temperature change are established. In view of the fact that the sedimentary mantle mainly consists of interbedded shale and sandy rocks, the description of geotemperature field may be done by one mathematical model, if there will be established the regularities in the thermal conductivity change with depth for every type of these rocks.

Generalization of the experimental thermal conductivity measurements of rocks, of persistent thermal logs clearly showed the dependence of the thermal conductivity $\lambda_L(x)$ on the depth x(Fig. 3). The laboratory measurements were performed in normal conditions at temperature $T_L = 20°C$. The relation between the thermal conductivity and the temperature T was calculated by the formula $\lambda = \lambda_L/[1 + \alpha(T - T_L)]$. Here α equals to 0.002 and $0.003 K^{-1}$ for sandy rocks and shales, correspondingly. If we know the density of deep heat flow q, variation of the geothermal gradient deviation from the steady-state ones with depth $\beta(x) = \frac{\Delta g}{g}$ (see Fig. 1), the temperature T_H at depth H, then in case of a uniform layer of sediments in a section, the temperature at depth x may be estimated by the formula

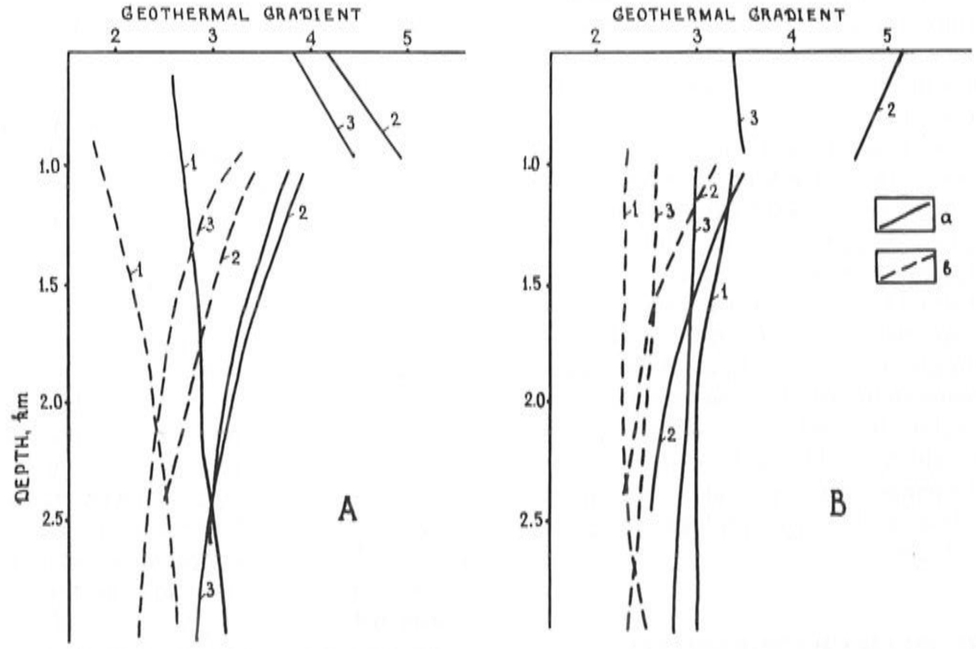

Figure 2 — Change of actual (A) and corrected (B) geothermal gradients with depth in shales (a) and sandy rocks (b) in boreholes: 1-59°10'N, 75°30'E, 2-61°10'N, 76°50'E, 3-66°00'N, 78°30'E.

$$T(x) = \frac{1}{\alpha} \{-1 + [1 + \alpha(T_H - T_L)] \cdot$$

$$\cdot \exp [-\alpha q \int_H^X \frac{1 + \beta(x)}{\lambda_L(x)} dx]\} + T_L, \qquad (1)$$

which is the solution of the differential equation $\frac{\lambda_L(x)}{1 + \alpha(T(x) - T_L)} \times \frac{dT(x)}{dx} = q(1 + \beta(x))$, given that $T(H) = T_H$.

Equation (1) is the base of the mathematical model of the geothermal pattern of the West Siberian basin, since in the presence of several uniform layers the computation of temperatures may be done in consecutive order from the upper layer to the lower one. As it is clear from the above all the parameter values in equation (1) are determined, except that of the deep heat flow. Therefore, determination of the latter is essentially important for the model of the present geothermal pattern as well.

