IOP Conference Series: Earth and Environmental Science

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To cite this article: Rzger A. Abdula *et al* 2022 *IOP Conf. Ser.: Earth Environ. Sci.* **1080** 012010

Abnormality of geothermal gradients in Iraqi western desert inferred from borehole temperatures

Rzger A. Abdula[1,2 *], Ahmed Srdah Al-zubedi[3] and Hedayat Hashmi[1]
[1] Department of Petroleum Geoscience, Soran University, Soran, Iraq
[2] Department of Petroleum and Mining Engineering, Tishk International University, Erbil, Iraq.
[3] General Commissions for Groundwater, Ministry of Water Resources, Baghdad, Iraq.
*Correspondence author's e-mail: rzger.abdulkarim@tiu.edu.iq

Abstract. Geothermal gradient is an important tool in petroleum exploration and critical to several reservoir evaluations. Borehole Temperature data from 14 wells are utilized to find the geothermal tendency of the Western Desert in Iraq. The discrepancies in geothermal gradients throughout the area are a consequence of variability of sediment's thermal conductivity, direction of groundwater flow, fault pattern, and heat generation. High value converts liquid hydrocarbon to dry gas and low value will not help organic matter to reach maturity level. The lowest gradient within the units above Palaeozoic Era's section is 12.2 °C/km for well KH-9/7 in the eastern part of the area and the highest is 31.3 °C/km for well KH-5/4 in the middle part of the region. Whereas, the highest geothermal gradient which is 61.0 °C/km within the Palaeozoic section is recorded within Akkas Formation in 2100-2350 m subsurface. The mean geothermal gradient in Western Desert is 26 °C/km within the units younger than the Palaeozoic, but this average rises up to 40 °C/km within Palaeozoic units due to existence of Silurian hot shales and heat flow from the Proterozoic section especially from Halaban Group andesites.

1. Introduction

Geothermal gradient is a rate of temperature with respect to the depth. It is an important parameter during petroleum exploration and essential to several reservoir evaluations, (e.g. basin analysis, pressure/volume/temperature investigation, scheming well completion processes, and all the rest) [1]. Additionally, geothermal energy is a comparatively clean, renewable means of heat and electricity production [2].

The history of geothermal studies in Iraq is relatively recent. Systematic investigations began during the first half of the decade of 1980's. Prior to this period there are only several documented numbers on oil well temperatures. The bottom hole temperature in Basra Province is 95 ºC at 3000 m under the ground [3;4]. The geothermal gradient in Mosul Province (28 ºC/km) is higher than in Kirkuk Province (25 ºC/km) [5;6]. The geothermal gradients are relatively low in High Folded and Thrust zones [7], while it is high in Rutba-Jezira Zone [8;9]. The average geothermal gradient in Kurdistan Region-Iraq was determined to be 21 ºC/km [10].

This study is based on a recorded temperature in 14 boreholes, as shown in figure (1) from Western Desert, Iraq to deduce geothermal gradient deviations throughout the region. The differences in geothermal gradients were utilized to draw a map to identify geothermal gradient irregularities throughout the area.

2. Geological Background

Western Desert is situated within Rutba-Jezira and Salman zones, in the Stable Shelf [11]. The Stable Shelf is a steady monocline slightly exaggerated by Late Mesozoic and Cenozoic distortion in which the thickness of the sedimentary cover above the Precambrian foundational rocks are 5, 11, and 13 km in the center, west, and east, respectively [12].

The most obvious topographical characteristic in the region is the depressed Ga'ara [13]. Based on presented facts, the Hail Arch spreads from the northern border of the Arabian Shield northward to northwest Iraq, northeastern Jordan, and southeastern Syria which has a chain of anticyclones (e.g. Rutba High where Ga'ara Uplift is the highest area) and Khleisia High detached by numerous depressions such as Anah Graben [13].

