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# Geothermal conditions of hydrocarbon formation in the South Caspian basin

Vagif Kerimov<sup>1</sup>, Michael Rachinsky<sup>1</sup>, Rustam Mustaev\*<sup>1</sup>, Uliana Serikova

*1. Department of geology and exploration of hydrocarbon deposits, Russian State Geological Prospecting University*

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## Abstract

The geotemperature factor of the subsurface is among the important reasons for defining hydrocarbon generation conditions, which characterize migration processes and the accumulation of oil and gas in sedimentary rocks. It also has an application aspect, which is very important for potential oil and gas forecasts and the selection of exploration plays. It provides a practical capability to use the data of disruptions in the regional and local geotemperature field for tracking hydrocarbon migration paths, determining discharge zones, areas and foci of geo-fluid-dynamic systems. This is one reason why temperature conditions in the geologic section of oil and gas regions, areas, zones and prospects may be weighty arguments in oil and gas exploration. The study results may benefit planning and conducting exploratory operations in other basins of mobile belts, similar to the studied ones in their tectonotype.

**Keywords:** South Caspian basin, Geotemperature regime, Oil and Gas field, Local structures, Basin modelling, Earth's depth heat

## 1. Introduction

It is very difficult to objectively estimate the present-day thermal regime at great depth intervals not studied in wells. This is due to mistakes in the admission regarding the values of thermophysical parameters in porous media and in the solutions of complex heat conductivity equation systems. The application of such temperature forecast techniques results in a difference of tens and even hundreds of degrees in the temperature values estimated by different scientists for various deep stratigraphic surfaces and depth subcrops. One example is the South Caspian Basin (SCB). There, Geodekian estimated a temperature at a depth of 30 km of 525°C (Geodekian 1968).

Such discrepancies occur when extrapolating actual temperature values in the deepest wells for ultra-depths. Two conditions should be met for such assessments. First, it is necessary to determine and substantiate the acceptable depth range of the forecast. Second, it is necessary to correctly select the extrapolation function. This technique is only acceptable for the temperature estimates within a relatively narrow depth interval and within a single stratigraphic complex, where thermophysical properties are reasonably consistent laterally and down the section. For the SCB, it means that within the PT-KT range, such extrapolation is justified only within this complex in compliance with the general temperature trend between its top and base, where actual observations are available. The same approach should be considered for forecasting within the Miocene–Paleogene and Mesozoic sediments.

The utilization of the “temperature vs. depth” function pertaining to the uppermost stratigraphic unit for the entire underlying section is absolutely unacceptable.

We performed a systematization and statistical analysis of large amounts of data. The database includes over 10,000 temperature measurements in long-shut-in wells, over 200 fields, and materials on the geology of local structures. These data have been partially borrowed from referenced publications, field data, and books and articles (Carlson 1930, Borger 1952, Mekhtiyev and Rachinsky 1967, Guliyev and Kadirov 2000, Aliyeva 2003, Dmirtiyevsky and Volodin 2006, Förster et al. 2016, Kerimov et al. 2014a, 2014b, 2015a, 2015b, 2016a, 2016b, 2016c, Guliyev et al. 2016).

## 2. Materials and Methods

A basin analysis has been conducted using the software package and sedimentary basin modelling techniques by *PetroMod*, a *Schlumberger* company. This technique is a major strategic tool for evaluating the risks of exploratory operations and the support means of the decision-making in oil- and gas-producing companies.

The authors proposed a cardinal new technique for the estimation of geotemperature at great depths not covered by the well thermometry, to study the geologic environment of the SCB. The technique eliminates the previously identified errors. This is the way the geotemperature is forecast for deep stratigraphic and physical levels.

The actual temperature at the base of the PT-KT is built-up using the temperature gradients of the standard correlation,  $t = f(H)$ , for the Miocene–Paleogene within the depth range of its actual presence in the section of a

\*Corresponding author.

E-mail address (es): [r.mustaev@mail.ru](mailto:r.mustaev@mail.ru)

local structure. Once obtained this way, the temperature at its base is built-up using the temperature gradients of the standard correlation for the Mesozoic through its entire range, down to the surface of the crystalline basement (Kerimov and Rachinsky 1989). This temperature estimation technique indirectly takes into account the real variations of thermophysical parameters of the entire forecasted sedimentary section. The reason is that the temperature gradient (the rate of geotemperature change with depth) is included in latent form and determines specific parameter values of the correlations “temperature vs. depth” and “geotemperature gradient vs. depth”.

For the calibrating correlation of “temperature gradients vs. depth”, for the Mesozoic interval in the Azerbaijan portion of the SCB, the data are taken for prospects over the SE plunge in the central zone of the Caucasus Major meganticlinorium. In the central zone, these prospects are Keshchay, Begimdagh, Sovetabad, Sitalchay and Gyadysu. In the North-Apsheron offshore zone of the highs, the prospects are Dva Brata Rocks, Tsurypa Bank, Apsheron Bank, Gilavar, Khazri and Nakhichevan prospects. The penetrated thickness that the complex reaches there is 5.5 km in some cases, such as at the Sovetabad prospect. The  $G_{mz}^t = f(H)$  correlation is actually  $G_{mz}^t = 5.5522 \cdot H^{-0.13375}$ . For the Turkmenistan part of the basin, the data for the complex are available from the Karadepe, Kumdagh and Boyadagh prospects; and the actual correlation is  $G_{mz}^t = 6.2111 \cdot H^{-0.1494}$ .

The Paleogene-Miocene interval in the Azerbaijan portion is collected at the Kobystan prospects of Umbaki and Adjiveli, in the Apsheron Peninsula prospects of Shorbulag and Zigilpiri, and at prospects in the North-Apsheron zone of highs, such as Tsurupa Bank, Dva Brata Rocks, Apsheron Bank, Gilavar, Khazri and Nakhichevansky. The correlation is  $G_{pg-mi}^t = 6.1678 \cdot H^{-0.1542}$ ; for the Turkmenistan portion at Karadepe, and for Kumdagh and Boyadagh, the same correlation is  $G_{pg-mi}^t = 32.3725 \cdot H^{-0.398}$ .

The material composition and the thermophysical properties of the Mesozoic and Paleogene-Miocene rocks do not vary much over a large portion of the SCB (Renz et al. 1989). That is why it is deemed legitimate to also use the quoted “geotemperature gradient vs. depth” correlations as the standard for other areas of the region. There is no need to use the temperature gradients to calculate the temperature for the PT-KT of the basin, as there are reliable direct temperature vs. depth correlations for the depth range from 0.05 to 8.0 km. For the Azerbaijan portion of the region, this correlation is  $t_{PS} = 13.7 + 0.149 \cdot H^{0.716}$  and for the Turkmenistan portion,  $t_{RS} = 13.7 + 0.488 \cdot H^{0.607}$ .

