Role of regional basement faults in forming geothermal field of young platforms

M.S. Arabadzhi et al.

The character of the geothermal field of young platforms is a major factor in the processes of oil and gas formation and accumulation. The thermal regime of the strata affects the regeneration of organic matter, and also the lateral and especially the vertical migration of the oil and gas fluids.

We have made a study of the distinctive features of the geothermal field of a young epi-Paleozoic platform in Central Asia (the Turanian plate), on the example of the Aral-Caspian region, on the basis of theoretical constructions elaborated by Lyubimova (4), D'yakonov (3) and the Dept. of Geology of the I. M. Gubkin MINKh and GP [Moscow Institute of National Economy (G. V. Plekhanov) and Geological Industry] (1).

The raw data for the study of the geothermal field were industrial-geophysical (geothermal) measurements made in wells that were in a state of quiescence for no less than 10 days before the beginning of the geothermal investigations.

Inasmuch as at present there are not sufficient data for solidly founded geothermal reconstructions by the classic methods, for the study of the geothermal field of the Aral-Caspian region a method was developed for processing the results of geothermal investigations in wells on the basis of the correlation between the geothermal gradient and the depth at which the folded basement occurs. The crystalline basement rocks were assumed to have a higher thermal conductivity than the sedimentary mantle and are the main heat-conducting body.

It is natural to suppose that in areas with the same mean annual temperature, a change in the depth of the folded basement will lead to a change in the geothermal gradient — that is, the areas with smaller thickness of the sedimentary mantle will correspond to the zones of maximum geothermal

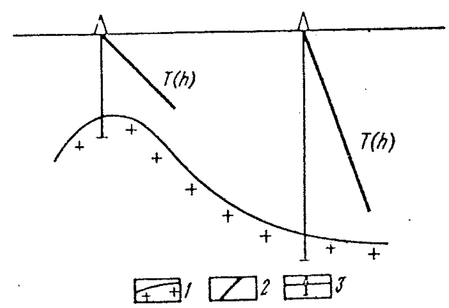


FIGURE 1. Diagram of relationship between geothermal gradient and depth of occurrence of the basement:

1) position of top of basement; 2) curve of changes in temperature, 3) exploratory wells.

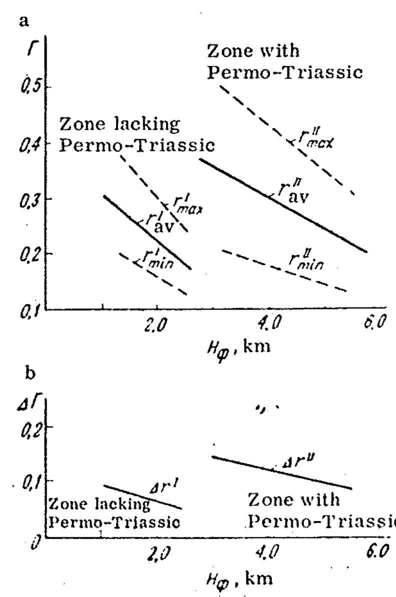


FIGURE 2. Graphs of correlation between geothermal gradient and depth of occurrence of the basement:

a) relation of geothermal gradient to depth of basement; b) relation of range of variation in geothermal gradient to depth of basement.

Translated from Rol' regional'nykh razlomov fundamenta v formirovanii geotermicheskogo polya molodykh platform, Sovetskaya Geologiya, 1972, no. 10, p. 116-123. Co-authors with Arabadzhi are Yu. M. Vasil'yev, V. P. Gavrilov, and V. S. Mil'nichuk. They are with the Gubkin MINKh and GP.

gradient, and vice versa (fig. 1). The available temperature measurements in 27 prospecting areas have enabled us to study this relationship quantitatively, in statistical form. Comparison of the measured values of the geothermal gradient with the depth to the folded basement (fig. 2a) indicates a linear relationship of two types between these variables for zones with a platform mantle of specific structure.

