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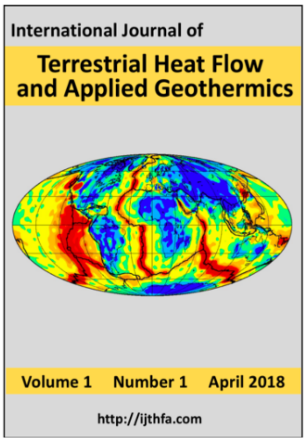

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Shallow and Deep Temperatures in the South-Caspian Basin

Abdulvahab Mukhtarov[1]

[1] Institute of Geology and Geophysics, Azerbaijan National Academy of Science, Baku, Azerbaijan.

Email address
abdulvahab.mukhtarov@gmail.com (A. Mukhtarov)
Corresponding author

Abstract

Distribution of shallow and deep temperatures in the sedimentary cover of the South Caspian Basin (SCB) is addressed. Analysis of soil temperature data recorded in meteostations of Azerbaijan and its neighboring regions provide clues as to the temperatures at near surface layers. Such layers, where seasonal variations of temperatures converge to near-stable values have been designated as the "neutral" layer. In many localities, the bottom parts of such layers extend to depths of around 20 m. In addition, temperature data of over 150 wells, obtained from depths varying from 100 to 6000 m in oil and gas bearing areas of Azerbaijan have been used in assessment of deep temperatures. Data bases were generated for study of lateral temperature fields (in other words, geothermal sections) at depths of 500, 1000, 2000, 3000, 4000, 5000, 6000 and 7000 meters. The results reveal that low temperature areas extend from the north-west to south-east and covers low-lying areas of SCB. Thus, local temperature minimums (30-35°C) are found in Neftchala area, the other larger temperature minimum (35-40°C) covers the structures of Dyvanni-deniz and Here-Zire adasy and expands along the strip Khamamdag deniz, Garasu, Sangi Mugan, Aran deniz. On the other hand, local temperature maximums are observed along the Kura Depression: in Ajinour area with an amplitude of 80°C; to the west of Kyurdamir in Sorsor and Amirarkh areas with an amplitude of 65-70°C; in Sarkhanbeyli-Garabagly-Kyurovdag areas with an amplitude of 60-65°C.

1. Introduction

Many studies have addressed distributions of parameters that determine the thermal field of Azerbaijan (e.g. Mehtiyev et al, 1960; Mukhtarov et al, 2007; Rustamov, 2001). The density of terrestrial heat flow is determined by determination of temperature gradient in boreholes and wells and measurement of thermal conductivity of subsurface rock formations at the fields, in mud volcanoes (e.g. Aliev et al. 2002; Aliev and Mukhtarov, 2000; Mukhtarov, 2011) and at the bottom of the Caspian Sea (e.g. Aliev et al, 2002; Cermak, 1979; Mukhtarov, 2011). This article uses geological data published in the following publications: McKenna and Sharp (1998), Aliev et al (1982), Aliev et al (2002), Aliev and Mukhtarov (2000), Aliev and Aliev (1995).

2. Neutral layer and its temperature

The thermal field of near surface layers of the Earth is determined under the impact of internal and external sources of heat. External source of heat is thermal energy associated with the solar radiation reaching the surface layers. Internal sources include mostly heat generated during decay of radioactive isotopes of uranium, thorium, potassium and heat associated with different processes occurring in the interior of the Earth. This latter one includes release of potential energy arising from differentiation under the gravity field, latent heat associated with chemical reactions with production or absorption of heat and tidal deformation generated by the Moon and the Sun.