The differentiation between regions, in the indicated geotectonic attribute, is causally associated with the

elevated heat activity in the eugeosynclinal zones, caused mostly by thermal effects of Cenozoic and recent volcanism. The temperature correlation of subcrops vs. sediment thickness is indirect. This is a result of heat field distortion progressing with the growth in the deposition rate, shown by hysteresis in the deposits' conductive heating relative to their accumulation. This effect is determined by a nonstationary geotemperature field distribution in the regions of intense recent subsidence and causes a heat flow and therefore a temperature distortion of 15-20% decrease compared with stationary conditions.

There is no contradiction between the actual data and the functional correlation of formation temperature, from subcrops vs. closeness to the surface of basement rocks, heated by the depth generation heat. In this case, the heating of the sections correlates with the depth to the basement. Wherever they are close to the surface, the conductive depth heat transfer into the upper intervals of the sediment fill occurs with a much lower dissipation compared to the regions with thicker sediment. This concept establishes the correlation between the section's heating and the basement surface topography, between heat-conductive and heat-insulating intervals.

Shielding of the depth heat-flow by clayey sequences causes relative overheating of the underlying section and a bounce in the geotemperature gradients. It may drastically increase within undercompacted or decompacted clay, as it varies in direct proportion with their degree of water-saturation and thickness. In the Alpine folded belt regions, such a trend geologically follows the preservation of primary, or with the formation of secondary, high porosity-decreased density-elevated clay wetness at low depth levels (Smirnov 1972, Salle and Debizer 1976). In the former case, this is causally related to the lag of the pore-water outflow from the deposit subsidence rate in the process of rapid permanent immersion, and in the latter case with the volume increase of the clay matrix up to its dehydration. Both mechanisms result in the generation of pore volume of abnormally high fluid pressures (AHFP) or abnormally high pore pressures (AHPP) in clayey sequences. They are functionally and spatially associated with intervals of preservation and new-formation and development of elevated water-saturation-porosity zones in clays. This is a statement of an indirect connection between the AHPP and the geotemperature regime of the deep subsurface. This explains the noticeable increase in temperature and the decrease in its gradients within reservoir members underneath thick clay fluid barriers with close-to-geostatic abnormal pressure.

Changes in the thickness, water content and areal extent of clay massive massifs affect the heat flow due to the action of two independent factors. One of them occurs in connection with boundary conditions along the contact of rocks with different heat conductivity.

Distortions of heat flow lines at the intersection of such boundaries are determined by the bed geometry and their heat-conductivity. The other one results from the change in heat conductivity of a sequence as affected by differences in the pore water content. Natural geotemperature conditions tend towards equilibrium, so the temperature underneath a thermal barrier must be high enough in order to provide heat flow through a bed; this temperature would be equal to the regional average. That is why the temperature observed at any depth is a direct function of rock heat conductivity in the entire overlying sequence (Jones 1975, Powers 1976, Pelet 1985).

The heat accumulated in a reservoir underneath a clay sequence with AHPP can be conserved for a long period of geologic time, practically until the moment of pore pressure relaxation and total clay conversion into argillite. This happens due to the thermo-insulating effect of the seal and the insubstantial outflow of compressed fluids. The thickness and porosity of clay, pore fluid loss rate by the clay, extent of thermal rock alteration, and areal extent of the reservoir affect the maximum generated temperature along with its lithology and time. The sedimentary sequences containing swelling clay varieties are subject to endothermic thermal metamorphism, which is an additional factor limiting the intensity of heat transfer upsection and decreasing the amount of heat transferred to the upper intervals.

Examples of this kind include the SCB, which includes an extremely thick montmorillonite clay sequence and depressed temperature regime; the Kerch and Taman regions in the Indolo-Kuban trough, where the thickness of the Maikopian Formation of Oligocene-Miocene age is composed of swelling clays reaching 3,000 m and greater; and the folded belt on the north coast of the Gulf of Mexico, its upper portion of the sedimentary section composed of Cenozoic montmorillonite clays, 3,000–4,000 m thick. The clay alteration influence on the geotemperature regime manifests itself in interval temperature variations over the entire interval of dehydration processes. As soon as this process is completed, the clay members begin behaving as usual thermal insulators. The halogen sequences are a factor of opposite directionality, facilitating the dissipation of the depth heat due to the high heat conductivity of salts. This mechanism manifests as a decrease in the formation temperature in the subsalt sediments and an increase in temperature gradients.

The effect of deeply-buried evaporite intervals on the geothermal regime of the subsurface is contrastingly displayed when comparing the vertical temperature distribution in the Indolo-Kuban trough, where salt-bearing sediments are absent, and in the Tersk-Caspian trough, where a thick Upper Jurassic salt sequence is encountered at a depth of over 5,500 m. In the former region, formation temperatures in the upper part of the section (to the -3,000 m subcrop) are 5–10°C lower than

in the latter, and at the same time are 18–25°C higher at depths between –6,500 and –7,000 m. The effect of the latter three mechanisms on the formation of geotemperature zoning is insufficiently studied and is a subject of controversy. These authors see their task in setting up the issue. A detailed review of the association between oil and gas occurrences and the geothermal component of the total geo-fluid-dynamic regime in the regions is best conducted using the SCB, which has been thoroughly studied. There, all correlations between hydrocarbon saturation and geothermal parameters have the most contrasting manifestation.

All over the basin, the geothermal parameters clearly correlate with structural parameters of local highs. These structural parameters are faults per unit area, structure steepness, surface geometry and PT-KT thickness. These also clearly correlate with geobaric parameters of the structures, such as formation and pore pressure abnormality factors, depth and thickness of AHFP and AHPP zones, and with hydrodynamic conditions of local structures, such as the depth of transition from hard water to alkaline, their distance from the PT-KT base, and the extent of the section's fill-up with alkaline varieties.

The convective component forms local positive geothermal anomalies against the regional conductive background. These anomalies are associated with hydrogeochemical, piezometric distortions of the respective fields and genetically are closely associated with the functioning of cross-flow mechanisms. They are concentrated in an environment where a set of geologic factors allows for the vertical hydraulic conductivity between the well-heated lower and the cooled upper section's intervals. Differential conductivity of fluid-conducting paths in different areas and parts of structures causes a mosaic pattern in their temperature field.