In areas with a thick Permo-Triassic complex, the relationship between the geothermal gradient and the depth to the folded basement has the form:

$$\Gamma^{I}_{av}(x, y) = -0.57 h_{\Phi}(x, y) + 5.75 [^{\circ}C/100\,m]. \qquad [1]^{1}$$

For areas where the Permo-Triassic complex is of smaller thickness or completely lacking, this relationship differs from expression [1] above in the values of the constant coefficients and therefore has the form:

$$\Gamma_{av}^{II}(x, y) = -0.61 h_{\Phi}(x, y) - 4.06 [^{\circ}C/100\,m]. \qquad [2]$$

Statistical evaluations were made for both these correlations, indicating their stability. But the actual values of the geothermal gradient are known to be determined not only by the region's geothermal regime, which is related to the depth of occurrence of the basement, but also by the lithology (thermal conductivity) of the rocks. The correlations in formulas [1] and [2] above express the relationship between the depth to the basement and the average (weighted for thickness) values of the geothermal gradient along the vertical section, whereas the partial values of the gradient for the separate bodies of rocks change within a certain interval $\Delta\Gamma(x, y)$. These values of $\Delta\Gamma(x, y)$ are related to the depth of the basement's occurrence (fig. 2b), both in zones of considerable thickness of the Permo-Triassic complex

$$\Delta\Gamma^{I}(x, y) = -0.39 h_{\Phi}(x, y) + 4.40 [^{\circ}C/100\,m]. \qquad [3]$$

and in zones where it is of reduced thickness or wedges out

$$\Delta\Gamma^{II}(x, y) = -0.50 h_{\Phi}(x, y) + 2.90 [^{\circ}C/100\,m]. \qquad [4]$$

A characteristic feature of the relationships in [3] and [4] is the diminished range of change in the thermal conductivity of the rocks with depth, which is evidently owing to the compaction of the rocks as the depth of their occurrence increases and to the relative stability of the hydrogeological regime of large basins.

The value of the geothermal gradient at any point in space within the region studied thus is determined both by the average value of the geothermal gradient (geothermal regime of the region) and by the thermal conductivity of the rocks in the section (their lithology):

$$\Gamma(x, y, z) = \Gamma_{av}(x, y) + \Delta\Gamma(x, y)\,[1 - \xi(x, y, z)], \qquad [5]$$

where $\xi(x, y, z)$ is a function allowing for the changing thermal conductivity of the rocks both in area and along the section.

Integrating equation [5] for z, we obtain

$$T(x, y, z) = \Gamma_{av}(x, y) \cdot z - \Delta\Gamma(x, y) \int_0^z [1 - \xi(x, y, z)]\,dz. \qquad [6]$$

The greatest difficulty in solving equation [6] lies in computing the value of the function $\xi(x, y, z)$. For this purpose we have used the potential of the thermal field — that is, the condition for the validity of the Laplace equation

$$\Delta T(x, y, z) = 0, \qquad [7]$$

where Δ is the Laplace operator.

It can be seen from equation [6] that the partial derivatives of T(x, y, z) are expressed in terms of the change in the geothermal gradient $\Gamma_{av}(x, y)$ and the interval $\Delta\Gamma(x, y)$, which are related to the known depth of occurrence $h_{\Phi}(x, y)$ in equations [1] to [4]. Thus the integral-differential equation [7] can be solved in relation to the function $\xi(x, y, z)$. This was done on the Minsk-22 electronic computer, using a specially prepared program (1). The resulting values obtained for $\xi(x, y, z)$ were substituted into equation [6] and the values of T(x, y, z) at the nodes of a network of squares 10 km on a side, at a series of fixed hypsometric levels from 0 to 3500 m.

The result of this study was a series of geothermal maps for the horizontal sections of -500 m, -1000 m, -2000 m and -3000 m, as well as maps showing the distribution of temperatures at the surfaces of the Lower to Middle Jurassic and the Lower Cretaceous oil-producing complexes.

Analysis of the geothermal maps by horizontal sections shows that the values of the Aral-Caspian region's geothermal field are, in general, directly related to the depth of the basement's occurrence (the relative anomalies of the geothermal field correspond to elevated or depressed blocks of the basement). But there are also exceptions to this rule. For example, in certain structures (the Khoroy, Arstanovskaya, Zhetybay, Tenge, Kokumbay, and others), the relative temperature values are higher than in the adjacent areas, although the basement within these structures is at

---

[1] Values of the constant coefficients in equations [1]-[4] were computed by the standard methods on the basis of least squares.