Thermal energy of tidal sources released in near surface layers per unit time is significantly higher than the energy of tectonic, seismic, hydrothermal processes. These are some of the interesting aspects in the studies of Earth's thermal field. Daily, seasonal, centennial scale and long-term variations of solar activity result in relevant cyclic changes of air temperature. The longer the period of cyclicity the deeper its thermal impact. For example, daily variations of air temperature affect soil layer to the depth of 1 to 2 m. Seasonal (annual) variation cause temperature changes at depths of up to 20 to 40 m. At such depths heat is transferred mainly through molecular thermal conductivity and, in some cases, movement of ground water. Neutral layer (or layer with near-permanent annual temperature) is situated at depths of 20 to 40 m. In many localities, temperatures are on the average 3.7°C degrees higher than the average annual air temperature

(Mukhtarov, 1984; Mukhtarov, 2011; Frolov, 1991). Long period climate changes affect temperature variations at relatively larger depths. For example, there are evidences indicating that cooling and warming of the Quaternary Period penetrate down to depths of 3 to 4 km. But the magnitudes of such changes are extremely small, often falling below limits of measurements. Thus, it seems reasonable to consider that seasonal cyclicity is below detection limits at depths of near-permanent temperatures. The temperature conditions at such depths are determined by thermal interactions of shallow and deep heat flux.

Figure 1 illustrate a summary of soil temperature data acquired by meteostations at Baku and Kyurdamir in Azerbaijan, for depths of up to 1.6 m (left panel) and 3.2 m (right panel). The analysis of this data reveal that temperatures recorded at the depth of 3.2 m are close to the temperature of neutral layer.

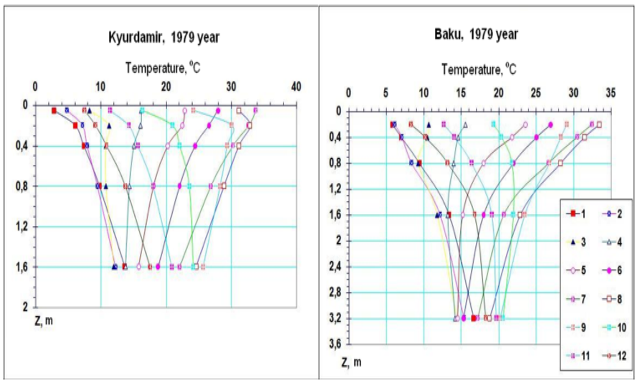

Figure 1 - Variations in soil temperatures at depths of up to 1.6 m (left panel) and 3.2 m (right panel), according to data recorded at Baku and Kyurdamir meteostations.

According to Frolov (1991) the lower boundary of this lays lies at the depth of around 20 m. This conclusion is also supported by data acquired at 24 meteostations of Azerbaijan. The vertical distribution of the "neutral layer" temperature is developed based on these evidences.

This analysis also includes hydrological data of several latitudinal temperature profiles of the Caspian Sea area. In the Caspian Sea areas, the temperatures of neutral layer vary from lower limits of 5 to 6°C and upper limits of 10 to 12°C. Lower limits of neutral layer are related to the temperatures of the water layer (Mukhtatov, 2011). In fact, "neutral layer" temperature in Azerbaijan varies within the range 5.8-18.1°C. The lowest "neutral layer" temperatures with values below 12°C are observed in the Caspian Sea and in high-altitude areas (Fig. 2). High-temperature areas of the "neutral layer" occurs in the Kura Depression, where temperatures range from 16 to 19°C.

Subsequently, this work was expanded by the author of this paper, who determined neutral layer temperatures for 82 localities using the data acquired at Azerbaijan's meteostations. The map of Azerbaijan neutral layer temperature is plotted in Figure 2.

3. Temperature distributions at deeper depths

Temperature data of over 150 wells, were obtained from depths varying from 100 to 6000 m in oil and gas bearing areas of Azerbaijan. These, including development well data, were used in deriving temperature maps. Thermal properties of more than 3000 rock samples of Mesozoic-Cenozoic sequences of Azerbaijan were measured (Mehtiyev et al, 1987; Mekhtivev, 2003; Aliev et al, 2002; Aliev and Aliev, 1995; Mukhtarov, 2011). The values of these parameters are close to the values of the properties of samples from similar regions in the world (McKenna and Sharp, 1998; Cermak, 1979). For example, results were useful in obtaining thermal properties of main lithological and stratigraphic complexes of Azerbaijan, occurring at around two hundred localities. Consolidated geological and geothermal sections were derived for different areas (Figure 3).