In Western Iraq, the exposed rock categories and their areal distribution have systematized by tectonic and structural settings [14]. Lateral facies changes, as shown in figure (2) are connected to the Rutba High which was the main factor of depositional settings morphology. Alternatively, Nukhaib Graben has helped the deposition of vast volumes of gravel sediments, Pliocene–Pleistocene Zahra Formation [14].

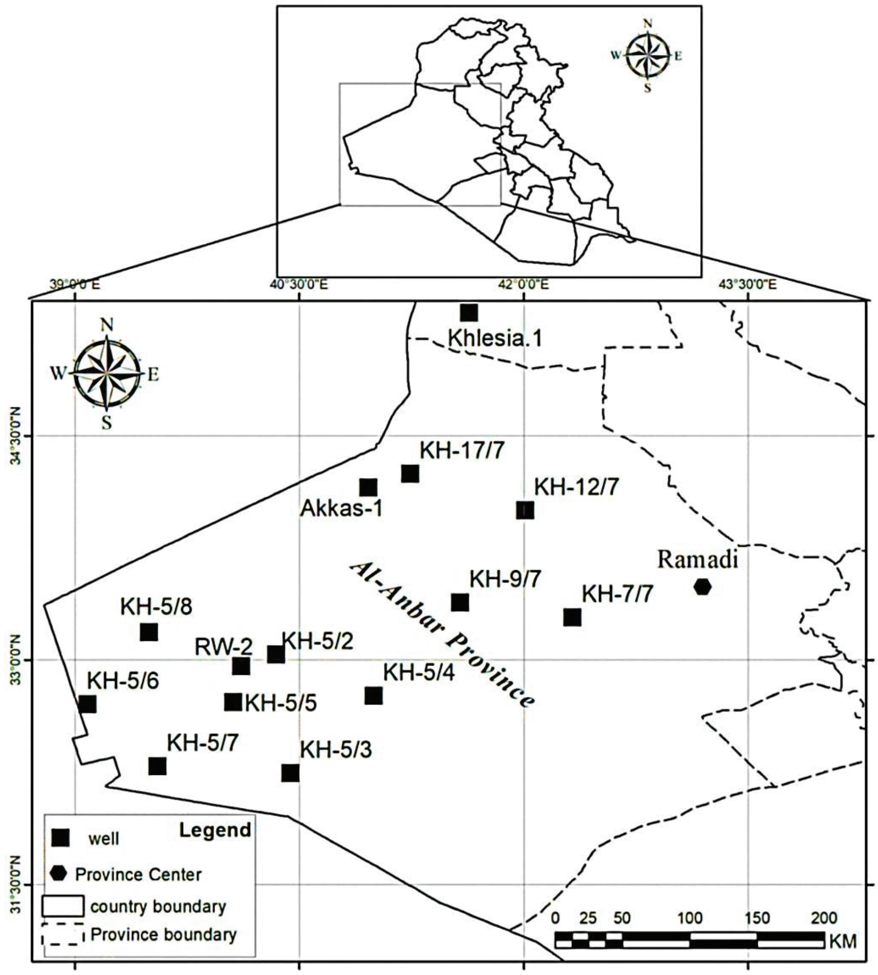

Fig. 1. Location map of studied wells.

3. Methodology

Borehole temperatures measured in water and oil exploration wells in the studied region were utilized for inferring geothermal gradient. Figure (1) shows 14 water and oil exploration wells in Western Desert that were selected for this study. These wells have suitable circumstances (e.g. total depth and the availability of corrected borehole temperatures). The borehole temperatures were collected throughout the region to display horizontal and vertical temperature vicissitudes. Tecplot 360 software is used to draw the diagram of the temperature variation. The recorded temperature in open hole during the drilling procedure is lower than original formation temperature due to mud circulating consequence [15]. Thus, the chart offered by [16], the frequently utilized techniques for temperature correction, was applied. Using an average surface temperature of 21 ºC, the accurate temperature at the designated depth can be acquired from the straight line. The fundamental equation for determining geothermal gradient which suggested by Forrest et al. [17] is:

$$\text{Geothermal Gradient} = \frac{\text{Formation Temperature} - \text{Mean Annual Surface Temperature}}{\text{Formation Depth}}$$

