Use of trend analysis for geothermal investigations in oil-gas regions (as in Crimean plain and northern Black Sea region)

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The geothermal method is finding increasing use in the field of geology. Therefore the differences between the numerous existing geothermal procedures are determined essentially by the specific problem to be solved.

The principal factor in thermal field formation is conductive heat transfer from great depths. The distribution of heat in the layers of the crust, reflecting the effect of various different natural causes, gives extensive information on the structure, evolution, and minerals of the region under investigation. To interpret geothermal curves, many factors must be taken into account: tectonics, lithology, hydrogeology, etc. Due to the predominant role of conductive heat transfer, the thermal field of the underlying strata usually distorts the actual picture of temperature distribution in the rocks above them. Therefore if the effects of the individual factors can be differentiated, their analysis is greatly simplified.

In geological investigations one has to deal with systematic and local changes in the variables under examination, both horizontal and vertical in character. Modern mathematics provides geologists with methods enabling them to distinguish between local and systematic changes. Trend analysis (Krumbein and Graybill, 1969) is such a method.[1]

Any chart of observations (in our case the geothermal gradient for Maykopian rocks, fig. 1) is divided into two parts. One part is related to changes reflecting tendencies in the behavior of a feature over the whole of the mapped surface (background, fig. 2); the other part characterizes random fluctuations (local deviations, fig. 3) which have little bearing on the systematic variability. To distinguish a regional component (the background distribution of the geothermal gradient), the method of averaging — the "sliding average" — is used.

Note that when this method is used, the choice of the averaging scale coordinate grid on transparent paper is very important. To single out (smooth out) the effect of local factors on the geothermal gradient, we must select a coordinate grid, the dimensions of which are somewhat greater than the minimal dimensions of the anomalies revealed on the initial chart of observations.

In our case conversion was effected by means of a square coordinate grid with 2 cm sides; on a scale of 1:500,000 this corresponds to 10 km, i.e., it ensures elimination (smoothing out) of local anomalies.

In preparing the data for constructing the distribution pattern of the regional trend of the geothermal gradient (fig. 2) from the initial chart (fig. 1), we recorded the observed values of the geothermal gradient, using a uniform orthogonal grid (1 cm intervals). Using the coordinate grid, we then converted (averaged) the values at each point. The "sliding spacing" was taken as 5 km (1 cm) and averaging (arithmetic mean) was performed for eight values, in accordance with the setting of the coordinate grid. On the basis of these results we constructed a new diagram indicating the regional trend (background distribution) of the geothermal gradient (fig. 2).

The next stage amounted to the accumulation of data for constructing a diagram of the local components (residual trend, free from background distribution of the geothermal gradient). The new value was obtained by algebraic subtraction of the background values of the geothermal gradient from its absolute (observed) values. The resulting diagram (fig. 3) is more highly differentiated than the initial one (it exhibits two types of fields: positive and negative); this enables one to interpret more accurately the origin of the existing anomalies in specific (Maykopian) strata.

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[1] In mathematics the word "trend" denotes any systematic changes.