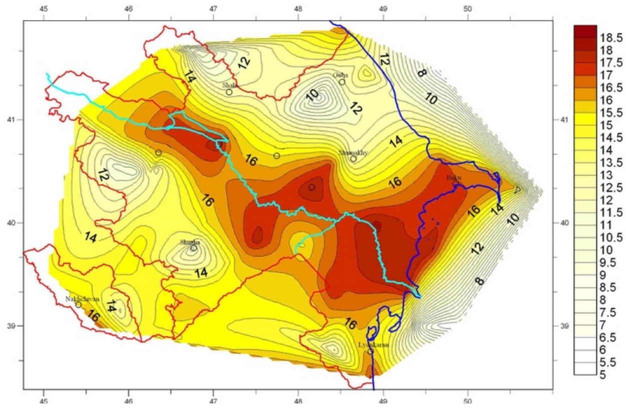

Figure 2 - Map of distribution of "neutral layer" temperatures in Azerbaijan. Color scale refers to temperatures in °C (Mukhtarov, 2011).

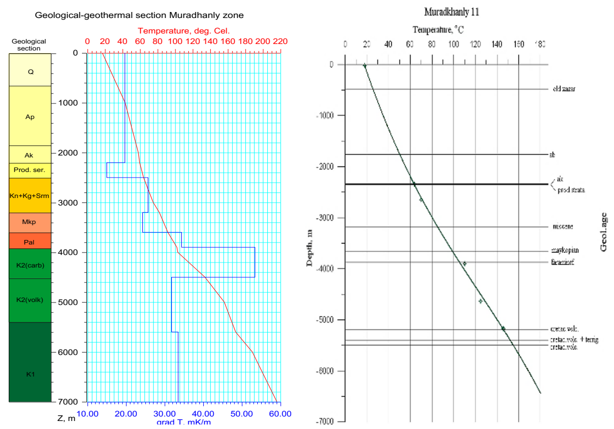

Figure 3 - 1D model of Muradkhanly geological and geothermal section. In panel (a) the red dashed line refers to the vertical temperature distribution. Blue stepped line indicates temperature gradient. Panel (b) refer to temperature log of well 11.

Two data bases were generated using these geothermal sections: horizontal section data base (for temperatures at depths of 500, 1000, 2000, 3000, 4000, 5000, 6000 and 7000 meters) and a geologic data base for the sedimentary complex (indicating temperatures at top of productive strata, at footwall of productive strata and at footwall of the Maikop Suite).

4. Maps of lateral variations at selected depths

Initially, map of horizontal temperature distributions at depth level of 500 m was derived. Following this a 3D model of this distribution was built based on analysis of temperature data across the entire area of Azerbaijan (Figure 4). Isothermals ranging from 15 to 85°C were observed. Low temperature isothermals (below 25°C) were found to occur along Kura Depression and in the Baku Archipelago. Local positive anomalies were found in thermal water areas Istisu (85°C and greater), Masally-Lyankyaran (50°C) and Shamakhy (45°C). It was observed that depending on the geological and especially hydrogeological conditions the footwall of the neutral layer may sink by 200-300 m and more (Mukhtarov, 1984; 2011). Hence, the map of hypsometric section 500m provides the best representation of the thermal field created by internal sources.