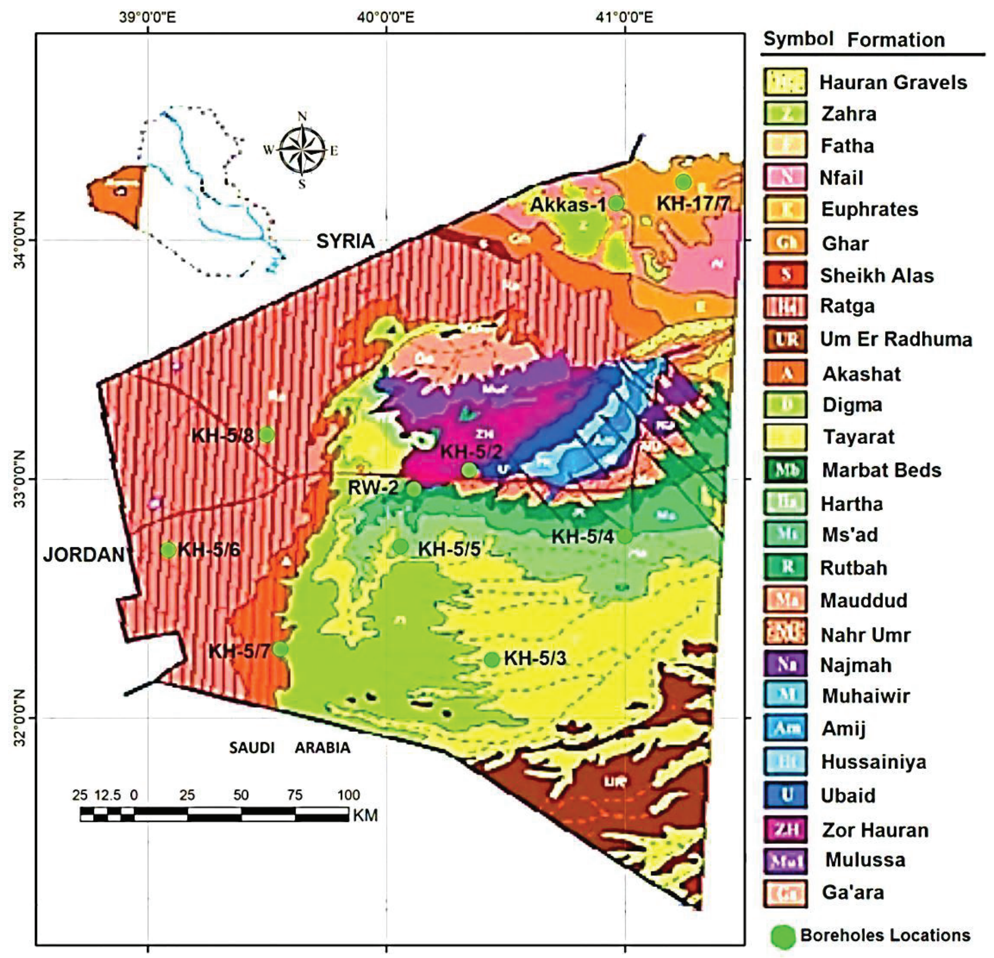

Fig. 2. Geological map of studied area [18].

4. Outcomes and Debate

Conferring to meteorological data provided by the Iraqi General Institute of Meteorological Information (2000) for the years 1981 – 2000, the annual average surface temperature is 21 °C [19;20]. Correspondence examination displays a sturdy and substantial optimistic relationship between depth and temperature, as displayed in Table (1), but this relation does not occur as a direct route, as shown in figure (3).

Its variation is linked to thermal conductivity and is accordingly connected to types of rock which are usually not constant through the entire succession. In addition, the compaction rates and porosity reduction rates of siliciclastic rocks positively correlate with the geothermal gradient. Accordingly, the geothermal gradient differs horizontally from location to location and vertically from horizon to horizon.