Moderate geothermal gradients in each area of the basin in the intervals of the main PT-KT productivity, combined with relatively high temperature at 1,000 m subcrop and normalized for the base of the complex and with relatively moderate AHFP baric gradients, indicate a geologic environment of relative temperature levelling in the vertical section of the structures. The maximum gradient values match an environment of very limited or absent water-exchange. Minimum gradient values match an environment of very intense fluid-mass transfer. This results in the impossibility of the preservation and the destruction of hydrocarbon accumulation in the areas where such a combination of the stated parameters is very contrasting.

### 3. Results

Analysis of the geothermal component of the SCB's total geofluid-dynamic field enables the following conclusion. The present-day geothermal regime of the region's sediment cover is controlled by the section's lithofacies composition in individual regions and by the

extent of local structure faulting and thermal ground water mobility conditions. It is formed, to a substantial extent, by the convective component of the total heat flow, which in turn results from the cross-flow processes that hydraulically join the lowermost and the upper stages of the basin's lithosphere.

The entire SCB represents a relatively weakly heated area with respect to geotemperatures. Analysis of the temperature distribution maps at various depth cut-offs (3,000; 6,000; 9,000; 12,000; 15,000; and 18,000 m – Fig 1) is based on the actual and calculated well data and models. It shows that temperature at a depth of 18 km does not exceed 400 °C; at a depth of 5 km in the area of Talysh Vandam field, it is around 130-140 °C; in the Pirsagat area at the same depth, it is 90 -100 °C.

Modelling indicates the existence of a few stratigraphically, hypsometrically and laterally separate fluid formation foci in the Mesozoic, Paleogene-Lower Miocene and diatomaceous sediments. It means that in the SCB, with its sediment cover reaching 32 km and low geothermal gradient, the fluid generation range is highly extended.

For the most subsided SCB portion, the oil and gas generation zone is “stretched” over 8-10 km with its upper limit at 10 km and lower limit at 18-20 km. The “oil” and “gas window” zone is so thick in the central SCB that it enables forecasting the involvement of the entire sedimentary complex in the fluid-generation zone. An important factor for the identification of the generative potential is the geotemperature regime of the subsurface. It defines the hydrocarbon (HC) generation conditions within the sedimentary sequence. The geotemperature condition results in the sections of oil and gas regions provide weighty arguments in resolving the questions of identifying the type, form and spatial orientation of fluid migration in the geologic medium and the specifics of the hydrodynamic and thermobaric environment in natural reservoirs.

The technique of basin modelling was used for the evaluation of the region's thermal history and the sedimentary complexes' oil and gas generation potential. Temperature data from wells in the Kyanizadag, Sangachal, Duvanny, Khara-Zirya and Bulla-Deniz fields were utilized. Based on these data, the actual geothermal gradient of the SCB structures was evaluated. The lowermost geothermal gradient was determined along the fields from Bulla-Deniz to Duvanny. Calibration was performed between the measured and simulated temperature in all control points, using the thermal history. The temperature distribution and calibration results are displayed in Figs. 1 and 2.

The forecast temperature gradient is lower in marine structures than on land. In the modelling of unsteady heat flow using HFU, the heat flow emanating from the basement or the base of the sediment cover was not identical with the surface heat flow. Modelling results

suggest that the SCB was at a state of thermal equilibrium prior to Pontian time, which was later disrupted. The paleo-heat flow early in the Mesozoic drastically declined in the period of the deposition of the productive sequence due to very rapid subsidence and deposition. Even at present, the disruption is substantially increasing the thermal equilibrium in the basin and on the offshore structures and forecasts a much lower geothermal gradient of the near-surface temperature compared with on land structures. The basin subsidence models are shown in Fig 2, with indications of lithology and temperature, at the subsidence of the basin where temperature reaches 300 °C at great depth.

As Fig. 3 demonstrates, the maximum heat conductivity values are found in the Lower Permian sediments of the Middle Caspian, which is due to the presence of salt with its elevated heat conductivity and minimum ones in the SCB. The rock maturity may be followed by vitrinite reflectance values. The current temperature distribution in the SCB indicates that temperature at a depth of 23 km reaches about 450 °C, and at a depth of 5 km in the Talysh-Vandam area, it is about 130-140 °C, while in the Pirsagat area, it is 90-100 °C. Under the SCB environment, in particular in the Lower Kura Depression and Baku Archipelago, this process is substantially delayed due to anomalously low values of the geothermal gradient (1.3–1.7 °C/100 m). There, temperature at a depth of 6,500 metres does not exceed 100-110 °C. The formation of metamorphogenic water solutions under such SCB subsurface thermal regime may be suggested to occur at depths of 20-25 km, where the temperature must reach 250 °C. In the northwestern and northern near-coastal parts of the basin, within the Shemakha-Gobustan and Absheron zones, the geothermal gradient is somewhat higher (2-2.2 °C/100 m). For this reason, the generation foci there are somewhat looser depth connected relative the axial and deeply subsided portions of the depression. Thus, according to a 3D basin model by D. Guseynov, the 120 °C isotherm on the Absheron Peninsula and adjacent offshore area of the Baku and Absheron archipelagos extends to the depth of the Maikop and diatomaceous complexes (Fig 4). This temperature zone is associated with the middle portion of the diatomaceous complex in the southern offshore zone, corresponds with depths around 8,000 m in the western South-Absheron Trough, and subsides to 9,000 m in the eastern portion of the trough. The Maikopian complex at these cut-offs is involved in the heating zone over a much greater area. In most subsided portions of western South Absheron Trough at the formation top, at a depth of about 9,200 m, temperature reaches 145-150 °C. At the formation bottom, at a depth of approximately 11,000 m, the temperature reaches 170 °C.



