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EVALUATION OF HEAT GENERATION BY RADIOACTIVE ELEMENTS IN JURASSIC AND CRETACEOUS SUCCESSIONS OF THE ZAGROS BELT, NORTHERN IRAQ

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Abstract

This study presents data on Radioactive Heat Generation (RHG) from Jurassic and Cretaceous successions in selected wells along the Zagros belt in Northern Iraq. A total of 2,600 meters of rock intervals were analyzed, encompassing all Jurassic and Cretaceous successions within the conjugated zone of the High and Low Folded zones. RHG values were obtained from Uranium, Thorium, and Potassium concentrations, measured using Gamma Ray Spectrometry and Normal Gamma Ray logs. These measurements reflect the RHG resulting from the decay of Uranium-Radium series isotopes (U^{238}, U^{235}, and U^{234}), the Th^{232} series, and the primary decay of K^{40}.

In the Jurassic section, the heat generation rate ranges from 1.51 μW/m³ in the upper part of the Butmah Formation to 5.52 μW/m³ in the Naokelekan Formation. In the Cretaceous section, it varies from 0.77 μW/m³ in the Kometan Formation to 1.48 μW/m³ in the Sarmord Formation.

The contribution of these RHG rates to the subsurface temperature is approximately 2.60 mW/m² for the Jurassic section and 1.54 mW/m² for the Cretaceous section. These findings can be applied to evaluate how lateral variations in RHG rates influence heat flux and temperature distribution within the upper crust and sedimentary basins, particularly in terms of radioactive heat flow (RHF).

Keywords: Radioactive Heat Generation, Heat Flow, Geothermal Gradient.

1. Introduction

Subsurface temperature is a crucial parameter in geological studies, particularly in the context of sedimentary basins. It plays an essential role in hydrocarbon exploration, influencing the

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maturation of organic matter and the generation of hydrocarbons. Moreover, subsurface temperature impacts the well drilling and production processes. Also, the subsurface temperature has a great role in the stability depth of oil or gas occurrence; in other words, the subsurface temperature controls the quality and stability of oil and gas in reservoirs. In addition, knowledge of the temperature distribution in the subsurface and the physical rock properties is fundamental in the development of an underground storage system (Schütz et al., 2018).

In stable continents, subsurface temperature in terms of heat flow variations reflects variations in crustal heat production (Rolandone et al., 2013). The thermal structure of a rock pile is influenced by a variety of internal and external factors. External factors, which are controlled from outside the rock pile, include the basal heat flow (measured in mW/m^2) from the upper mantle. This heat flow is both spatially variable and time-dependent, being higher in regions such as the seafloor, tectonically active areas, and young geological formations, while lower in stable continental interiors and Precambrian shield areas. The basal heat flow can range from less than 40 mW/m^2 to over 150 mW/m^2 Figure 1; (Burrus et al., 1986); (Hamza et al., 2010).