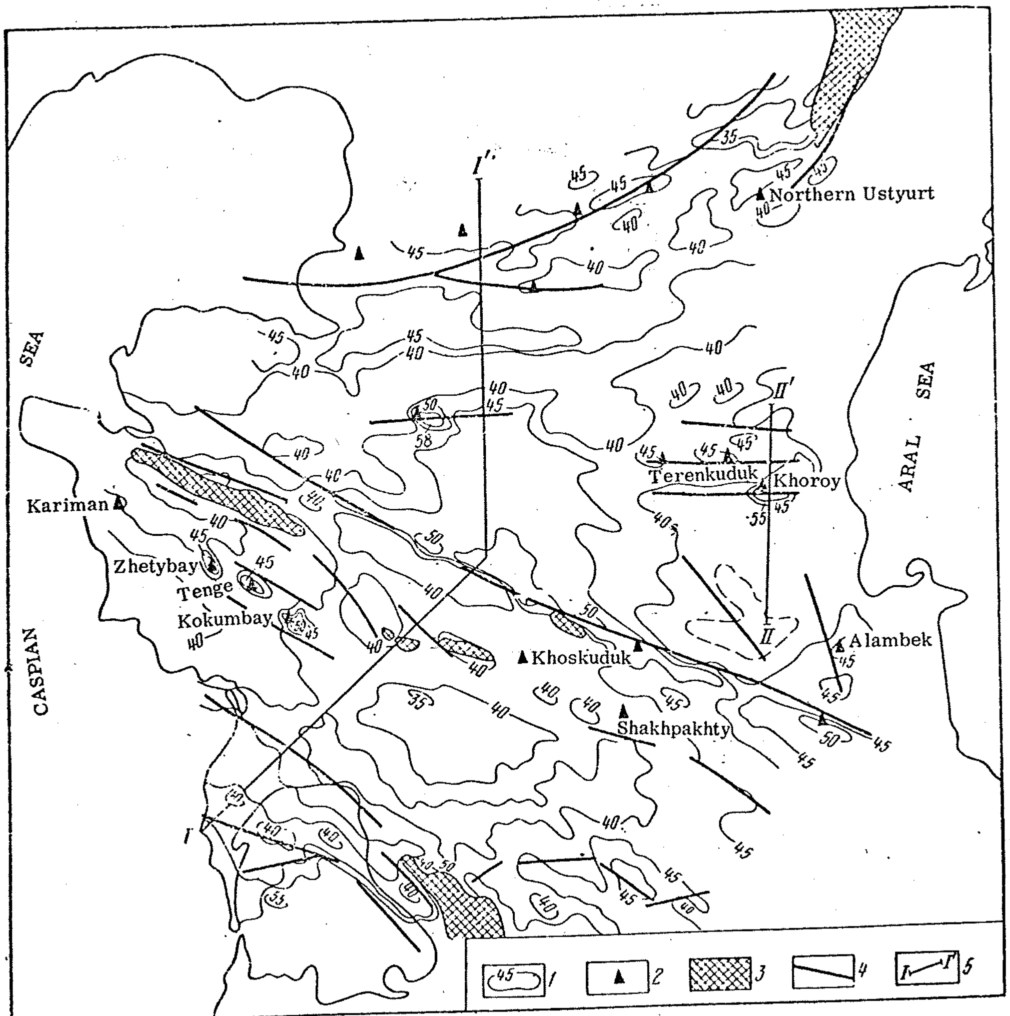
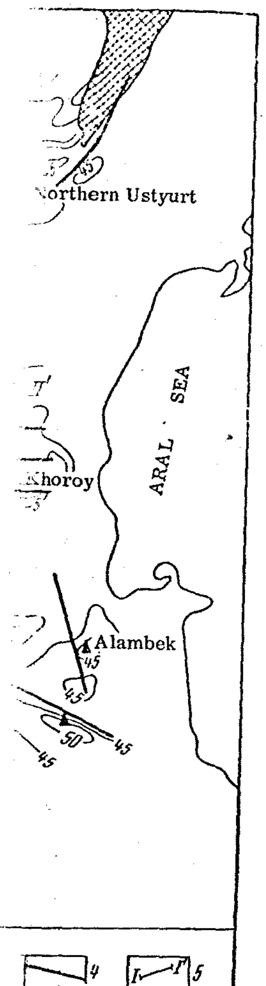


FIGURE 3. Sketch showing expressions of regional faults in the geothermal field of the area between the Aral and Caspian Seas at the – 1000 m level:

1) lines of equal temperatures (isotherms), 2) points at which temperatures were measured in wells, 3) intersection of plane of horizontal section with surface of Permo-Triassic, 4) regional faults, 5) lines of profiles.

greater depth than in the adjacent areas (fig. 3). The deviations obtained were checked by direct geothermal measurements in wells drilled in fault zones. In our opinion these can be explained by the effect of regional faults in the basement which, penetrating into the lower layers of the earth's crust, create favorable conditions for heat flow from depth into the sedimentary mantle. It is along such faults that the geothermal anomalies arise. The character of the anomalies is directly related to the regime of development of the regional faults in the platform stage. According to the prevailing ideas concerning the development of faults in the Turanian plate, four main categories of faults can be distinguished: faults not penetrating into the sedimentary mantle, faults partly penetrating the sedimentary mantle, faults of continuous development and reactivated faults (2).

The faults of the first category were formed in the pre-platform stage of the plate's development. The formation of the faults partly penetrating the sedimentary mantle was confined to the initial phase of platform development (Permo-Triassic and Jurassic). The faults of continuous development were active throughout the whole platform history of the region and were characterized by gradual weakening of their activity from the Permo-Triassic to the Neogene-Anthropogene. The



...ea between the Aral and

...n wells, 3) intersection
... lines of profiles.

...nto the sedimentary
...enetrating the sedimen-
...continuous development
...2).

...rst category were
...orm stage of the plate's
...nation of the faults
...sedimentary mantle was
...hase of platform devel-
...ic and Jurassic). The
...elopment were active
...atform history of the
...terized by gradual
...ity from the Permo-
...-Anthropogene. The

reactivated faults developed in three phases: a first active phase (Permo-Triassic, Jurassic), a second passive (Cretaceous, Paleogene) phase and a third phase (end of the Paleogene to the beginning of the Neogene) marked by a sharp renewal of the faults' activity, expressed in differential movements of the basement blocks along the faults and in the formation of large ruptures in the sedimentary mantle.

These differences in the regime of development of the regional faults have substantially affected the character of the Turanian plate's geothermal field, as may be seen from the geothermal map of the Aral-Caspian region along the -1000 m horizontal section (see fig. 3). Analysis of this map shows that the regional faults are expressed in the geothermal field in the following forms: sudden rises in temperature, chains of local relative anomalies and distinctive clear boundaries between different areas of the geothermal field.

Sudden rises of temperature are characteristic of reactivated faults. The most typical in this respect is the Central Ustyurt fault, which was active in the pre-Middle Miocene epoch of tectonic reactivation. On the geothermal map at the -1000 m horizontal section, it is marked by a rise of the temperature from +40° to +50° C. The geothermal anomaly along this fault is sharply linear. The geothermal field has the same character within the range of this fault's action on the maps for the -3000 m, -2000 m and -500 m horizontal sections; the sudden rises of temperature here are 10°, 6° and 15° C respectively.

The confinement of the stable linear geothermal anomalies to reactivated faults can be explained by the intensive activity of these faults, which rupture the whole sedimentary mantle and thereby create paths for the movement of heat flow.

The chains of local relative anomalies as a rule correspond to regional faults of continuous development. Relative geothermal anomalies oriented along their strikes are recorded along such faults. Thus, for example, along the Zhetybay-Uzen fault are the local anomalies found in the Zhetybay, Tenge, Kokumbay and other structures. The temperatures at the -1000 m horizontal section here increase to +55° C. In the adjoining areas of the Beke-Bashkuduk arch and the Southern Magyshlak basin, the temperature does not exceed +45° C. Another chain of geothermal anomalies is recorded in the zone of action of the Arstanovskaya fault, where the temperature rises to +55° C in the structure of the same name (see fig. 3). This character of the thermal field is due to the fact that the intensity of the faults of continuous development diminishes upward, so that the degree of rupturing of the higher strata is less than that of the lower, and the heat flow is partially blocked by the upper part of the sedimentary mantle, "breaking through" only at the points of greatest fracturing and rupture of the strata. In the geothermal field along the higher horizontal sections (-1000 m, -500 m) this is manifested as chains of geothermal anomalies, in contrast to the unbroken linear stable anomalies created by the reactivated faults.