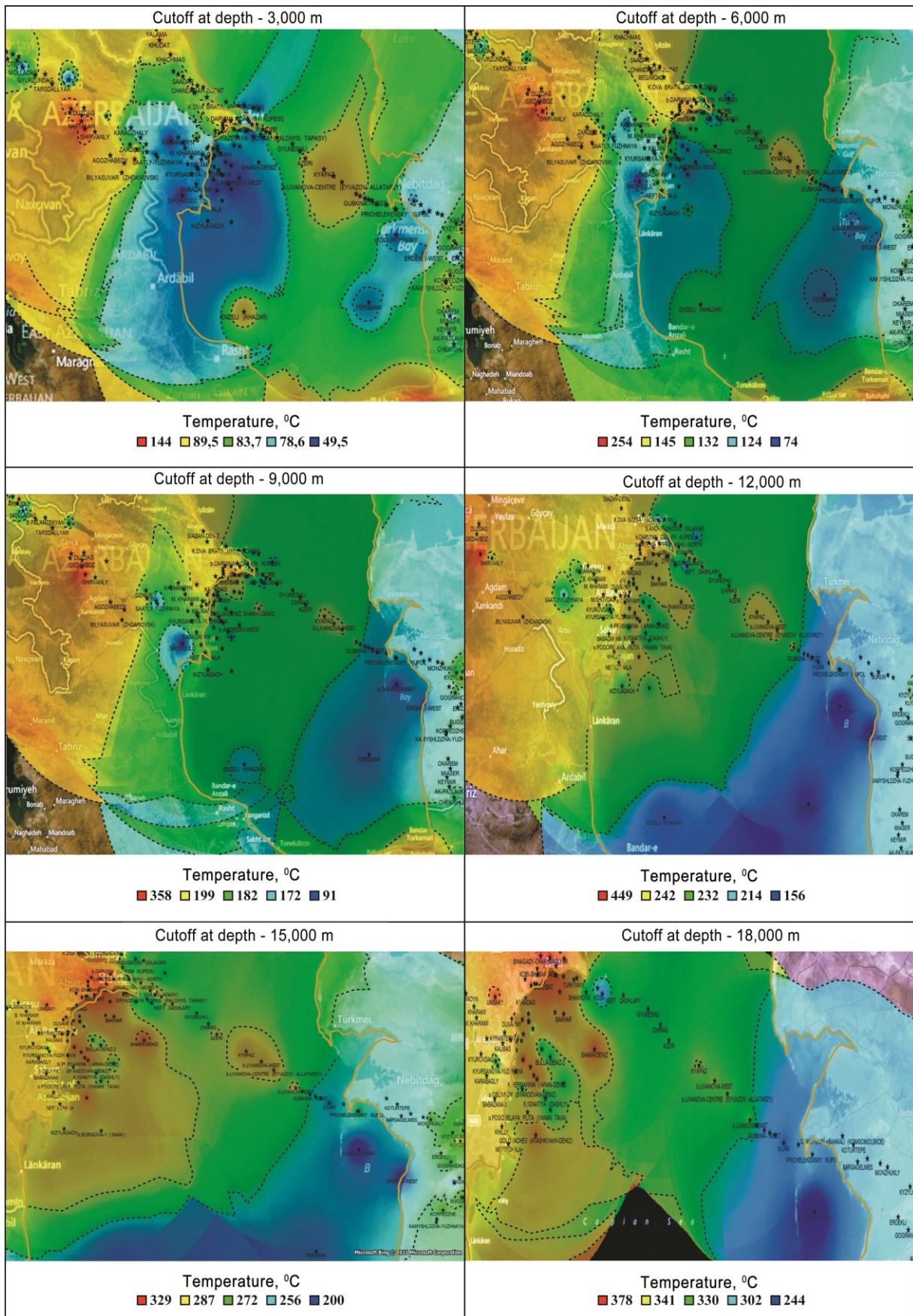


Fig 1. Temperature maps at present time with depth cut-offs (well-measured and calculated data).

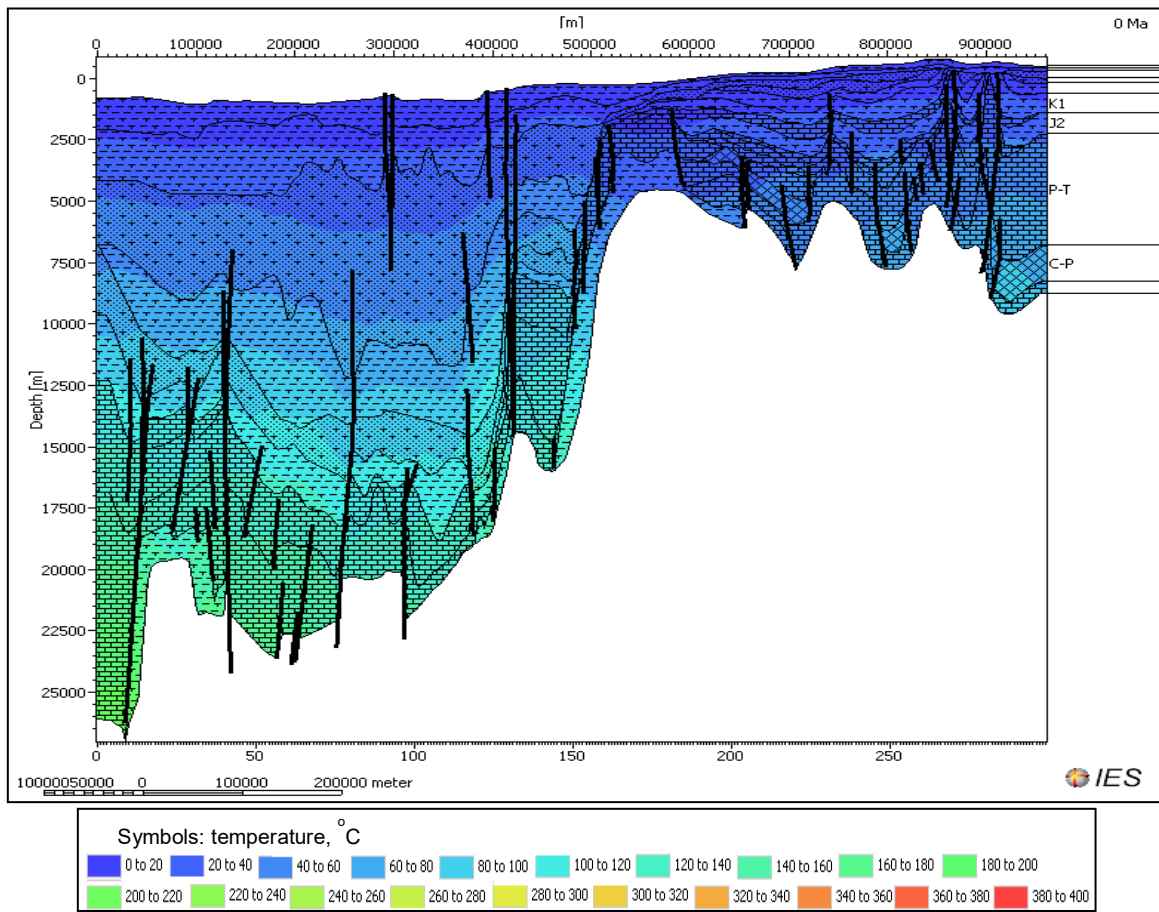


Fig 2. Evolution of the SCB geotemperature field.