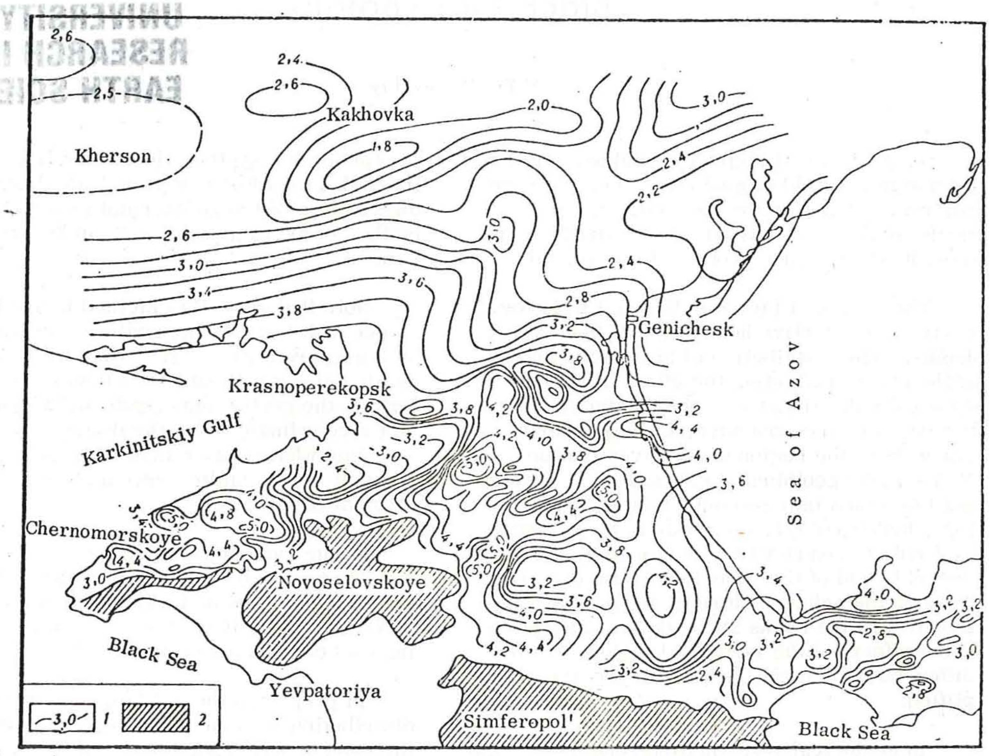

FIGURE 1. Geothermal gradient of Maykopian rocks of Crimean plain and the northern Black Sea region.

1 - isolines of geothermal gradient, °C/100 m; 2 - zone of absence of Maykopian deposits.

This operation was performed by hand, but the Laboratory of Mathematical Methods in Geology (All-Union Scientific-Research Geological Prospecting Oil Institute) has now developed a computer program which greatly reduces the time involved.

A comparative assessment of the schemes of trend surfaces with various different geological-geophysical investigations enables us to reveal the degree of influence of the factors involved in the formation and distribution of heat within strata. In analyzing the effect of a particular factor it was assumed that the fluctuation of the geothermal gradient is influenced only by the factor in question, and the other factors are balanced.

Porosity. The Maykopian strata consist of clays with low carbonate content (0-8%), among which are observed at certain points beds and lenses of siltstones, and in fewer cases of fine- or medium-grained sandstones. The porosity and density of the Maykopian strata in the Crimean plain depend only on their depth of occurrence. In the depth range 300-400 m the porosity of the sand-silt rocks (28-34%) is at times lower than that of the clays (30-36%). At a depth of 1300-1400 m, due to the marked compactability of the clays their porosity decreases to 24%, while that of the sand-silt rocks varies from 24 to 29%.

In the region in question the Maykopian rocks are located mainly in the depth range 200-1000 m and they are found at greater depths only in the extreme southeast (Kerch' peninsula and west closure of the Indol' trough). Thus, regardless of their facies, the Maykopian rocks have a high, slightly varying (over the main area of occurrence) porosity, which is closely related to the density and water saturation and therefore cannot have a marked effect on heat distribution within the strata.

Permeability of the rocks. In a permeable bed the geothermal gradient has reduced values (Ogilvi, 1959; Makarenko, 1966). Depending on the type of heat transfer predominating in the interior, the permeability may be a function of the lithological or hydrogeological factor. If the conductive type of heat transfer is predominant, the permeability will depend mainly on the lithological factor. If convective heat transfer predominates, the permeability must depend mainly on the hydrogeological (more precisely, the hydrodynamic) factor.