The area of the Aktumsuk group of uplifts is of special interest. The geothermal map for the -1000 m horizontal section in this area shows two linear anomalies: the first incorporates the Bayterek and Terenkuduk anomalous areas, and the second consists of the Khoroy area (see fig. 3). These sublinear areas are oriented submeridionally, corresponding to the Southern Aktumsuk and Khoroy regional faults in the basement. Within the first area, which corresponds to the Southern Aktumsuk fault, the temperature values reach +45° C and the depths to the (pre-Permian) basement are 2.5-3.0 km. The second area, corresponding to the Khoroy fault, is characterized by temperature up to +55° C, whereas the pre-Permian basement here, according to the geophysical data, lies at depths of 5-6 km. This deviation from the general rule of rising temperatures as the basement approaches the earth's surface can, we believe, be explained once again by the difference in the regime of development of the faults.

The Southern Aktumsuk fault, which belongs to the category of faults partly penetrating the sedimentary mantle, is less active than the Khoroy fault of continuous development. Hence the latter, which appeared in post-Jurassic time, when the activity of the Southern Aktumsuk fault was dying out, created favorable conditions for more intensive heat flow from depth into the upper layers of the sedimentary mantle. A similar picture can likewise be seen on the geothermal map for the -500 m horizontal section. The temperatures here in the first area change from +30° to +35° C, and in the second area amount to +45° C. The geothermal maps for the -2000 m and -3000 m sections show a leveling-out of the temperature values in both areas, where they are respectively equal to +70° and +100° C.

On the geothermal maps for the -1000 m and -500 m horizontal sections, the local anomalies confined to the Khoroy fault are far more distinctly expressed than the anomalies on the geothermal maps for the -2000 m and -3000 m sections, thus clearly recording a successive increase in temperatures from below upward. This is evidently due to the increased density of the heat flow at the base of the sedimentary mantle approaching the basement, leading to a general increase in the background of the geothermal field, against which the contrast of the rise in temperatures along a regional fault is reduced. The upper layers of the sedimentary mantle (the -1000 m and -500 m horizontal sections) show a sharp drop in the background values of the geothermal

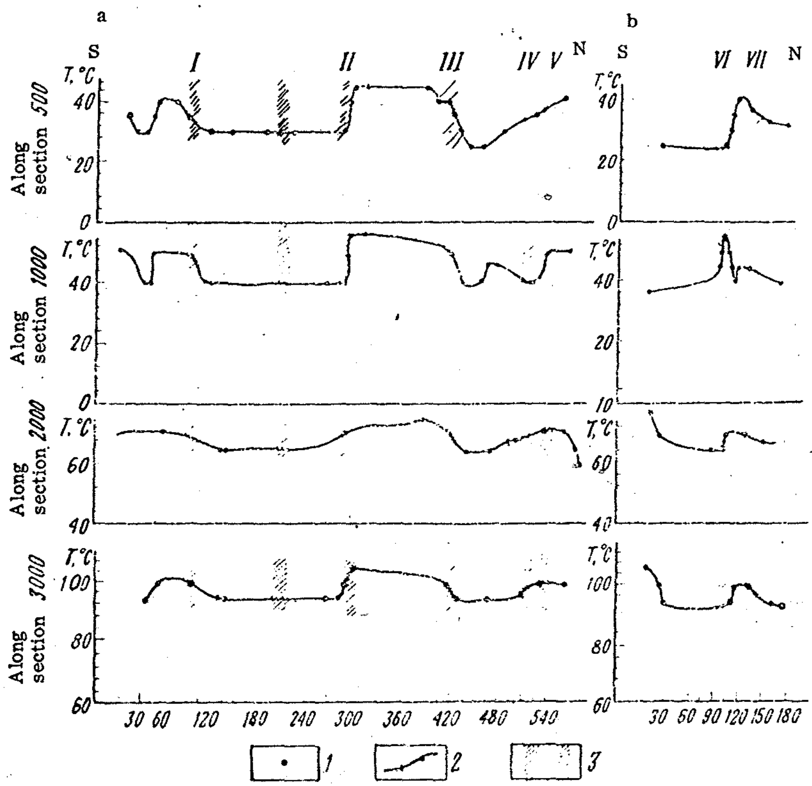


FIGURE 4. Geothermal profiles along the lines I - I' (a) and II - II' (b):

1) datum points, 2) lines of profiles, 3) zones of faults. I) Northern Karabogaz fault of continuous development; II) Central Ustyurt reactivated fault; III) Arstanovskaya fault of continuous development; IV) Mynsualmas fault, partly penetrating into sedimentary mantle; V) Southern Emba fault, not penetrating into mantle; VI) Khoroy fault of continuous development; VII) Southern Aktumsuk fault, partly penetrating into sedimentary mantle.

field as a result of the appearance of new thermo-insulating bodies, and only in the zone of a fault are favorable conditions maintained for the flow of heat from depth; this likewise determines the presence of distinct local anomalies within the sphere of action of the Khoroy and other faults of continuous development.