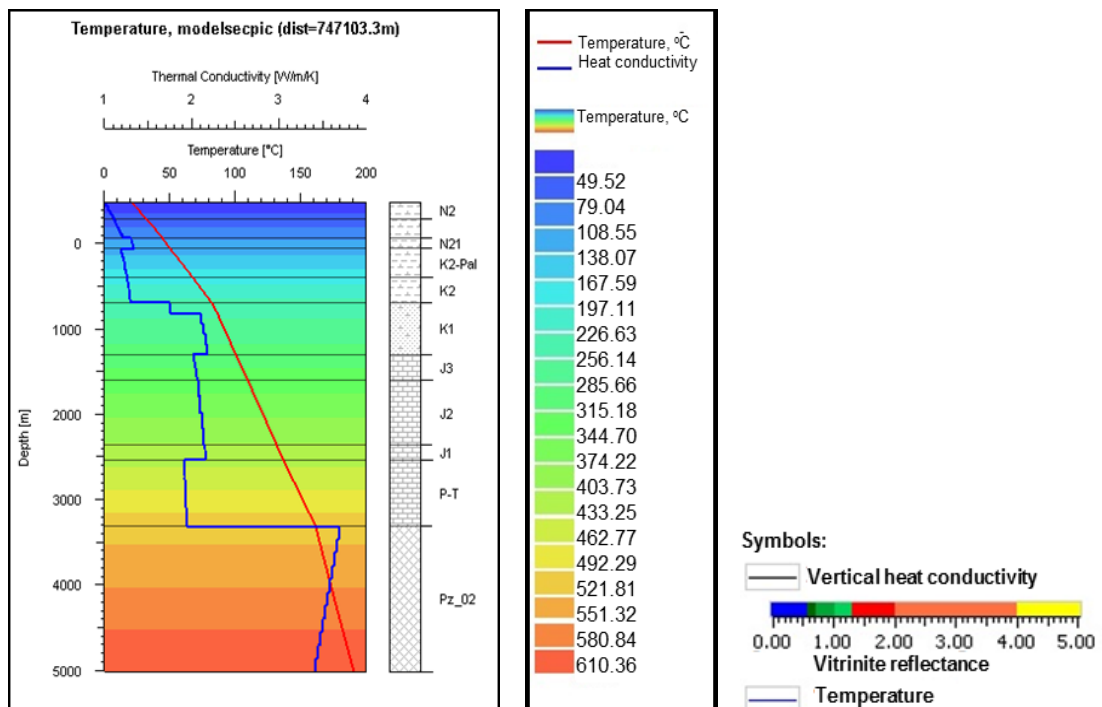


Fig 3. Temperature and heat conductivity vs. depth diagrams.

In the eastern portion of the trough at the top of Maikopian, at a depth of 10,500 m, the temperature is around 160 °C and at the bottom, at a depth of 12,000 m, it is over 180 °C. Models show that in the subsided areas of the South-Absheron Trough, the Paleogene complex has exhausted its dehydration water reserve and is, like its underlying sediments, at the stage of generating metamorphogenic water. The temperature area of 250 °C is positioned within the depth interval of 18,000-19,000 m in the Jurassic complex both in the western and eastern parts of the South Absheron Trough.

Using the proposed technique, the present-day physical and stratigraphic position of the 135 °C isotherm was estimated. This isotherm denotes the completion of the liquid oil generation process (mesocatagenesis substage - MC, gradation MC<sub>3</sub>). In the Lower Kura depression, it covers the Paleogene-Miocene complex at the 5.9-7.4 km depth interval. In the Alyat Ridge area, it covers the Paleogene-Miocene and 5.5-6.7 km. In Kobystan, it

covers the Paleogene-Miocene and 5.1-5.9 km; in the Baku Archipelago, the Paleogene-Miocene and 5.9-7.4 km; on the Apsheron Peninsula and the adjacent South Apsheron shelf, the Paleogene-Miocene and 4.1-7.6 km. In the Apsheron Archipelago and Apsheron subzone of the Apsheron-Balkhan Sill, it covers the Paleogene-Miocene and 5.0-7.5 km and the Mesozoic at 5.7-7.1 km. In the Balkhan zone of highs, it covers the Mesozoic and 5.5-7.9 km; and in the Gograndagh-Chikishlyar zone, the Mesozoic and 5.8-7.8 km.

The deeper Mesozoic sediments occupy a higher temperature range. At the current stage of geologic evolution, they sequentially generate the wet gas and condensate (mesocatagenesis and apocatagenesis substages AC, grades MC<sub>4</sub>-AC<sub>2</sub>, temperature 135-210 °C), the late-catagenic methane (apocatagenesis substage, grades AC<sub>3</sub>-AC<sub>4</sub>, temperature 210-300 °C), and dry and acid gases (metagenesis stage MG, temperature 300 °C).

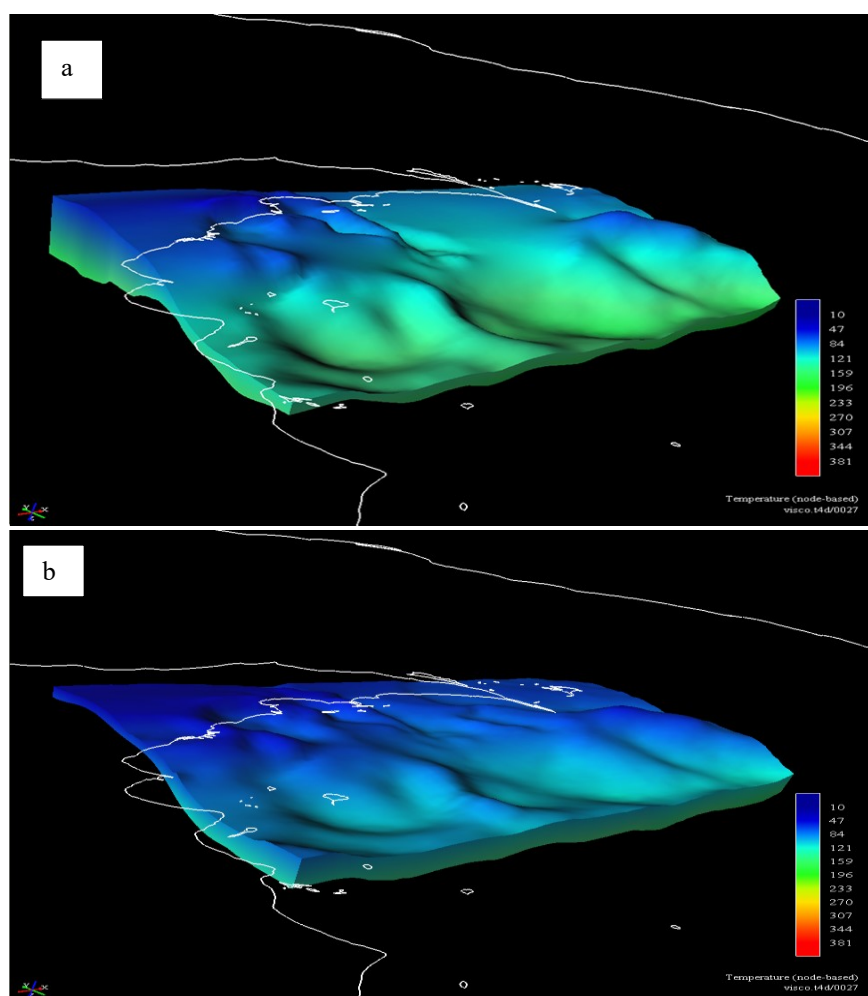


Fig. 4. A 3D model of the temperature distribution: a. In Maikopian sediments, b. In diatomaceous sediments (Guseynov D.A. data have been used).