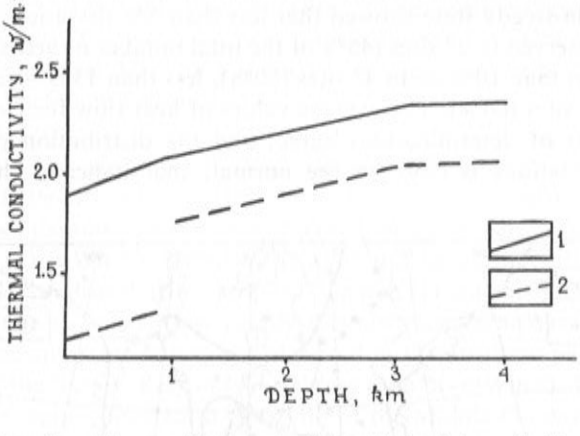

Figure 3 — Change of heat conductivity with depth in sandy (1) and clay (2) rocks.

METHOD OF DEEP HEAT FLOW CALCULATION

In most cases the heat flow density is calculated by the primal problem methods using the equation $q = \lambda g$ or their modifications. In this approach the errors of parameter determination are in direct relation to inaccuracy of λ and g measurements. In addition, the calculated heat flow value characterizes the thermal state of the key bed, and in the case of complicated conditions, for example, under essential changeability of the geothermal pattern, it differs significantly from the deep heat flow.

It is reasonable to follow the way of many applied branches of science, when the main parameter is determined through solution of the inverse problem, not the primal one. If there is the mathematical model of the geothermal field, it is easily performed.

Suppose we have N_T determinations of T_{Fi} temperatures measured at depths H_{Tj}. In this case the methods of the deep heat flow calculation include the following operations:

1. The sedimentary sequence is divided into N_L layers of lithologically homogenious rocks.
2. $\lambda_L(x)$ and α are calculated for every layer according to the content of shales and sandy rocks.
3. Function $\beta(x)$ is approximated for the point under study by the piecewise-linear function. The bounds of the linear variation of $\beta(x)$ are taken equal to 500, 1000, 1500m and so on, with the total number N_H.
4. After performing the above mentioned operations the investigated depth interval may be presented by $N = N_T + N_L + N_H$ layers (at the depth of temperature measurements the conventional boundaries are drawn), each characterized by the constant value of the temperature factor α and the linear change of functions $\lambda_L(x)$, $\beta(x)$. If at depth H_o the rock temperature is T_o, then subject to equation (1) the temperatures at bottom depths of the first and subsequent layers under the arbitrary value of q are calculated by the formula

$$T_1 = T_L - \frac{1}{\alpha_1} + [\frac{1}{\alpha_1} - T_L + T_o] \ \tau_1$$

$$T_2 = T_L - \frac{1}{\alpha_2} + [\frac{1}{\alpha_1} - T_L + T_o] \ \tau_1 \ \tau_2 +$$

$$+ (\frac{1}{\alpha_2} - \frac{1}{\alpha_1}) \ \tau_2 \qquad (2)$$

$$T_N = T_L - \frac{1}{\alpha_N} + [\frac{1}{\alpha_1} - T_L + T_o] \prod_{k=j}^{N} \tau_k +$$
$$+ \sum_{j=2}^{N} (\frac{1}{\alpha_j} - \frac{1}{\alpha_{j-1}}) \prod_{k=j}^{N} \tau_k$$

where $\tau_k = q\alpha_k \int_{H_{k-1}}^{H_k} \frac{1 + \beta_k(x)}{\lambda_{LK}(x)} dx.$

The unknown values are q and T_o. If 'iF' are the depth numbers of temperature T_{Fi} logging, the value q and T_o may be found through minimization of the following functional

$$S = \frac{1}{N_T} \sum_{iF=1}^{N_T} (T_{iF} - T_{Fi})^2, \qquad (3)$$

which may be done by standard methods.

5. If there is the necessity to calculate the heat flow for some interesting from the geologic point of view boreholes with poor thermal log data (2-3 measurements in

a narrow depth interval), the following may be done. On the base of the calculation data of T_0 and q (to provide the uniform approach the 500m depth was used for H_0 all over the West Siberian territory) in wells located in the same region there have been found the relation $T_0 = T_0$ (q) which is substituted in equation (2). In this case functional (3) minimization is done only by q value. The series of control calculations showed practically identical results.

The error of deep heat flow calculation is defined as the sum of estimation errors of parameters used in the method described: the heat conductivity of rocks, the degree of geothermal field instability, the distribution of temperatures.