The highest geothermal gradient is 31.3 ºC/km in shallow depths (600 m) which is recorded in well KH-5/4 in Wadi Alhazimi. This high value in this well is related to heat entrapment because this well is not located along fault and ground water movement is low as shown in figures (4 and 5), respectively.

Table 1. Well details and their calculated geothermal gradient. All wells are located in Rutba-Jezira Zone.

Well Name	Formation	Ground Level Elevation (m)	Depth Below Ground Level (m)	Recorded Temperature (ºC)	Geothermal Gradient (ºC/km)
Akkas-1	Kaista	352.0	1050	46.1	23.9
	Ora		1450	57.0	27.3
	Akkas		2100	83.0	40.0
	Akkas		2350	98.3	61.2
	Khabour		3150	137.6	49.1
	Khabour		4238	173.3	32.8
Khlesia-1	Khabour	293.5	3791	93.3	19.1
KH-5/2	Suffi	619.3	900	41.0	22.2
KH-5/3	Suffi	730.6	1188	33.0	15.8
	Suffi		1200	40.0	
KH-5/4	Suffi	559.0	600	39.8	31.3
KH-5/5	Suffi	728.5	852	37.7	19.6
KH-5/6	Suffi	807.2	1250	48.0	21.6
KH-5/7	Suffi	856.1	750	33.3	16.4
KH-5/8	Suffi	755.5	800	34.3	16.6
RW-2	Ga'ara	649.8	242	26.2	21.5
KH-7/7	Muhaiwir	282.0	863	35.0	16.2
KH-9/7	Muhaiwir	404.8	581	28.1	12.2
KH-12/7	Muhaiwir	276.4	903	38.8	19.7
KH-17/7	Umm Er Radhuma	283.3	708	38.7	25.0
Average					25.97

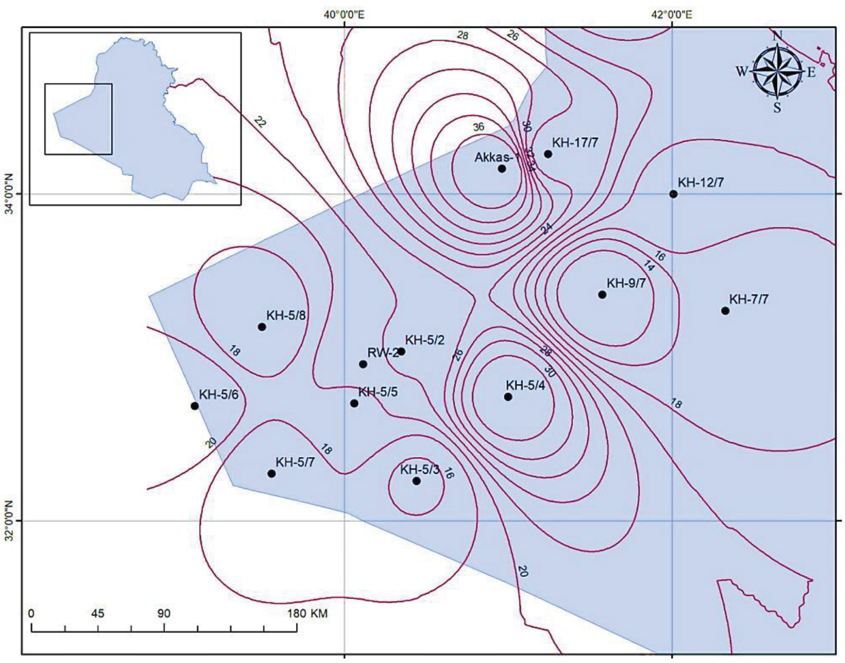

Fig. 3. Geothermal gradient contour map of the Western Desert.