These data indicate that the Mesozoic sediments in the basin practically exhausted their oil-generating resource during the previous stages of the basin's geologic evolution, during the deposition of the Upper Cretaceous and Paleogene sediments. Currently over most of the SCB, they are generating the gas phase, including the "dry" and acidic gases. This gas phase is "gassing-through" the entire overlying section.

The PT-KT sediments had not yet entered the final stage of oil-generation over most of their development area and are almost entirely preserved in their initial insignificant hydrocarbon-generating potential. As the region is differentiated within individual areas and zones by heat regime intensity, different stages, substages and grades of organic matter thermal metamorphism may be realized in each of them, and the total picture of the source organic transformation is a mosaic. A liquid hydrocarbon phase may be generated in one fault-block. The gas phase may be generated at the same depth in another one, whereas in the third one, such generation may not be occurring at all. The quoted data support a secondary nature of hydrocarbon saturation in the PT-KT of the region and the dominant role in the formation of accumulations and fields of the subvertical interformational fluid migration. For the purpose of studying and analysing the processes of hydrocarbon generation, migration, and accumulation at great depths, a reconstruction was conducted of these evolution processes during the basin's entire geologic history by modelling hydrocarbon systems. The study

results were integrated into an HC systems model (Fig 5) at great depth, accounting for the geodynamics and geo-fluid-dynamics in the study regions. The model results show that, along with other factors, the rates of deposition and basin subsidence have high importance for HC generation into oil and for positioning of the oil and gas generation zone, or the oil window. The sediment cover accumulation occurred at different rates and was associated with the subsidence and the amount of the basin's depositional fill.

Correlation diagrams of TOC vs. deposition rate and of sediment generative potential vs. subsidence rate (Fig 6) have been constructed for a study of the geochemistry of mud volcanoes' ejecta and the creation of the SCB depositional model. Averaged values of the stratigraphic complex have been used. The diagrams show that the Middle-Late Jurassic sediments with a deposition rate of 50-60 m/MMY and Cretaceous sediments with a deposition rate of 10-20 m/MMY have both low TOC values and low generative potential. Further on, since the Oligocene through the Miocene, we observe a gradual increase in both parameters. In the Pliocene, an inverse correlation is observed – the rate of deposition reached 2,000 m/MMY and the value of the generative potential substantially declined. The cause of that was the super-avalanche deposition, which decreased both the heat flow on the surface and the geothermal gradient, and also the heat-screening effect of the productive series underlying clay sequences.

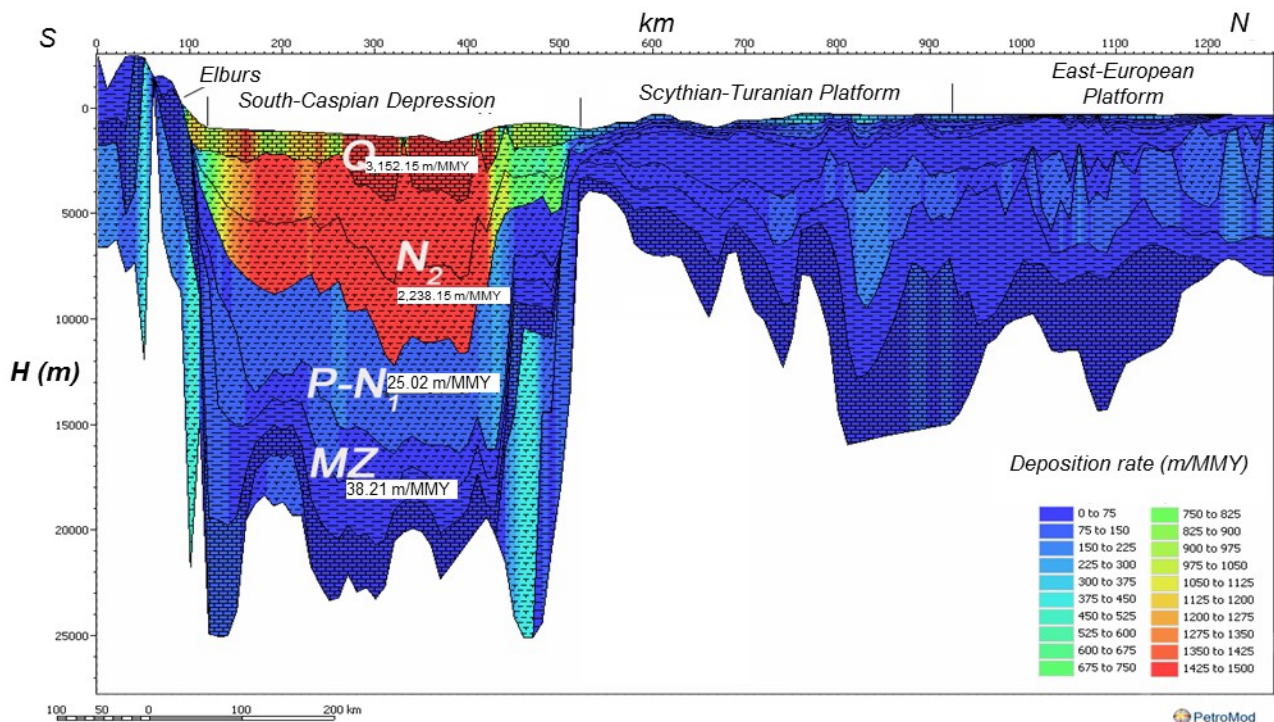


Fig 5. Depositional model of the SCB.