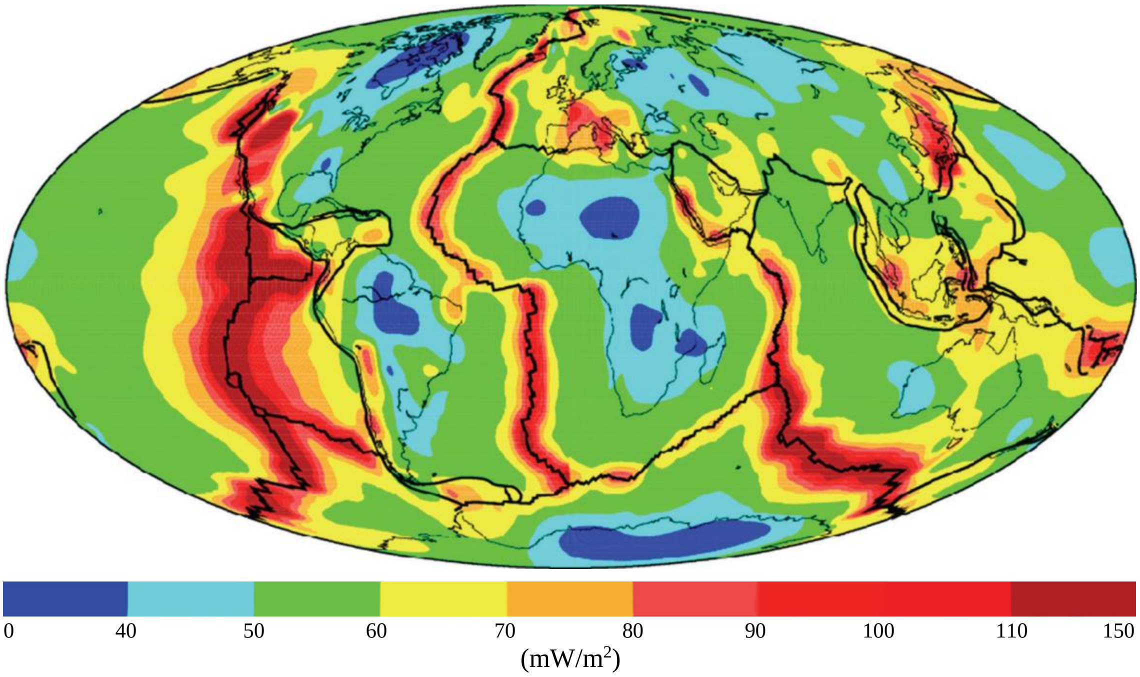

Figure 1. A global heat flow map was synthesized from various data sets, as referenced by Müller et al. (1997) and (Hamza et al., 2008), and subsequently adapted from (Hamza et al., 2010).

Internal factors, on the other hand, are determined by the properties of the sedimentary rock column within a basin. These include heat generation (measured in $\mu W/m^3$) due to radioactive decay in sediments, which varies widely with lithology and is related to the content of uranium (U), thorium (Th), and potassium (K) in the rocks (Abbady, 2010). Additionally, the thermal conductivity of the rock layers plays a crucial role, ranging from as low as 0.3 W/m·°C in coal to as high as 5.5 W/m·°C in minerals like halite and anhydrite (Burrus et al., 1986).

This research aims to assess the heat generated by radioactive elements within rocks of Cretaceous and Jurassic age in selected well sections. Several analytical techniques can be used to determine the concentrations of the heat-producing elements, but the gamma-ray spectrometry NGS log tool is the only one that enables simultaneous determination of U, Th, and K, and its accuracy is generally sufficient in most ordinary sedimentary rocks. During the radioactive decay of these elements, mass is converted to energy. This energy is set free as the kinetic energy of the involved particles and nuclei (emitted α and β particles, recoil nuclei) and as the energy of the accompanying gamma-radiation.

The response of the normal gamma ray log (GR) is made up of the combined radiation from U, Th, and K, while the spectral gamma ray (NGS) shows the amount of each individual element contributing to its radioactivity according to energy (Asquith & Krygowski, 2004).

Throughout Iraqi Kurdistan, the highest geothermal gradient was recorded at the Low Folded Zone, the central part of the studied area, and a minimum gradient was recorded at the High Folded Zone in the northern and northeastern parts of the area (Abdula, 2017).

2. Research Aim and Importance

This study aims to calculate and evaluate the heat generated from Jurassic and Cretaceous rock formations, both individually and collectively. This heat plays a significant role in shaping the geothermal gradient of the area, which is crucial to the geological processes responsible for the maturation and generation of hydrocarbons from source rocks. It also influences their stability in reservoirs or the breakdown of their components during later chemical processes caused by excess heat. Furthermore, subsurface thermal assessment is essential in oil exploration, from drilling to production. Despite its importance, this area of research is rare in the region and almost non-existent in Iraq today.

The study area is situated in the Miran oil field, Sulaymaniyah province (Figure 2), where wells have fully penetrated the Jurassic and Cretaceous geological formations. Additionally, data from wells in the nearby Taq Taq and Kor Mor fields were used to calibrate and enhance the equations applied in this article.