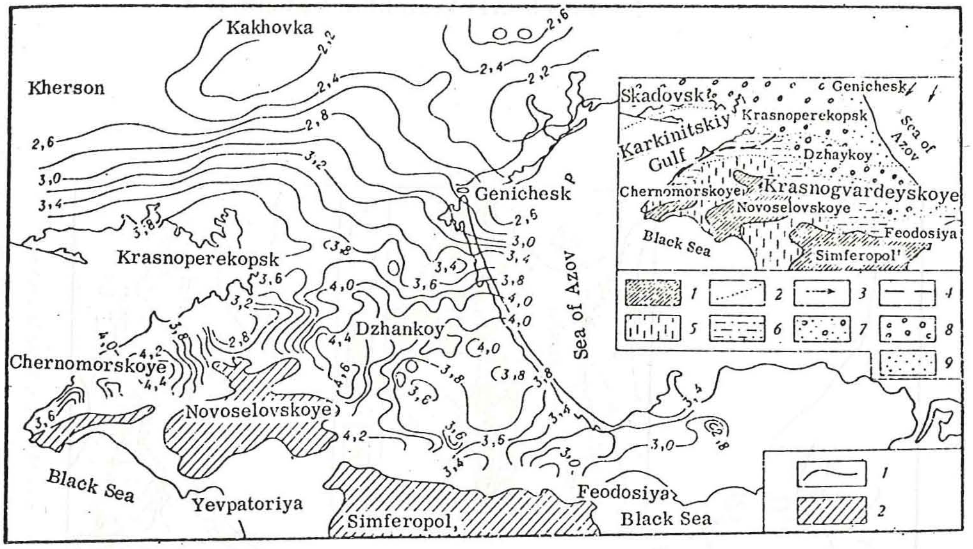

FIGURE 2. Regional trend of the geothermal gradient of Maykopian strata of Crimean plain and the northern Black Sea region:

1 - isolines of geothermal gradient; 2 - zone of absence of Maykopian deposits.

FIGURE 2a. Diagram of facies zones of Maykopian strata of Crimean plain and the northern Black Sea region (according to A. A. Lagutin, A. T. Bogayts, S. M. Zakharchuk, L. G. Plakhotnyy, and N. Yu. Chernyak).

1 - region of absence of Maykopian deposits; 2 - boundaries of facies zones; 3 - direction of removal of detrital material; 4 - postulated southern boundary of the zone with more than 10% of the sand-silt fraction, distinguished from geothermal data. Content of sand-silt fraction in the cross section, %: 5 - 0-5; 6 - 5-10; 7 - 10-20; 8 - 20-30; 9 - > 30.

The Maykopian deposits are on the whole impervious strata. The only collectors within them are intercalations and lenses of siltstones and sandstones with markedly varying permeability. A comparison of the permeability of the rocks as a component of the lithological factor with the horizontal variability of the Maykopian strata (fig. 2a) reveals that the facies bands (with equal contents of the sandstone-siltstone fraction)[2] have a southwest strike. Zones with maximal content of argillaceous material (and therefore less permeable) correspond to higher values of the geothermal gradient.

This law, which becomes very apparent in a comparison with regional trend diagrams, enables us to infer that the distribution of heat in Maykopian strata depends directly on the facies characteristics of the rocks.[3]

In connection with this dependence, the region north of Novoselovskoye (southeastern flank of the Karkinitskiy trough) is of definite interest.

By analogy with the northeastern and northern regions of the area in question, we are justified in assuming that the relatively reduced values of the geothermal gradient are due to the increased content of coarse detritus. However, a detailed facies analysis of this sector is impeded by the dearth of boreholes passing through Maykopian deposits. Nevertheless, even a fragmentarily traced facies change in the rocks shows that the coarse detritus (judging from the number of permeable beds on the electric logging diagrams) increases, albeit slightly, to the north.

Thus an investigation of the dependence of the geothermal gradient on the permeability of the rocks enables one to obtain the facies characteristic of the strata in question and what is more, the gradient itself may serve as a corrective of such a characteristic. In this connection, the southern boundary of the zone of occurrence of sand-silt rocks, which constitute 20-30% of the Maykopian strata in the cross

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[2]The sand-silt rocks are correlated mainly with the center of the Maykopian strata (with the exception of the southeast regions).

[3]Local deviations from this law are due to the predominant superimposed effect of other factors, examined below.