The heat conductivity of core samples is experimentally determined with 5-10% error. But due to specific changes of the rocks structure in the process of drilling, sampling and storing of cores, the samples brought to the surface are not always typical of the sediments under study, the measured values of heat conductivity may randomly and greatly differ from those in natural occurrence. Under the sufficient number of heat conductivity measurements for every rock type the statistical processing of data reduces to a minimum the influence of various technogenic factors. Hence, the deviation of the lines constructed on the statistical relations shown in Fig. 3 from the actual ones on the average in the section does not exceed the same values: 5-10%. Of special interest is the sudden change (to 20-25%) of heat conductivity in shales at depths 1000-1200m, established both from data of experimental parameter determinations and from geothermal gradient change in shales (Fig. 2). The discontinuous change of heat conductivity coefficient probably may be explained by rearrangement of the structural lattice of minerals at this depth.

Inaccuracy of function $\beta(x)$ assignments results from possible mistakes in determination of the cryolithozone thickness at different stages of its development. Estimations show that the errors in $\beta(x)$ calculations may be significant only in a layer of several hundred metres thick below the bottom of permafrost rocks; at depths exceeding 1000m the error is 2-3%, not more.

When using the continuous thermal log data from boreholes for a long time being shut-in, the errors in temperature measurements may be ignored. After proper rejection of individual temperature measurements, the distribution of temperatures in a section by the point temperature logs is determined to an accuracy of 2-3°C. And the deviation of measured temperatures from true values may be both positive and negative. On the account that the method for calculation of the heat flow is based on the computation of the theoretical distribution of temperatures very close to the actual one, the deviation of calculated values from real ones, given there are 5-6 measurements, with 90% probability does not surpass 1.0-1.5°C. Therefore, the error of heat flow calculations based on the data of deep seated horizons does not exceed 2-3%.

Thus, when using the thermal log data in the depth interval of 1000-1500m, the method proposed for determination of the heat flow density allows to provide the results with the total error of 10-15%, that correlates well with generally accepted standards.

DISCUSSION OF RESULTS

As compared with the traditional methods the algorithm described is more time consuming but is easily implemented by a computer, that makes it convenient in use. On its base there have been done calculations of the deep heat flow densities for more than 300 West Siberian boreholes.

In order to compare the heat flow values with those obtained by traditional methods one should correct for instability, which may be done by the formula: $q = q_{st}(1 + \beta)$, where β is the average value of the geothermal gradient deviation for key intervals. From the sites for which the parameter values were calculated by the above-described method, for 59 exploration areas the heat flow values were determined by other investigators. Comparison with geothermal field values corrected for non-steady state showed that less than 5% deviation is observed in 27 sites (46% of the total number of areas), less than 10% — in 47 sites (80%), less than 15% — in 51 sites (86%). The average values of heat flow for two sets of determinations agree, and the distribution of deviations is close to the normal, that indicates the

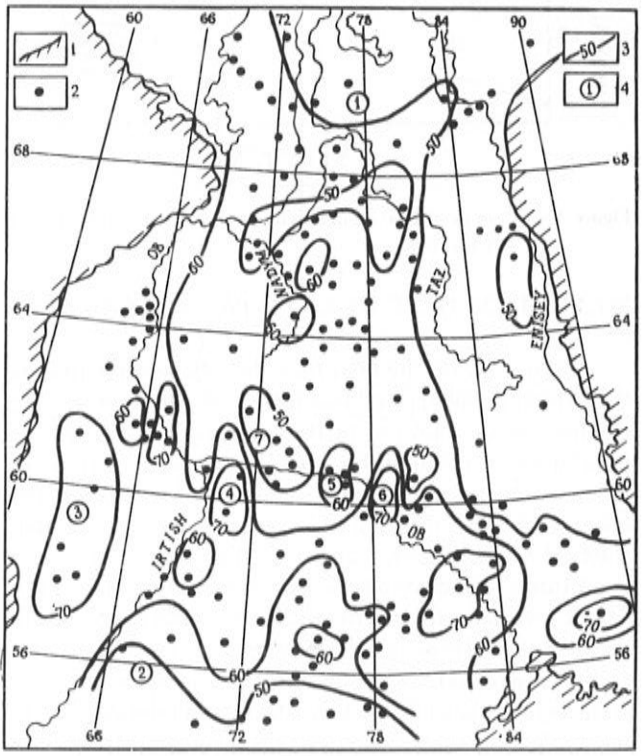

Figure 4 — Heat flow within the West Siberian Plate. 1 — margins of the West Siberian Plate; 2 — points of heat flow determinations; 3 — heat flow isolines (mWm^{-2}); 4 — regions mentioned in the text.

random nature of divergence. Therefore, the accuracy of heat flow determinations may be claimed to be not lower than those measured by traditional methods, i.e. 10-15%.