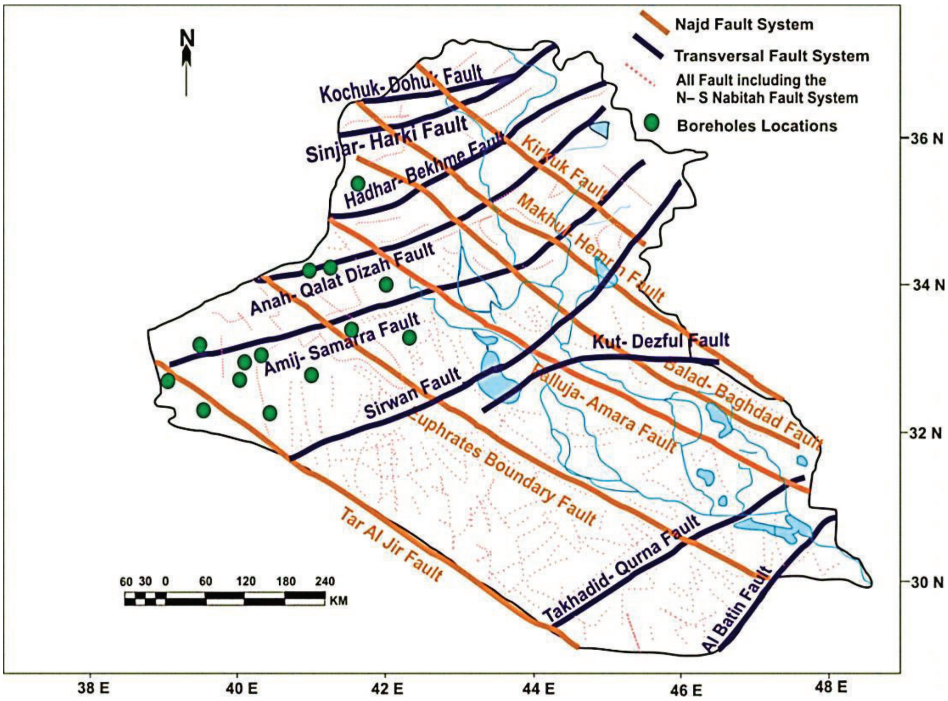

Fig. 4. Distribution of faults and fault zones in Iraq. The wells close to faults such as KH-5/8 has low geothermal gradient (16.40 Cº/Km) and wells far from the faults has high geothermal gradient (31.3 Cº/Km) such as Kh-5/4 (after [21;22]).

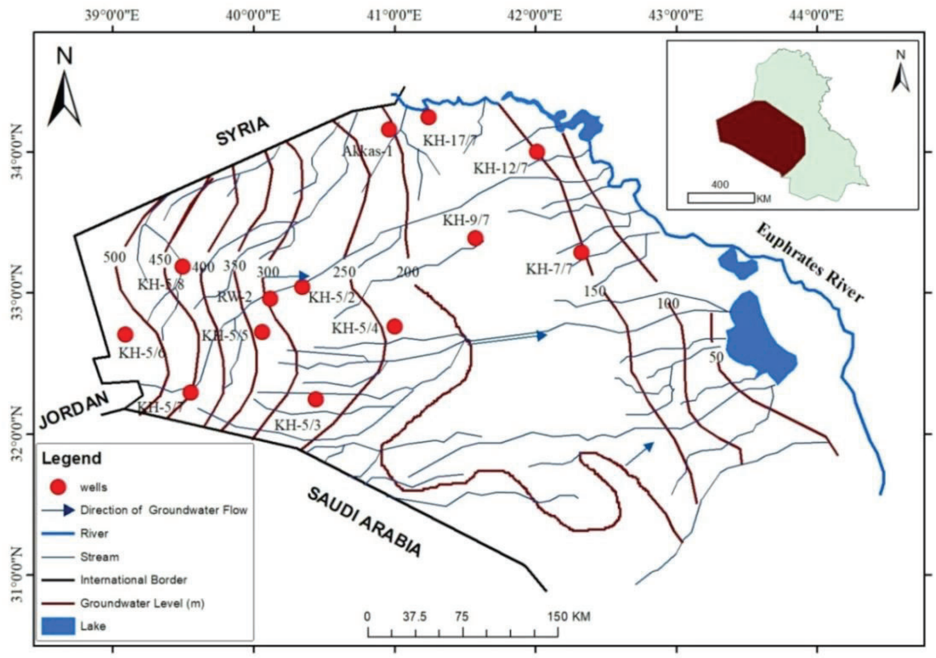

Fig. 5. Hydrological map of Iraqi Western Desert shows location of deep wells with static water level and direction of ground water flow. The geothermal gradients generally decrease with the direction of ground water (after [20]).