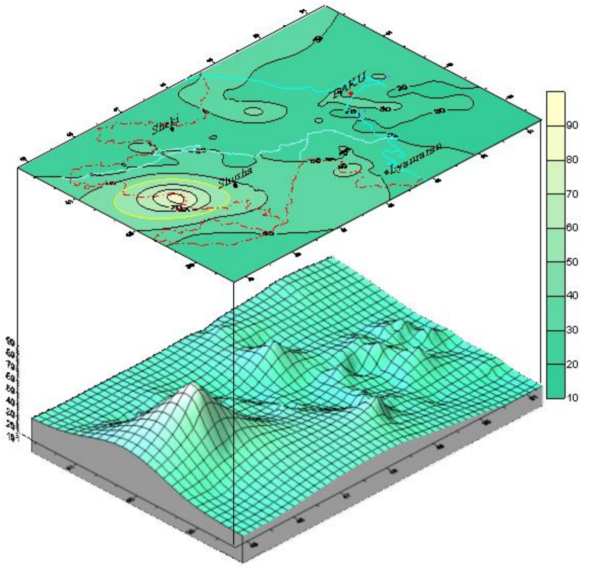

Figure 4 - 3D model – map of distribution of temperature at 500 m level.

On the horizontal section of 2000m low temperatures were observed at Garamaryam (38°C), Ajinour oil and gas bearing area, Agamamedli (39°C), Yevlakh-Agdjabedi oil and gas bearing region, Nakhchivan (39°C), Absheron oil and gas bearing region and Bulla deniz (40°C) and oil and gas bearing area of the Baku Archipelago (Figure 5).

Maximum temperature (110°C) at this section is observed in the Arkevan-Lankaran-Astara region. Local temperature maximums (80.4°C) are also observed in Bibi-Heybat and Garachukhur-Zikh areas of Absheron oil and gas bearing region. Low temperature area extends from the north-west to south-east of the considered region. Also, local temperature maximums (70-95°C) are observed in the deep-water part of the Caspian Sea (Summary Geothermal Maps of Azerbaijan, 1999); Geothermal Atlas of Azerbaijan. 1998; Mukhtarov, 2011).

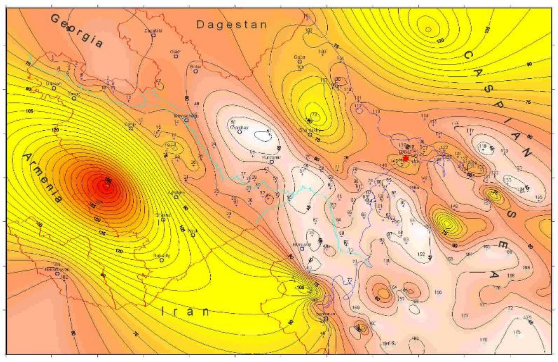

Figure 5 - Temperature distribution at 2000 m horizontal section (Mukhtarov et al, 2003; Yakubov and Atakishiev, 1973).

Temperature distributions display similar features at depth levels of 4000m (Figure 6) and 6000m (Figure 7). It is necessary to note that characteristics of isotherms correspond to features in structural contours of the region. At the same time, it is noticeable that regional structures are well defined at deeper levels (4000-6000 m), while local structural elements manifest better at depth levels of 2000 m.

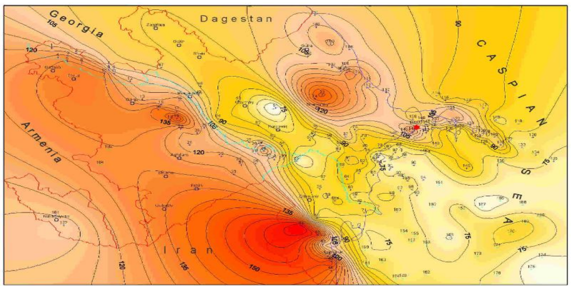

Figure 6 - Temperature distribution at 4000 m horizontal section (Mukhtarov et al, 2003; Yakubov and Atakishiev, 1973).

At 4000 m horizontal section the temperature decreases in the south-east direction from Middle-Kura depression (90-100°C) to the deep-water part of the Caspian Sea (70-75°C). High temperatures (above 130°C) are observed at the sides of the depression: Shamakhi and Ganja oil and gas bearing region (125°C) within the Lankaran-Astara thermal water area. The low temperature sections (< 70°C) were observed in the deep-water part of the SCB and in Garamaryam structure.