The analysis of the data obtained shows that the West Siberian thermal field is nonuniform. The deep heat flow density varies from 44 to 80 mWm^{-2}, averaging 56 mWm^{-2} (the standard deviation is 6 mWm^{-2}). The distribution of boreholes over the territory of the basin is regular enough, that is why the pattern of parameter distribution (Fig. 4) may be regarded as quite reliable.

It should be noted, that the regularities of the heat flow density change shown in Fig. 4 greatly differ from those established previously by traditional methods by Sergiyenko (1977) and Sokolov (1979). There may be distinguished two large areas with relatively low parameter values (up to 50 mWm^{-2}). One of them, meriodionally oriented, includes a large territory adjacent to the Siberian Platform. In the north of the region the area of relatively low heat flow values is expanded, involving almost all the Gydan Peninsular territory (site 1 in Fig. 4). The second area is in the south of the West Siberian Plate, including the whole Central Kazakhstan folded system (site 2) and some adjacent regions. The increased heat flow is observed in the west of the Plate. Here the parameter value reaches 70mWm^{-2} in the Shaim Region and 80 mWm^{-2} in the Karabash Region (site 3).

The deep heat flow changes abrupty in the Middle-Ob regions. Here several areas with relatively high parameter values are observed: in Salym (site 4) (up to 75 mWm^{-2}), Vartovsk (site 5) (up to 65 mWm^{-2}), Aleksandrovsk (site 6) (up to 75 mWm^{-2}) regions, and in between the heat flow usually does not exceed 60mWm^{-2}. The minimum values are observed in the northern part of the Surgut Region (site 7) (less than 50 mWm^{-2}). In the regions located to the south of the Middle-Ob Area the density of the deep heat flow, as a rule, is in excess of 60 mWm^{-2}, and to the north there in a zone with almost constant parameter values — 50-56 mWm^{-2}.

TEMPERATURE DISTRIBUTION

The resulting characteristic of the deep heat flow enables to proceed to description of temperature distribution in the sedimentary mantle of the West Siberian basin. The great advantage of the use of the mathematical model of the geothermal field is the possibility to calculate with high accuracy the temperatures at great depths in the West Siberian north where actual data characterize sediments only to the depth of 3-3.5km. The information about the lithologic composition of deep seated horizons needed for equation (1) was selected from geophysical data and paleogeographic reconstructions. A series of control tests showed very good agreement of actual and calculated temperature values. Fig. 5 illustrates the distribution of temperatures in the sedimentary mantle bottom.

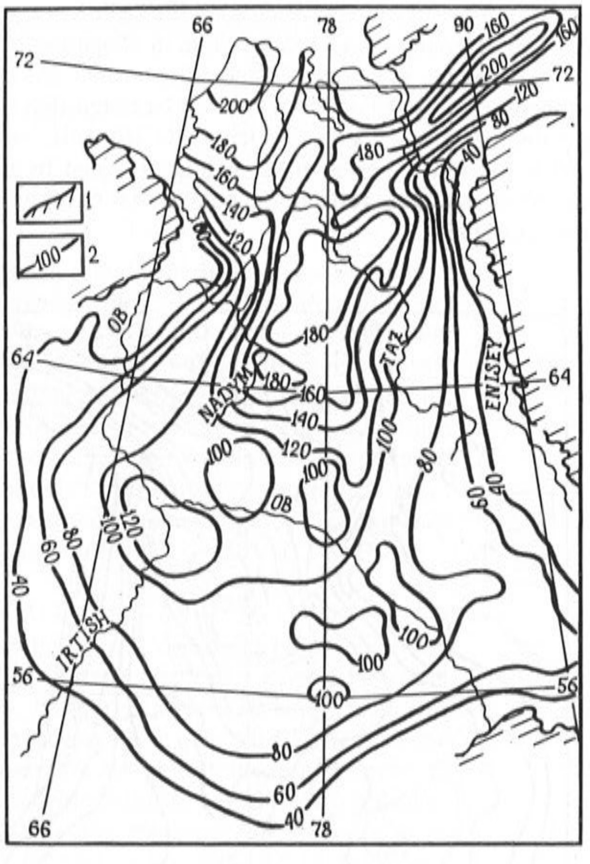

Figure 5 — Distribution of temperature at the sedimentary mantle bottom. 1 — margins of the West Siberian Plate; 2 — temperature isolines (°C).

PALEOTEMPERATURE CONDITIONS

The paleogeothermal history of sediments is of great interest, especially for evaluation of the scale of oil and gas generation and accumulation. The above-described mathematical model of the present geothermal field allows to solve this task. For this purpose it is necessary: first, on the base of the present distribution of rock types in a section with due regard for the compaction law to reconstruct the distribution of rocks in the sedimentary mantle at the given time. Second, using the dependency of the heat flow density from the age of basement consolidation (for example, according to Smirnov, 1980) [4] to calculate the value of this parameter for the same time. The temperature values at the surface were determined from the paleoclimatic reconstructions.