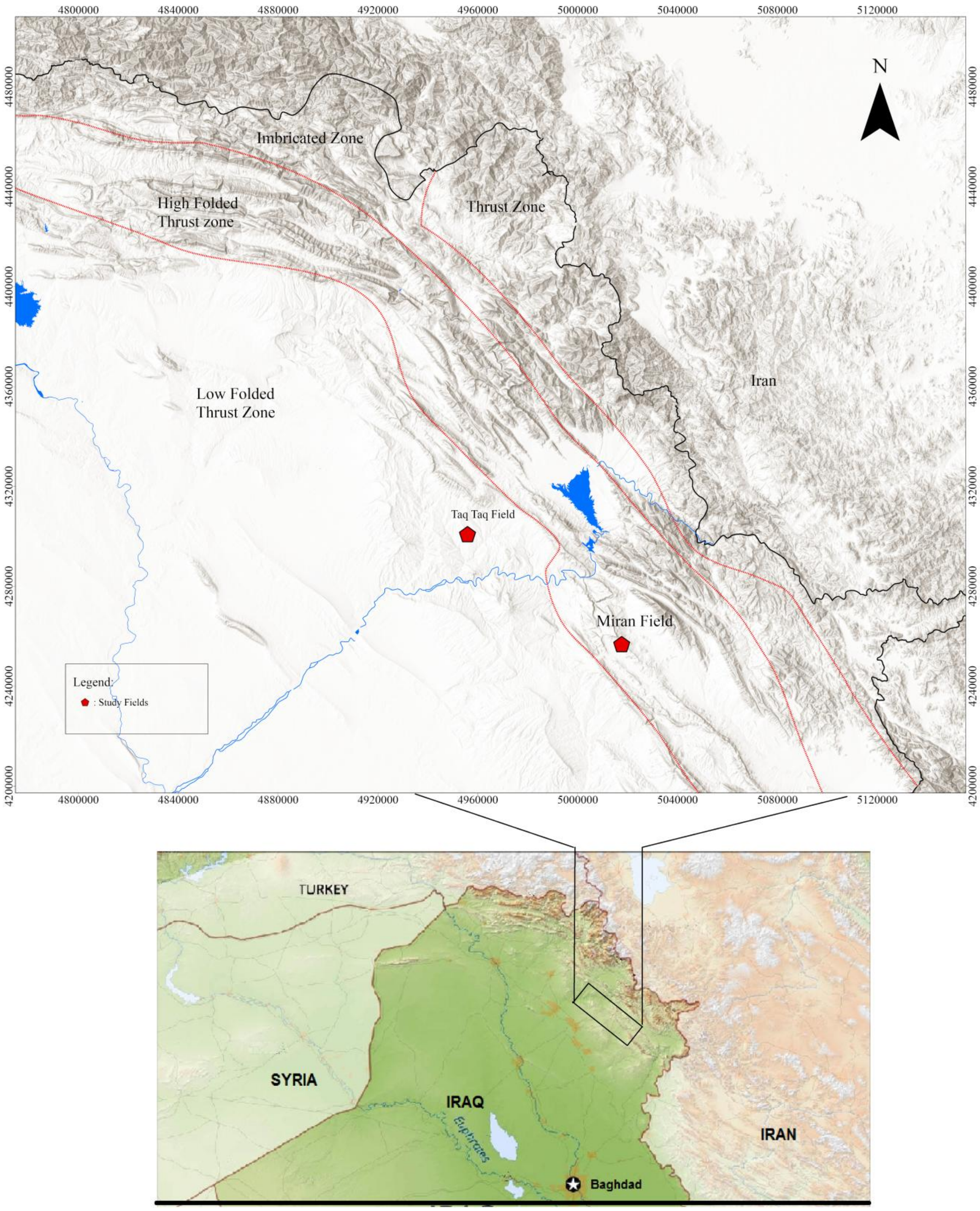

Figure 2. The studied area and structural provinces of Iraq after (Buday & Jassim, 1987).

3. Heat Generation in Sedimentary Rocks

Radiogenic heat in the sediments has a significant effect on temperatures within the sediments. Ignoring sediment heat production and calibrating a thermal model to temperature observations by optimizing the basal heat-flow density may overestimate the present-day temperature of a potential source rock at 10 km by as much as 28°C (Thomas E. McKenna2 and John M. Shar, 1998).

Most naturally occurring isotopes in rocks are either stable or present in such minimal concentrations that they do not contribute significantly to radiation levels. However, certain isotopes are noteworthy due to their abundance and radiogenic properties (Faure et al., 2013). Among these are:

- Potassium Isotope (${}_{19}K^{40}$): This radioactive isotope, which constitutes a small fraction of natural potassium, exists alongside the stable isotopes ${}_{19}K^{39}$ and ${}_{19}K^{41}$. Potassium-40 (${}_{19}K^{40}$) is notable for its role in radioactive decay processes, which contribute to the radiogenic heat generation within the Earth's crust.
- Thorium Series Isotopes (${}_{90}Th^{232}$): Thorium-232 is a naturally occurring radioactive isotope and is present in nature at nearly 100% abundance within its series. It is significant due to its long half-life and its contribution to natural background radiation.
- Uranium-Radium Series Isotopes: This group includes several isotopes of uranium and their decay products, which are significant due to their natural abundance and radiogenic properties:
  - Uranium-238 (${}_{92}U^{238}$), which constitutes approximately 99.27% of natural uranium, is a major contributor to radiogenic heat and radiation.
  - Uranium-235 (${}_{92}U^{235}$), present at about 0.72%, is notable for its application in nuclear reactors and its role in generating natural radiation.
  - Uranium-234 (${}_{92}U^{234}$), though present in much smaller quantities (approximately 0.0057%), is part of the decay series of uranium-238 and contributes to the overall radiation output.

The Radioactive Heat Generation (RHG) from these elements is calculated from well-log data according to Equation (1), from the rock's Uranium, Thorium, and Potassium contents. In sedimentary sections, the concentration of these elements can be measured directly by well logging: Natural Gamma Ray spectrometry (NGS) has today become available from many companies' services.