At 6000 m elevation section (Fig. 7) temperatures decrease from the sides of the depression (180-160°C) towards deeper parts (110-100°C). In the center of the depression minimum temperatures extend along the south-east direction from 120 to 100°C (Mukhtarov, 2004; Mukhtatov, 2004; Ftrolov, 1991).

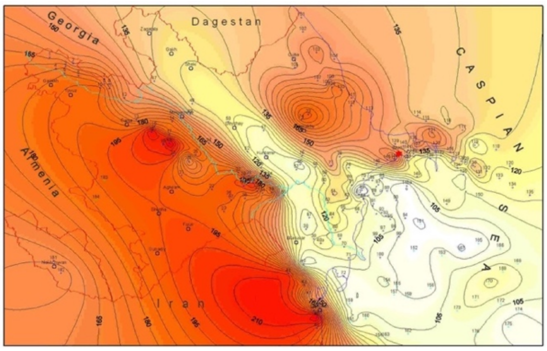

Figure 7 - Temperature distribution at 6000 m horizontal section (Mukhtarov et al, 2003; Yakubov and Atakishiev, 1973).

5. Local Thermal Anomalies

The sources of thermal anomalies identified include permafrost rock with thicknesses of up to hundreds of meters, sedimentary sequences with negative temperatures, high radioactivity rock and ore, zones of exothermic and endothermic processes (that occur in the oil and gas bearing horizons, coal deposits, sulfide and other ore), recent volcanism and tectonic movements and circulation of ground and thermal waters. The roles of each of these factors are determined by geological and hydrogeological structures. Local heat flow patterns also depend not only on the presence of sources but also on the conditions attributable to heat conductivity variations and convection systems in soil, air and ground water.

Temperature anomalies associated with local heat flow variations are found in geothermal maps (Figures 5-7) Such anomalies are also observed in Pre-Caspian-Guba region (Mukhtarov et al, 2007)

Analysis of heat flow maps also indicate correlations with tectonic structures in the study area. The sides of depressions are characterized by rapid changes in horizontal temperature gradients. Tracing these zones downwards on horizontal depth section reveals that at deeper levels zones of rapid changes in isotherms move to the north-east. This is evidence of a zone that dips to the north-east. Possibly, it is an expression of paleo-subduction processes in temperature field of the region.

6. Distribution of geothermal gradients

Vertical temperature gradients are determined using well temperature logs or measurements at intervals. Vertical geothermal gradients in exploration areas of Azerbaijan were measured by Mehtiyev et al (1960), Mehtiyev et al (1971), Aliev and Mukhtarov (2000), Aliev and Aliev (1995), Yakubov and Atakishiev (1973) and Mukhtarov (2011). Geothermal gradient values are found to change at different depths due to the changes in thermal properties of rock. In this case multiple well data had to be averaged for identifying regional trends.

The following methodology was used in calculating vertical and horizontal temperature gradients. First, temperature maps were built for different horizontal sections. Temperature difference (ΔT) for the respective depth difference (ΔZ) of the lower and upper horizon was then determined for calculation of vertical gradients (G). The relation in differential form is:

$$G\,(z) = \frac{\partial\, t(z)}{\partial\, z} \qquad (1)$$

Following this step maps of the distribution of vertical geothermal gradients at different depths were built. Fig. 8 illustrates the map of the distribution of vertical geothermal gradients at depth interval 500-1000 m.

Seven maps of the distributions of vertical geothermal gradients in depth intervals 500-1000, 1000-2000, 2000-3000, 3000-4000, 4000-5000, 5000-6000, 6000-7000 m were built (Mukhtarov (2011).