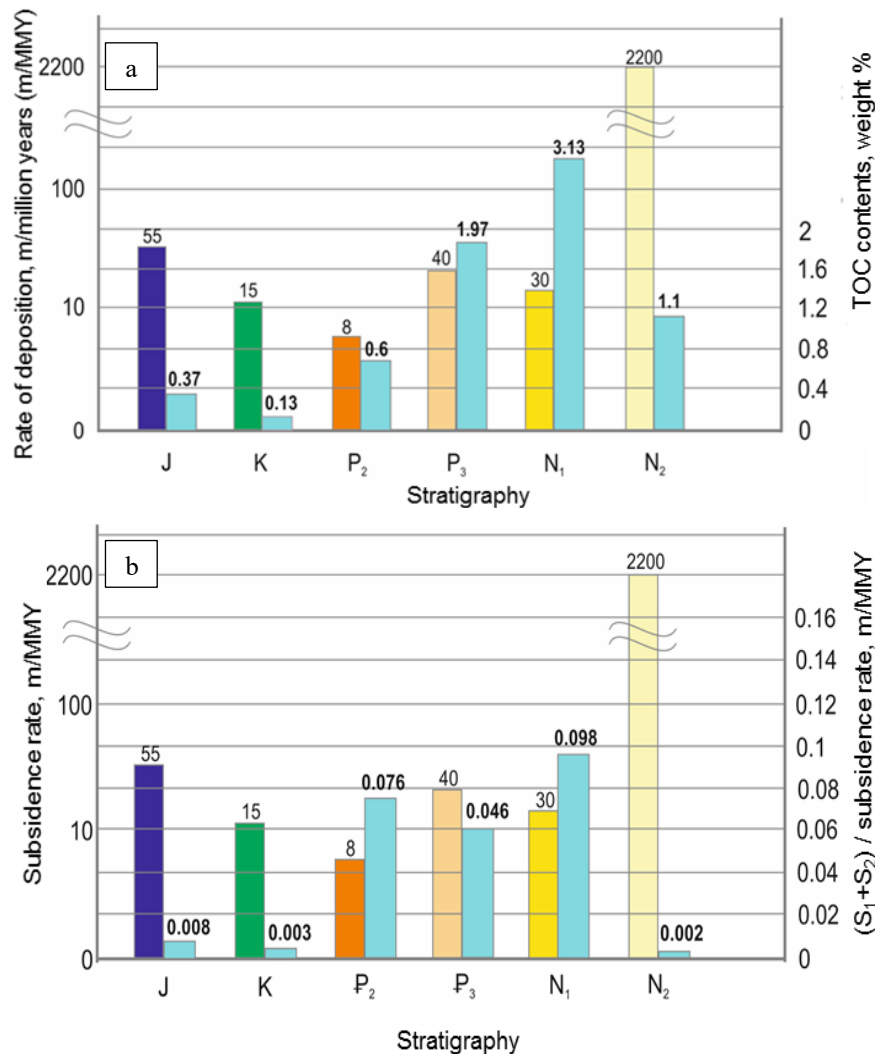


Fig 6. TOC vs. deposition rate (a) and sediments generative potential vs. subsidence rate (b) for the SCB.

The classic theory for the formation of the oil window is usually between 60 and 160 °C for 2-6 km depth, but this field shows more. Example: one result was the expanded oil and gas generation interval (for the most subsided SCB area, the upper boundary of the oil and gas generation zone is at 10 km and the lower at 18-20 km) and lowered generative potential.

Under classical oil and gas generation schemes, liquid hydrocarbons at such temperatures must be absent and in the natural gas, the methane concentration must drastically decrease, leading to carbon dioxide and hydrogen sulphide dominance (Ivanov, Guliyev, 2002). However, analyses of the rock organic matter in samples recovered from depths of 6,401 to 8,460 m at temperatures of 216 to 296 °C indicate the following. In numerous wells, the vitrinite reflectance (R<sub>0</sub>, %) is 3.57 to 7.50, which corresponds with the stage of apocatagenesis, AC3 – AC4. At that point, rocks from these wells (Forester-1, Ralph Lowe-1, Jacobs-1, Bertha Rodgers-1) include organic matter (0.11 to 3.59%),

which contains rather high concentrations of high-molecular hydrocarbons, C15+ (up to 1,610 mg/kg of the rock). Not only are high temperatures typical for great depths but also a high formation pressure, which often over exceeds the hydrostatic pressure. For instance, in the Mississippi salt basin at a depth 6,750 m (Piney Woods Field), the formation pressure abnormality coefficient is 2.44. In a Berkley gas field (southwestern portion of the Anadarko Basin), the initial formation pressure in Carboniferous reservoirs already reaches 77.3 MPa at a depth of 4,542 m.

Conductive heat transfer creates a general geothermal background for the formation of temperature fields in local structures of the alpine folding. The convective component of heat also plays a significant role, which is particularly contrasting due to geothermal regime association with structural and hydrogeological conditions of individual structures.

Local temperature maxima are associated with the crestal, tectonically most-stressed zones of individual

highs, with areas modified by mud volcanoes, faults, etc. Typical examples follow.

In the SCB:

- Balakhany-Sabunchi-Ramany field; at the same depth, the temperature difference in the Bog-Boga mud volcano area (structural crest) and over the flank is 4-5 °C.
- Lokbatan, Zyk, Peschany Isl. and Bibieybat fields; temperature in the areas of the same-name mud volcanoes is 5-10 °C higher than on the flanks and plunges.
- Neftyanje Kamni field; besides a temperature anomaly in the mud volcano area, the temperature near faults is higher by 6-8 °C, compared with more quiescent areas of the structure.
- Artem Isl. and Sulu-Tepe fields; the elevated 18 °C temperature tracks the faults, etc. (Mekhtiyev, Yakubov and Rachinsky, 1968; Mekhtiyev, Geodekian and Rachinsky, 1973; Rachinsky and Muradian, 1983; Rachinsky and Kuliye, 1984).

In the Los Angeles Basin: The Long Beach field; temperature in the crestal zone is 5-7 °C higher than in less deformed subsided areas (Carlson 1930; Van-Ostrand 1934).

In the Zagros Trough: Haft-Kel field; there, over the maximum fractured crest and in the near-crestal areas of the carbonate Asmari reservoir, at 1,500 m depth, the temperature is 10.5-11 °C higher than on the flanks (Van-Ostrand, 1941).

In the Vienna depression: in a number of fields, the surface discharges of thermal ground water in the most faulted parts of highs are located in the areas of contrasting temperature anomalies, 10-15 °C higher than the background.

In the Carpathian Trough: Borislav field; a 10-12 °C geothermal anomaly is recorded in the faulted crestal zone.