On the basis of the example just considered, one may conclude that regional faults considerably influence the character of the geothermal field, creating anomalous areas even when the basement — the main source of the heat flow — lies at considerable depth.

The regional faults of the basement sometimes act as distinctive boundaries between parts of the geothermal field with different background values. As a rule there are faults of continuous development bordering major areas. To this category belongs the Karabogaz-Karakumy fault, which separates the Aral-Caspian and Karabogaz-Karakumy regions of the Turanian plate. On the geothermal map for the -1000 m horizontal section there is a marked difference in character between the geothermal fields of these two regions. The former (Aral-Caspian) region shows a predominance of relatively low temperature values (+35° - +40° C), and the geothermal anomalies have diffuse outlines in plan. Toward the Karabogaz-Karakumy region the orientation of the anomalies changes from northwest to northeast; the temperature values rise to the +50° to +55° C level, indicating that the basement is closer to the surface.

The regional faults of the basement, depending on their regime of development, are differently expressed not only in the areal but also the vertical distribution of the geothermal field. To ascertain these distinctive features, two profiles were drawn along the geothermal maps for the -3000 m, -2000 m, -1000 m and -500 m horizontal sections, with graphs of the relationship between the increase in

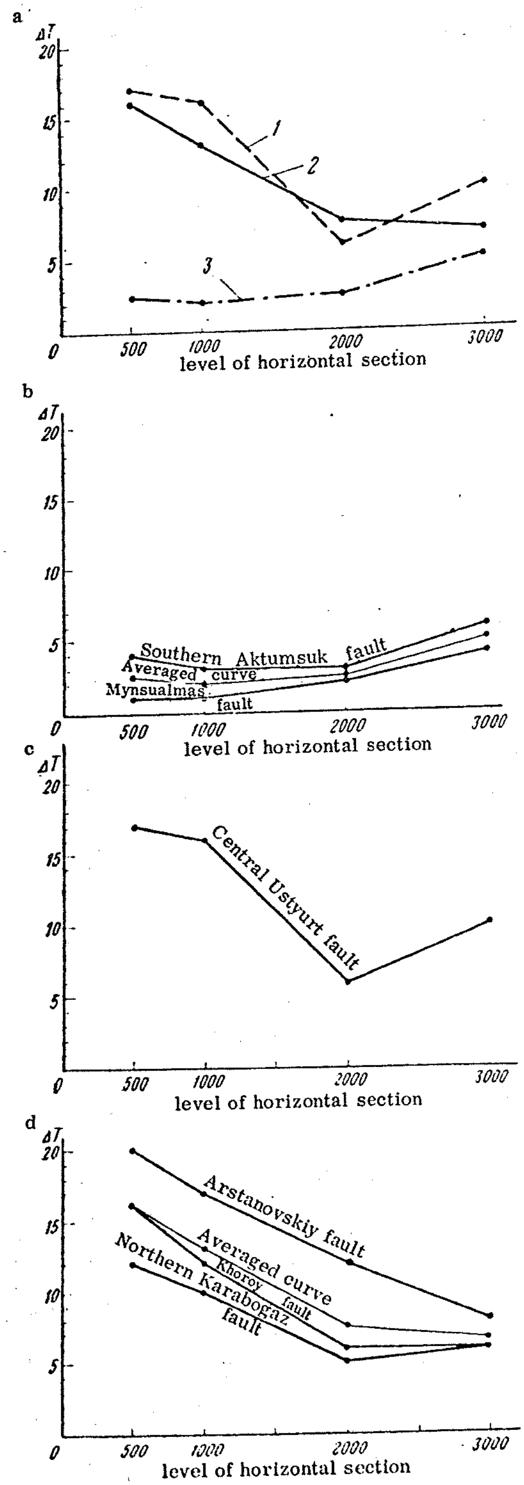


FIGURE 5. Graphs of relationship between increase in temperature and level of horizontal section in near-fault zones of Aral-Caspian region:

a) present time: 1 - curve for reactivated faults, 2 - same for faults of continuous development, 3 - same for faults partly penetrating into sedimentary mantle; b) faults partly penetrating into sedimentary mantle; c) reactivated faults; d) faults of continuous development.

temperature and the depth of the horizontal section (figs. 4, 5).