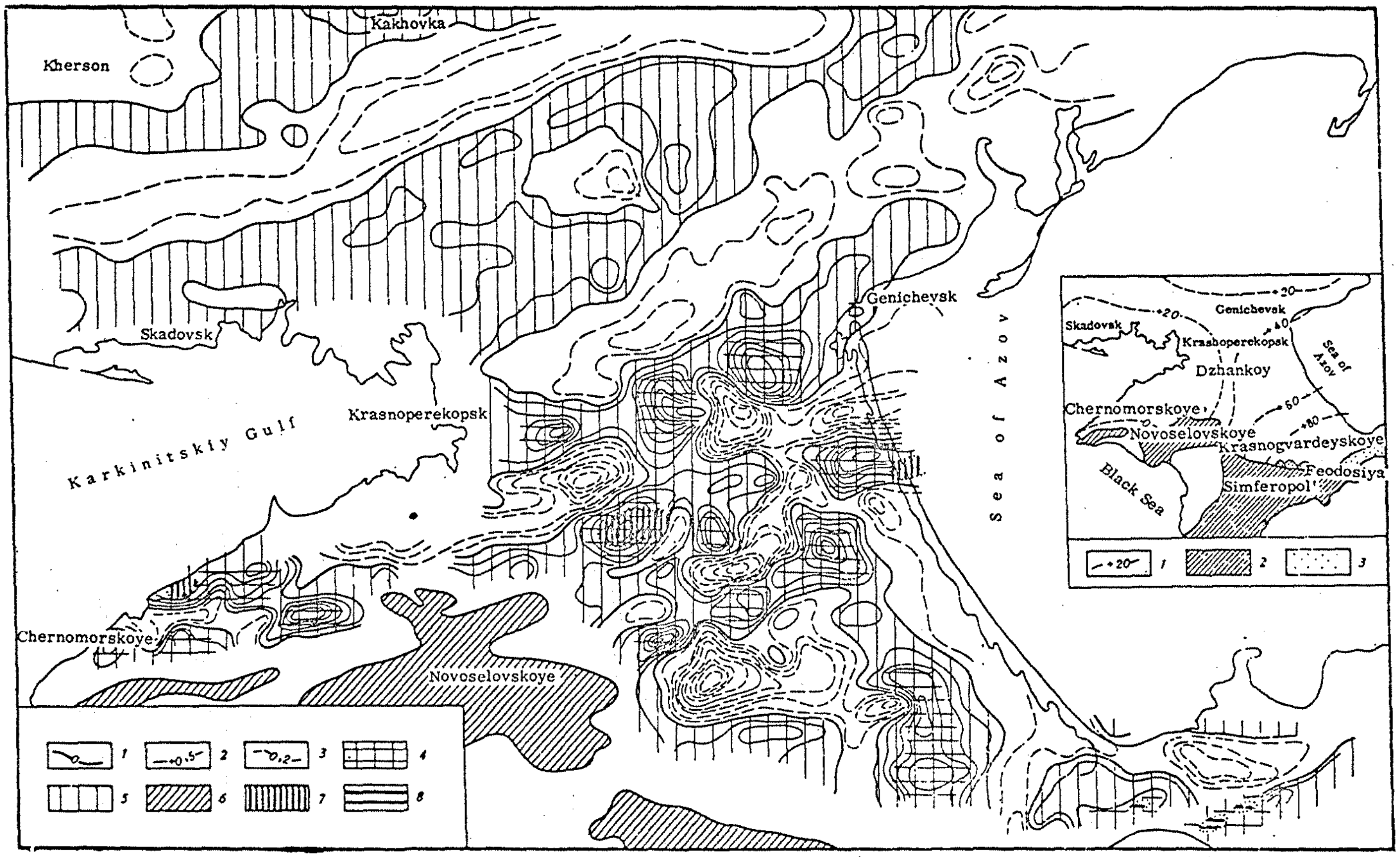

FIGURE 3. Isolines of local components (residual anomalies) of geothermal gradient of Maykopian strata of Crimean plain and northern Black Sea region.