In the Tersk-Caspian Trough: in some areas of the Karabulak-Achaluki, Malgobek-Voznesensk, Orlino, Eldarovo and Khayan-Kort fields adjacent to the intersection of large faults, the temperature is 10-20 °C higher compared with the background.

Taking into account the origin of the quoted local temperature excess over regional background values, it is possible to estimate the heat flow's convective component as the ratio of the temperature difference between the anomalies and the temperatures outside them, to the temperature within the anomalies. These calculations show that in the fields of the South Caspian Depression, the geothermal fraction due to heat transfer by the migrating water is 7-18%. In the Los Angeles Basin, it is up to 17%. In the Zagros Trough, 8-15%; in the Vienna depression, up to 18%; in the Carpathian Trough, up to 20%; and in the Tersk-Caspian Trough up to 15%.

The data quoted above show that heat flow on the local structures of the South Caspian Depression, besides the conductive component, which is caused mostly by the

thermal effect of radioactive decay in the Earth's crust, form, to a large degree, from the convective component. The integral effect of both components manifests as a dual correlation of average geothermal gradients. The first correlation is geothermal gradients vs. depth to the base of the productive (Red-Bed) sequence (Hbase PT, Hbase KT) with the conductive component prevailing. The second one is geothermal gradients vs. depth to the top of the transition zone of syngenetic chlorine-calcium waters into hydrocarbonate-sodium waters genetically foreign to the enclosing sediments (Htran.zone) (convective component shows up).

Determining the role and place of each of the stated factors in the formation of geothermal fields in oil and gas accumulations is of significant interest. Also important is the determination of the spatial (depth) position of the zones and therefore of the boundary between them, where the convective component of the total heat flow acquires a noticeable role. The lower boundary of a clear manifestation of the convective heat transfer may be interpreted to be the initial segment of intense generation and broad development of hydrocarbonate-sodium waters and of their transit into the overlying sediments.

#### 4. Discussion

The necessary precondition in the discussion of these issues is a review of the theoretical temperature and temperature gradient models as functions of the status of the geologic medium and realized fluid-transfer processes accompanied by the heat exchange. In the absence of fluid flow, the geothermal regime of local structures is defined mostly by the conductive heat transfer controlled by the relationship of heat-transferring and heat-insulating intervals in the section. Strong positive temperature anomalies cannot form under these conditions, and formation temperatures must remain approximately at the background level. When lateral fluid mobility dominates, the fluids flow and updip over a significant area. The heat-exchange between the migrants and the enclosing rocks occurs over a long time and along the entire path.

Under the lateral filtration model, the heat exchange between slow flowing fluids and the enclosing geologic medium cannot form and be preserved in time-noticeable temperature anomalies. Under vertical flow, the contact area of the flowing fluids and enclosing rocks is limited by the gaping-opening-conductivity of the channels, fracture zones, mud volcano eruptions, hydrogeological "windows", etc. The heat exchange between them occurs within a much smaller volume. The flow of high-temperature fluids from the generation intervals to the accumulation volumes happens there much faster and, in general, over a shorter path. The combination of these factors eventually results in the injection of very hot fluids into the zones of lowered temperature and the emergence of positive temperature anomalies.

In the tectonically quiet areas of buried structures and of insignificantly faulted areas, the temperature field is practically unaffected by the convective component. Variations of geothermal gradients at depth correspond with the conditions of the conductive heat-transfer, which is mostly a function of the variability in the section's thermophysical properties and the cooling effect of the surface. Average gradients for the local structures under such a geologic environment should have maximum values determined by a substantial temperature difference between hydrodynamically insulated heated-lower and cooled-down-upper section intervals that corresponds with broad manifestations of vertical thermal fluid cross-flows into the upper stages of the sediment cover (faulting, mud volcanism, diapirism, etc.). In this case, minimal values of average geothermal gradients are caused by the convection levelling in the formation temperature within the interval of hydrodynamic connection between the underlying and overlying rocks.

In the case of the lithofacies similarity between the sections of local structures, the conductive component of depth heat-flow will be approximately the same on all structures in the region. The difference between the average geothermal gradient values may be interpreted as a result of the convective component's inequality on individual structures, which is associated with variations in heat exchange conditions during the process of migration through faults between thermal fluids and their accumulating porous medium.

Thermally-closed and thermally-open structures have different water-exchange intensities, due to the direction and tempo of changes in geothermal parameters with depth. The first correspond to a geologic environment with water-exchange absent and the dominance of conductive heat-transfer caused by weak structural deformations. The second correspond to a geologic environment of relatively unrestricted water-exchange and a substantial role of the convective component in their sections.

The veracity of correlations between geothermal parameters, tectonic attributes of local structures and ground water dynamics, as identified in the SCB, is supported by the materials from other basins. The stated Alpine folded belt regions display a qualitatively similar type of definitive geologic factors and mechanisms.

## 5. Conclusion

The major factor in the differentiation of geothermal regimes on local structures is the extent of vertical migration, which is controlled by the throughput capacity of faults, eruption necks of mud volcanoes, and contact zones of diapir formations with the surrounding rocks. This extent is determined by the degree to which lower hydrotherms invade the section.

The functional association between the gradients, the structures' per unit volume faulting and intensity, the formation pressure abnormality and the extent of the

section's invasion by thermal fluids is a testimony of the accord and objective nature of the geologic process causing them. This process is vertical oil, gas and ground water migration from deeply buried intervals of the sediment cover typical of the Alpine zones. Thus, we established several important factors based on the data from the present-day geo-fluid-dynamics of the basins in the South Caspian basin:

(1) There is very limited development of infiltration waterhead systems within these basins, showing up mostly within narrow peripheral piedmont zones of the intermontane basins and foredeep troughs;

(2) The presence of thermobarically-open and thermobarically-closed local structures in the sedimentary sections. The former ones have minimal geothermal gradients and formation pressure abnormality factors and optimal conditions for intense vertical discharge and natural fluid migration. The latter ones have maximum values of these parameters and substantially limited ground water and hydrocarbon flow oriented in the same direction. Some general conclusions may be made based on the reviewed materials: Geo-temperature values of individual regions do not display a correlation with their tectonic nature. Models of temperature distribution in their sections are defined in each specific case by the sediment cover thickness, deposition rate, regime of geotectonic evolution and by the ratio within the sediment cover of heat-generating and heat-insulating intervals, i.e., by the conditions of conductive heat transfer. Zones of high temperature in all fields are usually associated with diapirism, mud volcanism, areas of intense faulting, and elevated fracturing with active shows of thermal ground waters from the injection/cross-flow penetration. The part of the convective component in total heat flow of the South Caspian basin is 7-20%.

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