The first profile runs from the shore of the Caspian Sea (the Karabogaz bar) through the Central Ustyurt area and beyond it northward as far as the Southern Emba deformations; the second intersects the Aktumsuk group of uplifts from south to north. The reactivated faults and faults of continuous development are most persistently reflected in the profiles. In all the horizontal sections these are marked by sudden rises of temperature, these being more prominent at the reactivated than at the continuously developing faults. Sharp steps on the geothermal profiles correspond to the Central Ustyurt reactivated fault in all the horizontal sections. An increase in the geothermal field can be seen within the whole of the Central Ustyurt horst uplift, which corresponds to a major deep-seated fault in the earth's crust. In the geothermal field the whole zone constitutes a single anomalous belt, whose boundaries coincide with the regional faults bordering it. The temperature leap within the zone of this fault increases as depth to the horizontal section decreases: in the -3000 m section it is 10° C, at -2000 m it is 6° C, at -1000 m it is 10° C and at -500 m it is 15° C (fig. 4). The increasing contrast of the rise in temperature may perhaps result from the increasing thickness of the thermo-insulating bodies in depressed areas.

The faults of continuous development are also characterized by sudden rises of temperature with depth. For the Arstanovskiy fault, for example, the temperature change is: 6° C at -3000 m, 10° C at -2000 m, 12° C at -1000 m and 16° C at -500 m. In the case of the Northern Karabogaz fault, these respective values at the corresponding depths are: 6°, 10°, 12° and 15° C (see fig. 4).

The most weakly reflected in the geothermal field are the faults that only partly penetrate or do not penetrate the sedimentary mantle. Thus the Mynsualmas and Southern Aktumsuk faults, which penetrate from the basement part way into the sedimentary mantle, are characterized by the following increases in temperature at the respective horizontal sections (from bottom up): 4°, 3°, 2° and 2° C (see fig. 4).

Thus the faults penetrating partly into the sedimentary mantle have the most distinct sudden rises in temperature in the lower horizontal sections (-3000 m and -2000 m), but are virtually not recorded at all in the higher sections.

The faults not entering the sedimentary mantle have no clear reflections in the geothermal field, as exemplified by the Southern Emba regional fault, which separates the Precambrian Russian platform from the epi-Paleozoic Turanian plate. The -3000 m, -2000 m and -500 m sections show no sudden increase in temperature; only in the -1000 m section is the fault marked by a fairly sharp (by 8° C) rise of temperature (see fig. 4).

The behavior of the Gornyy Mangyshlak area's faults within the geothermal field of the Aral-Caspian region is particularly noteworthy (the Northern and Southern Karatau, the Northern Bekebashkuduk, the Tumgachin, the Karashek faults and others). None of these are reflected in the geothermal field, against the background of its relatively low values (see fig. 4). This can be attributed to two causes: first, the presence of a thick body of Permo-Triassic rocks serving as a distinctive thermo-insulator on the path of the heat flow from depth; second, the fact that the faults in the Gornyy Mangyshlak area probably do not penetrate far into the pre-Permian complex and thus do not expose the horizons from which the heat comes.

For the same reasons, apparently, such faults of continuous development as the Shakhpakhty and Eastern Yarkimbay are relatively weakly reflected in the geothermal field of the region under study.

Thus a study of the manner in which the regional faults are expressed in the geothermal field of young platforms can reveal the regime of their development. This is very clearly illustrated by the graphs of the relationship between the temperature increments (ΔT) and the depth of the section (fig. 5). The temperature increments in the different horizontal sections within the sphere of action of faults of one category or another will likewise differ. Thus the faults of continuous development are characterized by gradual rise in the magnitude of the temperature increments from the -3000 m to the -500 m sections; the reactivated faults also follow this rule, but the temperature increments rise not evenly but with a relative drop at the -2000 m level; the faults penetrating partly into the sedimentary mantle are characterized by the reverse relationship: the amount of the temperature increment diminishes from the lower horizontal sections to the higher (see fig. 5).