1 - zero values; 2 - positive values; 3 - negative values; 4 - highly promising sectors for oil and gas finds; 5 - promising sectors for accumulation and preservation of oil and gas; 6 - region of absence of Maykopian deposits; 7 - gas deposits; 8 - oil deposits.

FIGURE 3a. Distribution pattern of pressure heads of Maykopian aquifers of Crimean plain and northern Black Sea region (according to Yu.Kh. Ovcharenko 1969).

1 - hydro-isopiestic lines, m (reduced to sea level); 2 - region of absence of Maykopian deposits; 3 - outcrops of Maykopian deposits.

section, may be set farther south to include the region of the Karkinitskiy Gulf as well (fig. 2a).

The above exposition shows that the parameter of the regional trend scheme of the geothermal gradient of Maykopian strata reflects not only the effect of conductive heat transfer from below, but also the marked effect of the petrographic characteristics of the rocks composing these strata.

By distinguishing local components we become virtually free from their effects. Thus the parameter of the residual geothermal gradient reflects the effect of local factors (hydrodynamic, structural, oil and gas content) only within the Maykopian strata.

Displacement of fluids — agents of convective heat transfer — occurs in any permeable medium. The more active their displacement, the more intense will be convective heat transfer, accompanied by a decrease in the geothermal gradient (Ogilvi, 1959; Makarenko, 1966; Makarenko, Polyak, et al., 1970). Such a dependence enables one to trace the degree of effect of the hydrodynamic factor on thermal field formation.

To determine the role of permeability as a component of the hydrodynamic factor influencing the distribution of heat in Maykopian strata, let us deal with its hydrodynamic characteristic in the region in question.

Despite the fact that the Maykopian strata constitute a regional confining layer, intrinsic hydrodynamic conditions exist within them, the principal role in their formation being played by elision waters. It may be seen from the hydrodynamic scheme that the extruded waters form radial currents, running from the zones of maximum geotectonic loads (Karkinitskiy trough and Indol' basin) toward the elevated peripheral sectors (central and western sectors of the Sivash basin).

The currents of extruded waters move toward one another from the different basins and meet to form a zone with retarded water exchange. Calculations of the speeds of the subsurface waters, performed in this sector (Likhomanova and Propevyat, 1968, verbal communication), also show extremely retarded water exchange in the Maykopian strata. The ascensional movement of the waters in this zone is accompanied by retarded seepage through the water-confining strata and by formation of a region of concealed (pulverized) relaxation.

It is known that such regions are favorable for the accumulation and preservation of hydrocarbons and simultaneously favorable for heat accumulation. This explains the increased intensity of the thermal field of the central and western sectors of this territory, expressed in the case in question by positive values of the residual geothermal gradient (fig. 3).

The negative anomalies of the residual geothermal gradient, observed among regions with retarded water exchange, may be attributed to the local manifestation of free convection. This assumption is confirmed by the occurrence of negative anomalies mainly at the boundaries with known structural complications (flexures, anticlines, faults) in the sedimentary cover of Maykopian strata, i. e., at sites where the effect of free (natural) convection is manifested more acutely (Ogilvi, 1959; Makarenko, Polyak, et al., 1970).

Another type of hydrodynamic conditions, namely infiltration conditions, occurs virtually throughout the northern Black Sea region and in the south of this territory in the form of a narrow band along the Crimean foothills. In the north the entry of cold infiltration waters from the present-day intake areas of the Maykopian rocks (the Ukrainian crystalline shield) reduces the geothermal gradient. In this sector we observe two currents of infiltration waters of south-southwest strike, namely eastern and western, corresponding to the negative anomalies on the diagram (fig. 3). The currents are separated by a band (along the Chaplinka—Melitopol' line) of relatively retarded flow of water (positive values of the residual geothermal gradient).

Hydrodynamic zonation of this type is explicable. In the north the boundary of occurrence of Maykopian deposits lies outside the territory under investigations. They have a thin cover of Neogene-Quaternary deposits, which cannot provide reliable screening against penetration of surface waters into the Maykopian rocks.