The lowest geothermal gradients 12.2, 15.8, 16.4, and 16.6 ºC/km are observed in wells KH-9/7, KH-5/3, KH-5/7, and KH-5/8, respectively. The low values in KH-5/7, KH-5/8, and KH-9/7 are related to their positions which are close to the major faults and KH-5/3 is close to the minor fault, as appeared in figure (4). Furthermore, their positions are located within the direction of ground water movements [23].

The low geothermal gradient values for shallow depths in the wells Khlesia-1 and Akkas-1 are connected to the presence of faults, as shown in figure (4). The well Khlesia-1 is located on the Hadhar-Bekhme Fault [22], while the well Akkas-1 is located on the Anah-Qalat Dizeh Fault, which starts in Western Iraq as a succession of E-W oriented faults, creating the Anah Graben [22]. These wells are located within the area that has low surface radiation which is 1000-1100 counts/sec [24].

The gradients are substantially lower in the wells that are located within the fault zone (Figs. 3 and 4). The fault acts as a path for escaping heat and helps ground water movement as well.

Figure (3) shows that the temperature in well Akkas-1 is higher than that in well Khlesia-1 for nearly the same depth. This lower temperature in the well Khlesia-1 is related to presence of Cretaceous thermal conductive carbonate units compared to Cenozoic rocks that contain more low thermal conductive rocks (e.g. claystone). Furthermore, the thickness of hot shale, Akkas Formation, is higher in well Akkas-1; consequently, the amount of generated heat is higher in well Akkas-1 than in Khlesia-1 Well. Extensively fractured rocks in Khlesia-1 Well facilitate a better ground-water flow as well, as displayed in figure (5).

Each lithology has specific thermal conductivity because it transmits heat at different rate, (sandstone > limestone > shale) [2]. The lowest mean thermal conductivities, 2.5-2.7 wmk, occur in western Iraq and are associated to the occurrence of dense Lower Palaeozoic mudstones such as hot shales in the depth of 4238 m [8;9]. In addition to this low thermal conductive Palaeozoic mudstone, the existence of thick horizons of mudstones within the Fatha (Lower Fars) Formation is also responsible of the higher geothermal gradient in the western part of Iraq.

In Khlesia-1 Well, the anomalous temperature increase can be observed at depth of 2135 m under the Rotary Table Kelly Bushing (R.T.K.B). This depth designates the first occurrence of the Silurian Akkas Formation with a thickness of 155 m. The high temperature is also observed throughout the Palaeozoic formations in Akkas-1 Well as the temperature reaches 83.0 ºC and 93.3 ºC in 2100 m and 2350 m, respectively.

Consequently, the geothermal gradient reaches 61.0 ºC/km within this interval. This increase in temperature is stemmed from probably two dynamics related to nature of the detritus sediments with dominance of the shale deposits, Silurian Akkas Formation, between 1463 m and 2326 m below R.T.K.B. These two factors are: the existence of extraordinary radioactive elements with a rate of radiogenic heat of about 5.0 micro-watt/cubic meters of these rocks [25]; and low thermal conductivity of rock sequence which helps to accretion of temperature. Nevertheless, it is obvious that the geothermal gradients are not constant through the whole borehole, Akkas-1 Well, as indicated in figure (3). It is 40.0 ºC/km and 49.2 ºC/km, as shown in Table (1) within the overlaid and underlain intervals, respectively, but decreases within the units beneath 3150 m to reach 32.8 ºC/km [25]. The high geothermal gradient value, 40 ºC/km, was also recorded at Risha Field in the East Hashemite Kingdom of Jordan [26] due to existence of organic-rich black shales of the Batra Formation [27].