Our analysis of the geothermal maps of the Aral-Caspian region shows that sharply higher stratal temperatures, reaching 15 - 20° C, exist within the areas affected by the faults of continuous development and the reactivated faults. Such a sharp change in the temperature regime of a stratum evidently creates favorable conditions for the vertical migration of hydrocarbons, especially liquid hydrocarbons.

The mobility of oil and gas condensate evidently increases with a rise in temperature and they become capable of more readily penetrating into the upper layers of the section. In addition, high stratal temperatures in the fault zones may also promote oil- and gas-forming processes. In view of the subsequent negative effect of the reactivated faults on the formation of oil and gas bodies (2), these should be excluded from the category of structures with promising oil and gas potential. The increased density of the heat flow in the zones of faults of continuous development raises the temperature of the buried organic matter, promoting its regeneration into hydrocarbons and their subsequent vertical and partly also lateral migration. Thus the continuously developing faults, by creating areas of anomalously high stratal temperatures, promote the processes of oil and gas formation and accumulation within the areas of their influence.

Our analysis of the expression of the regional basement faults in the geothermal field of the Aral-Caspian region of the Turanian plate suggests the following main conclusions:

1. Regional faults in the basement of young platforms affect the geothermal field.

2. The character of this effect is determined by the regime of the fault's development:

— reactivated faults are clearly marked by linear zonal anomalies with sudden rises of temperature in the fault zone, the degree of contrast of the rise increasing in the higher sections (-1000 m, -500 m), probably owing to the accumulation of thermo-insulating deposits in the depressed blocks of the basement;

— faults of continuous development are no less clearly reflected in the geothermal field in the form of chains of local anomalies or boundaries between zones of the geothermal field with different background values (this category of faults can be steadily traced in all the horizontal sections by the sudden rises in temperature);

— faults partly penetrating into the sedimentary mantle are far more weakly reflected in the geothermal field, and in the deeper horizontal sections (-3000 m, -2000 m) they have more contrast than in the higher (-1000 m, -500 m);

— faults not penetrating into the sedimentary mantle have practically no reflection in the geothermal field.

3. Regional basement faults in areas of thick deposits of the Permo-Triassic complex are only weakly or not at all reflected in the geothermal field.

4. Regional faults of continuous development diverge from the general regular increase in temperature values in areas where the basement lies at smaller depths. They create intensive local geothermal anomalies even if the basement is at greater depth than in the adjoining areas; in the higher horizontal sections (-1000 m, -500 m) the local anomalies are more distinct than in the lower (-2000 m, -3000 m), since near the base of the sedimentary mantle the background effect of the density of heat flow from the basement has a greater effect.

5. By drawing and analyzing geothermal maps for different horizontal sections, one can map the regional faults in the basement of young platforms and study their distinctive regime of development.

6. The anomalously high stratal temperatures that arise in the areas affected by regional faults in the basement, particularly faults of continuous development, promote the regeneration of organic matter into hydrocarbons of the oil series, increase the mobility of the fluids and thereby accelerate the lateral and especially the vertical migration of oil and gas.

REFERENCES

1. Arabadzhi, M.S., et al., 1968, DISTINCTIVE GEOTHERMAL ASPECTS OF THE FORMATION OF OIL AND GAS BODIES IN THE ARAL-CASPIAN REGION. In THEMATIC SCIENTIFIC-TECHNICAL SURVEY, "OIL AND GAS GEOLOGY AND GEOPHYSICS" SERIES: VNIIOENG.

2. Gavrilov, V.P., 1970, EXPLORATION AND PROSPECTING OF OIL AND GAS DEPOSITS IN THE NEAR-FAULT ZONES OF YOUNG PLATFORMS. In THEMATIC SCIENTIFIC-TECHNICAL SURVEY, "OIL AND GAS GEOLOGY AND GEOPHYSICS" SERIES: VNIIOENG.

3. D'yakonov, D.I., 1960, GEOTHERMY IN REGIONAL GEOLOGY AND STUDY OF TECTONICS AT DEPTH: Geologiya Nefti i Gaza, no. 11.

4. Lyubimova, Ye.A., 1968, THERMAL FEATURES OF THE EARTH AND MOON: Inst. Fiz. Zemli, Izd-vo Nauka, Moscow.