It is characteristic that, when continued toward the northeast, the thermal fields corresponding to negative anomalies coincide with the sectors where the boundary of tapering out of the Maykopian deposits has minimal northward extent (i. e., the intake area of the Maykopian complex is closest to the territory under investigation).

On the other hand, the band of positive anomalies is located on the continuation of the sector where the boundary of occurrence of the Maykopian deposits is furthest from this territory.

The origin of the zone of retarded water exchange is attributable to the fact that two currents meet here: infiltration waters draining the strata from the north, and elision

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waters ascending from the Karkinitskiy trough side.

In the south of the territory, in the region of the Crimean foothills, the negative anomalies identified with drainage by infiltration waters like those in the northern Black Sea region are also located in the immediate vicinity of outcrops of Maykopian deposits.

The Kerch' negative anomaly occupies a special place among the negative anomalies observed on the diagram (fig. 3). Here the hydrodynamic factor comes fully into play. On the one hand we have the cooling effect of infiltration water (although it is a fact that their penetration is not very great). On the other hand in this region we observe extensive development of mud volcanoes, which reduces the geothermal gradient due to the fast currents of water discharging into the upper horizons.

All the known structural-tectonic complications in the sedimentary cover of the Maykopian strata are reflected in some way or other in the scheme of residual anomalies of the geothermal gradient and emphasize the effect of the tectonic factor on heat distribution directly in the Maykopian strata. This is expressed in an increase in the local values of the geothermal gradient (within the limits of the positive anomalies), concentrated at the sites of known anticlines, where the law of anisotropy is manifested; the bunching pattern of the isolines of the geothermal gradient characterizes the steepness of slope of the rocks. The tectonic factor also finds such expression near faults, probably screening the movement of fluids.

However, faults may also provide possible paths of movement of fluids. In that event we must expect a negative anomaly of the geothermal gradient, a distinct example of which is the Kerch' anomaly.

The most distinct positive anomalies of the geothermal gradient (fig. 3) coincide with known gas fields in Maykopian strata (Dzhankoy, Strelkovoye, Mezhvodnenskoye).[4]

Extending this law, we may assume that residual anomalies of the geothermal gradient may be used as the initial data for assessing the prospects of oil and gas strikes in the corresponding lithological-stratigraphic complex. The prospects are assessed on the following principle.

[4]In the region under investigation trend analysis was performed for four lithological-stratigraphic complexes: in addition to the Maykopian complex, I investigated Paleocene-Eocene, Upper Cretaceous, and Lower Cretaceous complexes. All the oil and gas fields are concentrated within positive fields on the maps of residual anomalies of the geothermal gradient.

Fields where deviations of the geothermal gradient from zero correspond to 0.25 °C/100 m or more are regarded as highly promising, because these are minimal values corresponding to known deposits in the region and to commercial oil-and-gas occurrences. The residual field on the positive side of the residual geothermal gradient from the zero isoline contour is regarded as promising.

In assessments of the prospects of oil and gas strikes, particular attention has been paid to such criteria as oil-and-gas occurrences, the gas saturation and composition of free and water-dissolved gases, the hydrochemical characteristics of the waters, and general geological assumptions.

As a result, several sectors recommended for search for oil and gas have been distinguished.

The established fact that zones of elevated thermal conditions are correlated with regions of retarded water exchange, in which conditions for accumulation and preservation of hydrocarbons are optimal, enables one to use geothermal anomalies as a criterion for oil and gas searches. In this connection the oil-and-gas content factor may have additional significance, because the specific thermal resistance of water is approximately 4 times less than that of oil and 14 times less than that of gas; therefore the geothermal gradient increases when the water saturating the rock is replaced by oil or gas (D'yakonov, 1958).

Summing up, it may be assumed that the method of trend analysis of geothermal data makes it possible to delineate specific local sectors most favorable for accumulation and preservation of hydrocarbons, differentiated in terms of complexes, which increases the efficiency of oil and gas searches.

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