Total horizontal gradient of geothermal field (G) at horizontal coordinate locations (x, y) is then calculated from the following equation:

$$G(x,y) = \left[\left(\frac{\partial\, t\,(x,y)}{\partial\, x}\right)^2 + \left(\frac{\partial\, t\,(x,y)}{\partial\, y}\right)^2\right]^{1/2} \qquad (2)$$

where t (x, y) are the temperature values.

When defining temperatures at intersection points of rectangular grid horizontal gradients are calculated using the finite difference method. Map of distribution of total horizontal geothermal gradients for 5000m depth horizontal section is shown on Fig. 9. Maximum values of total horizontal gradients were found to correspond to active regional fault zones.

7. Distribution of geothermal gradients

Thermal conductivity values were determined for more than 3000 rock samples of Mesozoic-Cenozoic complexes of Azerbaijan. This allowed assessment of geothermal parameters of the main lithological and stratigraphic complexes of Azerbaijan.

The maps are built based on the structural schemes of the sedimentary complex. Temperature data were then analyzed using the sedimentary complex boundary data base (top of productive strata, footwall of productive strata and top of Mesozoic complex).

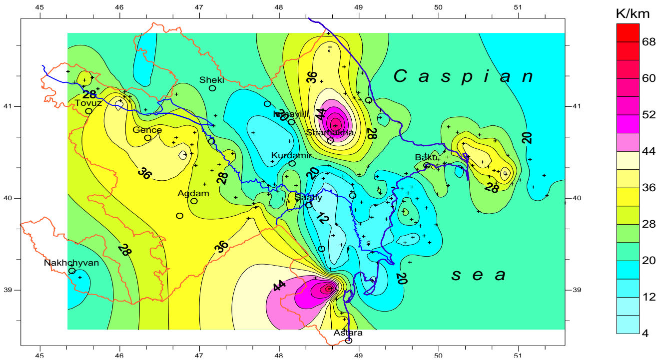

Figure 8 - Map of the distribution of vertical geothermal gradients at depth interval 500-1000 m (Mukhtarov, 2011).

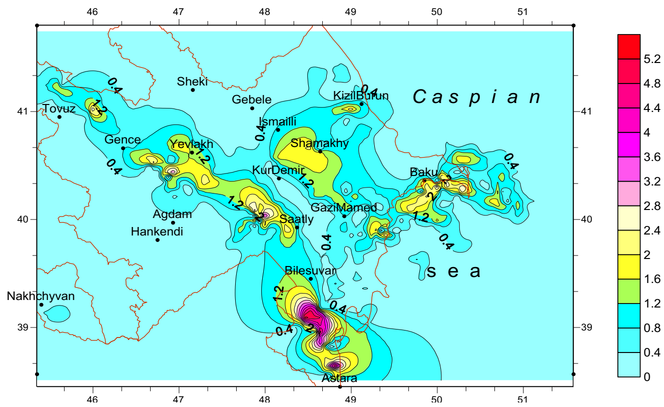

Figure 9 - Map of distribution of total horizontal geothermal gradients for 5000 m depth horizontal section (Mukhtarov, 2011).

7.1. Three-Dimensional model of temperatures at the base of the Maikop Suite.

The temperature at the footwall of the Maikop Suite (Figure 10) varies from 20°C (at pinching out boundaries) to 135°C in the submerged parts of the South-Caspian Depression.

It is necessary to note that the upper boundary of distribution of temperature at the footwall of the Maikop Suite is conditional because neither the footwall nor the top of the Maikop sediments has been intersected by drilling in the submerged parts of the South-Caspian Depression. Here wells reaching the depth of 7000 m have not yet intersected the footwall of productive sequence. For this reason, it is reasonable to assume that there are rather high temperatures in the deeply submerged part of the Maikop Suite that correspond to intensive generation of oil and gas.

Local temperature maximums that reach 130-135°C are located along deeply submerged part of the depression in Akhtepa-B. Palantekan, Amirarkh, Bozgobu-Muradkhanly and Kyurovdag areas. Local maximum that reach 125-130°C is observed in the eastern part of the Absheron Peninsula (McKenna and Sharp, 1998; Aliev et al, 2002; Geothermal Atlas of Azerbaijan, 1998).