In Western Desert, black shales in Akkas-1 and Khlesia-1 wells from Silurian Akkas and other Palaeozoic formations, Pirispiki, Kaista, and Ora have greater heat generation amounts than the Mesozoic and Cenozoic formations. However, a high thickness of shales is essential for considerable involvement to the total heat [28], and this is a case since the thickness of the Akkas Formation is about 150 m throughout the region. These gradient irregularities also designate the trap unit and are perhaps associated with heat transferring paths and entrapment [29]. In addition, a uniform heat flow of 58 kwm from the crust [30] has more influence since the sedimentary cover above the Precambrian foundational rocks is 5 km in this area, as shown in figure (6) [12].

The high temperature within shallow depths in the area may be linked to the presence of black shale and phosphorites rich uranium beds, 4.6 to 65 ava 26 ppm in the Maastrichtian and 2.9 to 50.9 ava 23 ppm in the Palaeocene successions [31;32;33]. The high temperature gradient in the Rutba-Jezira Zone decreases toward the Salman Zone to become around 12-18 ºC/km [8].

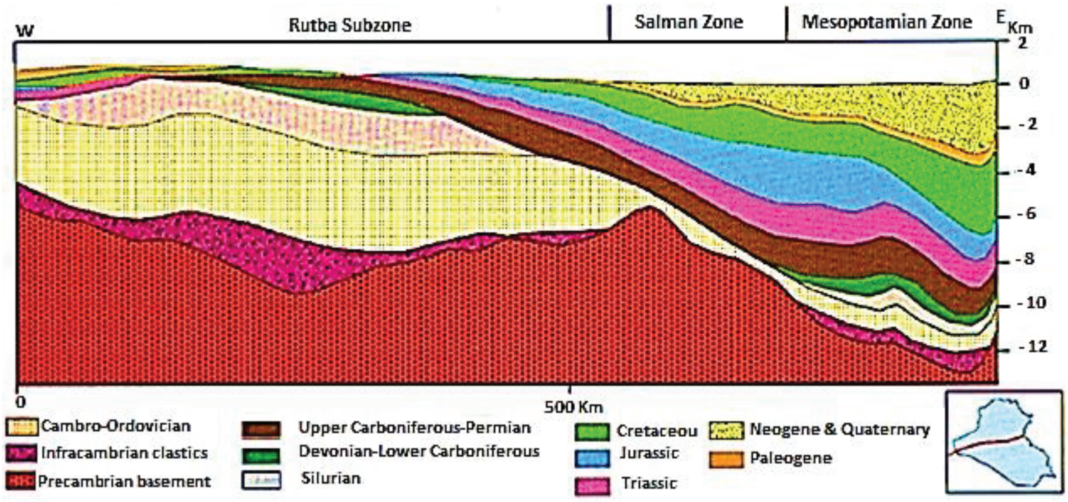

Fig. 6. Cross section from Risha, North-East Jordan to Naft Khana, North-East Iraq [12].

5. Conclusions

In Western Desert-Iraq, geothermal gradients vary significantly. This variability is inferred to replicate variances in thermal conductivity of rocks, heat production, ground water movements, and heat transfer through faults. The maximum and minimum geothermal gradient values are 31.3 ºC/km at the KH-5/4 in the center portion of the region and 12.2 ºC/km at the KH-9/7 in the eastern part of the region, respectively. The mean geothermal gradient in Western Desert-Iraq is 26 ºC/km for shallow depths, but it rises to 40 ºC/km or even higher for Silurian intervals. The highest geothermal gradient occurs in the central part of the studied area and decreases toward east and southeast. This high geothermal gradient raises possibility of existing wet and dry gas in the region, but not liquid hydrocarbons.

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Acknowledgement
The authors are grateful to General Commission for Groundwater, Ministry of Water Resources, Iraq for making borehole temperatures and related information available for this study.