Thus, from the formal point of view the task of paleotemperature reconstruction for any stage of the geological development of a region does not differ from the task of description of the present temperature distribution in rocks.

As a secondary concern, the characteristic of the maximum paleotemperature field observed in the Early Oligocene time is the most interesting. As it turned out, the temperature of the sedimentary mantle rocks in the West Siberian Plate in the last 25-30 million years have decreased by 20-55°C (depending on the region and the position of rocks in a section). Fig. 6 illustrates the distribution of maximum paleotemperatures in the sedimentary mantle bottom. It should be noted that the paleotemperature values calculated in this way sufficiently well agree with the values obtained by the method of vitrinite reflectance analysis (Kurchikov & Stavitsky, 1987).

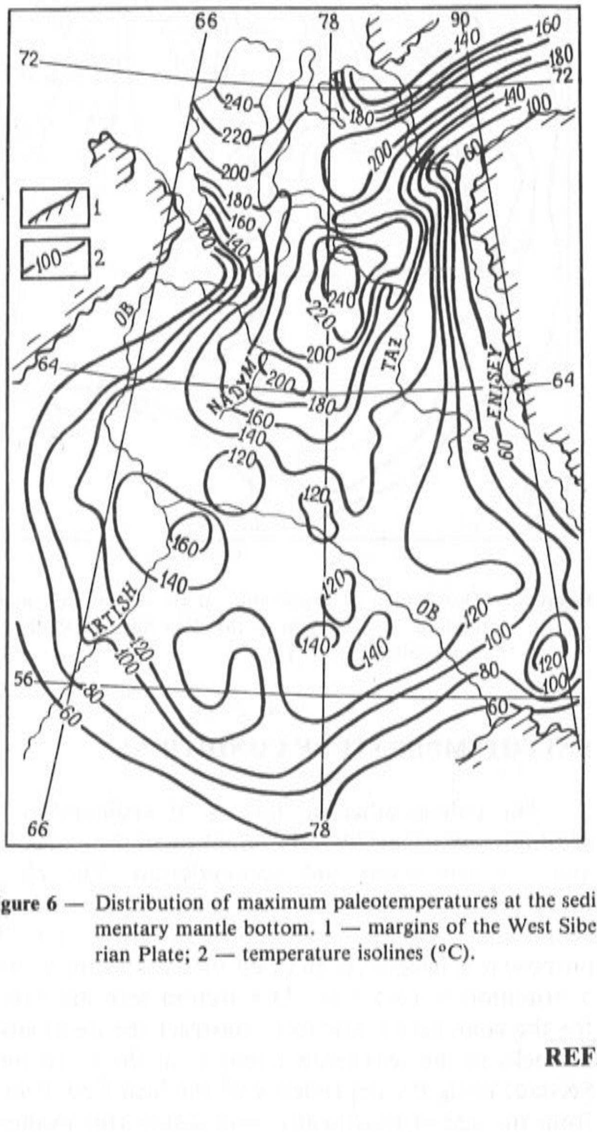

Figure 6 — Distribution of maximum paleotemperatures at the sedimentary mantle bottom. 1 — margins of the West Siberian Plate; 2 — temperature isolines (°C).

CONCLUSION

In the course of investigations the following main results, having the practical significance as well, were obtained:

1. The method of deep heat flow calculation was developed, enabling to use the point temperature measurements alongside with the continuous thermal log data.
2. The distribution of present and paleotemperatures in the sedimentary mantle of the West Siberian Plate was established.

It is important to stress sufficiently high reliability of the reconstructions. The correlation between the distribution of the heat flow density and the geotectonic structure of the West Siberian Plate basement testifies the proper approach in the calculation of this parameter. A large number of control calculations demonstrated the accuracy of the present temperature change forecast. The reliability of paleogeothermal reconstructions was testifield by the agreement of the maximum paleotemperature values with those obtained by the vitrinite reflectance method. To our opinion, such a result was possible due to the development of the correct, in toto, mathematical model of the geotemperature field of the West Siberian basin and the consecutive use of this model for solution of all the tasks.

The above-described principles and methods of the western Siberia geotemperature field study may be used for other regions. The main task consists in the analysis of all the factors affecting the structure of the geotemperature field, in order to distinguish the main, with the following construction of the mathematical model. Further generalization of the actual data available and their interpretation should be done on the base of this model.

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