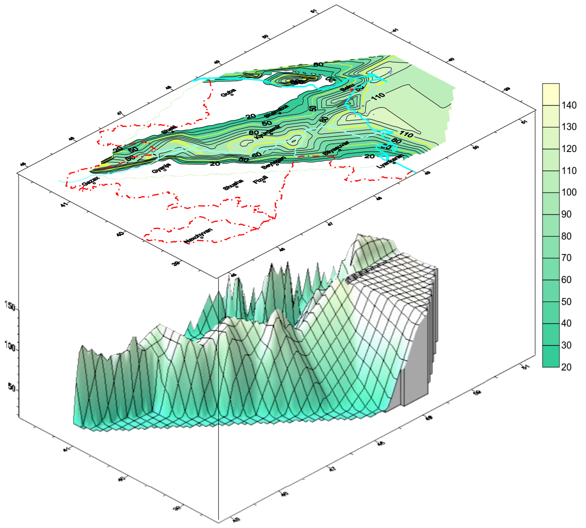

Figure 10 - 3D model of distribution of temperature at the base of the Maikop Suite (Mukhtarov, 2011).

7.2. Three-Dimensional model of temperatures at the base of productive strata.

The temperature at the footwall of the productive strata (Fig. 11) varies from 20°C (at pinching out boundaries) to 130°C in the submerged parts of the South-Caspian Depression.

The isotherm of 50°C lies very close to the pinching out boundaries and the isotherm of 100°C covers most part of the Lower Kura Depression and South-Caspian Depression. It indicates that there are temperature conditions that are close to hydrocarbon generation conditions in the deeply submerged parts of the South-Caspian Depression, situated in the lower layers of the productive strata.

7.3. Three-Dimensional model of temperatures on the surface of productive strata.

On this map (Fig. 12) temperatures range from 17 to 20°C at the boundaries of pinching out of productive formation to values of 80 to 85°C at the most submerged parts of the top of the productive formation.

Distribution of temperatures in general correspond to the structure of the top of productive formation. Temperature increases from the sides of the depression towards its center and in the south-east direction towards submerged part of the SCB. It is necessary to note that temperatures predicted by Rustamov (2001) were used for the structures of the deep-water part of the SCB.

Local temperature maxima are observed along the Kura Depression (Fig.12): in Ajinour area with an amplitude of 80°C; to the west of Kyurdamir in Sorsor and Amirarkh areas with an amplitude of 65-70°C; in Sarkhanbeyli-Garabagly-Kyurovdag areas with an amplitude of 60-65°C. Local temperature minimums (30-35°C) are found in Neftchala area, the other larger temperature minimum (35-40°C) covers the structures of Dyvanni-deniz and Here-Zire adasy and expands along the strip Khamamdag deniz, Garasu, Sangi Mugan, Aran deniz (Aliev and Mukhtarov, 2000; Aliev and Aliev, 1995; Yakubov and Atakishiev, 1973; Mukhtarov, 2011).

The lowest temperature in the top of productive formation (13.5°C) is observed in the structure Palchyg pilpilyasy of the Absheron oil and gas bearing region. Maximum temperature (84.5°C) at this horizontal section is observed in Janubi Sabuhi area of the deep-water part of the SCB. Local temperature maximums (82°C) are also observed in Sabuhi and Alesker Alekperov (SCB). Local temperature maximums reaching 83.5°C are found in Ajinour area in Ajinour oil and gas region (Geothermal Atlas of Azerbaijan, 1998; Mukhtarov, 2011).

Low temperature area extends from the north-west to south-east and covers depression areas of the considered region. At the same time as it is mentioned above local temperature maximums are observed along the Kura Depression: in Ajinour area with an amplitude of 80°C; to the west of Kyurdamir in Sorsor and Amirarkh areas with an amplitude of 65-70°C; in Sarkhanbeyli-Garabagly-Kyurovdag areas with an amplitude of 60-65°C. Local temperature minimums (30-35°C) are found in Neftchala area, the other larger temperature minimum (35-40°C) covers the structures of Dyvanni-deniz and Here-Zire adasy and expands along the strip Khamamdag deniz, Garasu, Sangi Mugan, Aran deniz.

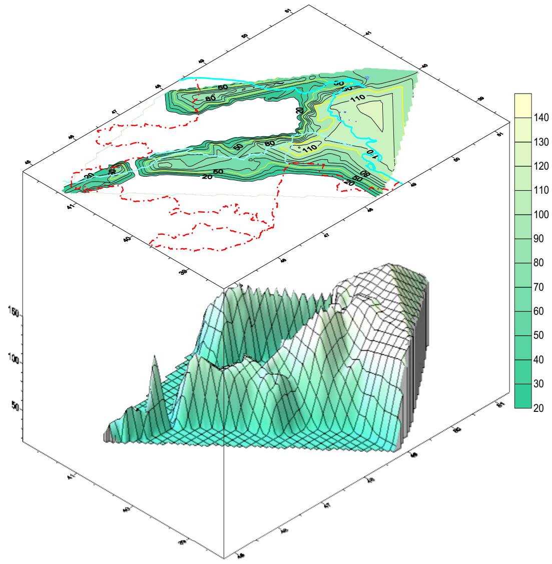

Figure 11 - 3D model of distribution of temperature at the base of productive strata (Mukhtarov, 2011).

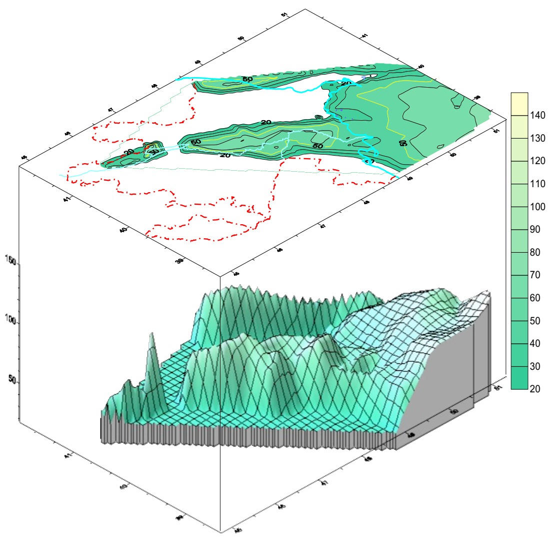

Figure 12 - 3D model of distribution of temperature on the surface of the productive formation (Mukhtarov, 2011).

8. Conclusions

Space and time structure of the thermal field of the South-Caspian Basis is defined using new schematic geothermal maps and models. This include the following:

a- map of temperature distribution of "neutral layer" of the SCB,

b- maps and 3D models of distribution of temperature on the surface of several sedimentary complexes where alignment of regional temperature maximums with maximum thickness of the overlying sediments is revealed,

c- maps of temperature distribution at each 1000 m horizontal depth section to the depth of 7000 m and temperature minimums were found in the deeply submerged parts of the depression,

d- vertical and horizontal geothermal gradients were calculated, and their spatial distribution studied using schematic maps of vertical 1000-meter vertical intervals and horizontal sections at every 1000-meter level down to the depth of 7000 m.

Using temperature distribution maps and 3D models we found that there are sufficient temperature conditions (50-130°C) which are favorable for the initiation of generation of oil in the lower layers of productive strata. There are temperature conditions (from 80°C to over 135°C) for more intensive generation of oil and gas in the Maikop Suite.

A range of geothermal anomalies was found and studied in the SCB: regional thermal anomalies can be explained by the conductive heat transfer and local thermal anomalies can be explained by the convective heat transfer.

9. Acknowledgments

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