The rock density, which is also needed to calculate heat generation, can be read by density logs; formation density logs (FDL), or formation density compensated (FDC), which are available in all well-logging device companies.

Natural gamma spectrometry (NGS) is a relatively new technique in geological logging, and consequently, few drill holes have been logged using NGS tools so far. However, the normal gamma ray (GR) log is a standard method in most logging programs. Therefore, for the majority of logged boreholes, information on rock radioactivity is typically provided through GR logs.

The normal gamma ray log, also known as the natural gamma ray log (GR), measures the natural radioactivity in rocks by recording the total gamma ray count rates, which include contributions from uranium (U), thorium (Th), and potassium (K). Unlike NGS, the GR log does not differentiate between the gamma-ray pulses based on their energy, so it does not distinguish the individual contributions from each element. Notably, the sensitivity of GR tools to U, Th, and K is proportionate to their respective heat generation constants, as described by the corresponding equation. Therefore, it is reasonable to establish an empirical relationship between GR log readings and heat production (A). Wells were collected and utilized to validate the groundwater potential zones, as illustrated in Figure 3.

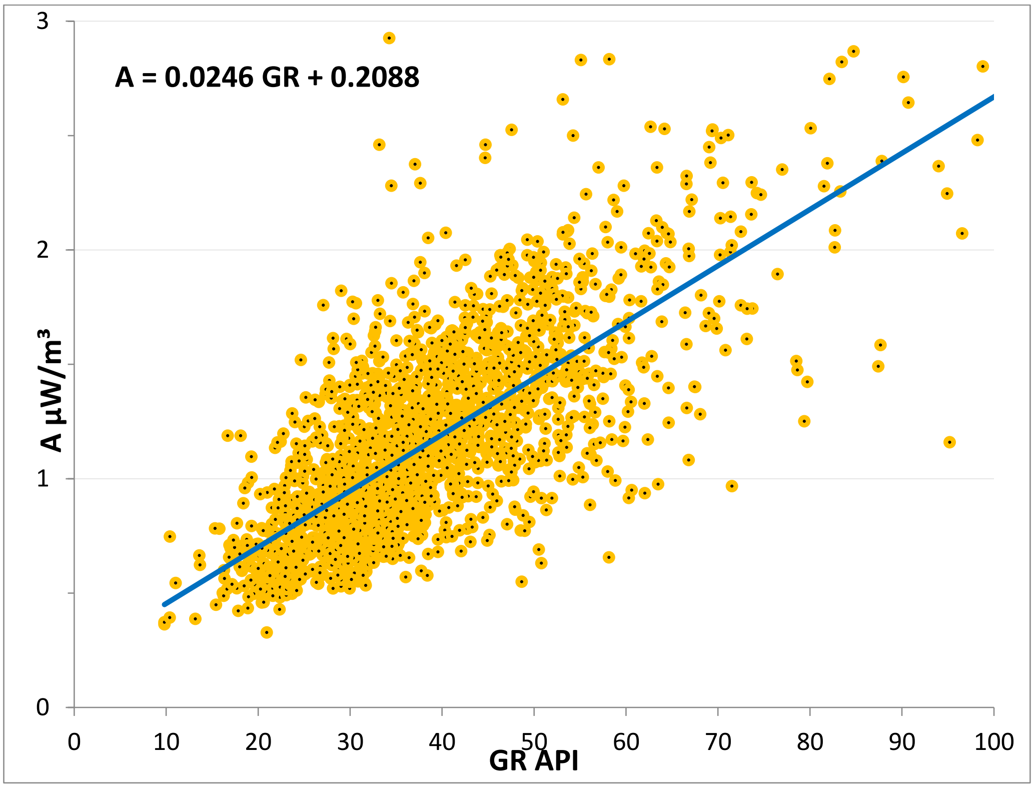

Figure 3. Empirical relationship to determine radioactive heat generation (A) from GR log readings in API units.

4. Methods

The data for this study were primarily derived from three types of well-log tools:

- Gamma Ray Logs (GR): These are lithology logs that measure the natural radioactivity of geological formations. The typical response of a gamma-ray log reflects the combined radiation from uranium, thorium, potassium, and several associated daughter products of radioactive decay.
- Natural Gamma Ray Spectroscopy (NGS): This technique independently measures the mass concentrations of uranium (U), thorium (Th), and potassium (K). Since these radioactive elements emit gamma rays at different energy levels, the contributions from each element can be analyzed separately.
- Density Log: The density log provides a continuous record of the bulk density (ρb) of the formations. This bulk density represents the density of the entire formation as measured by the logging tool.

The heat generated by radioactive elements is typically calculated using the (Burrus et al., 1986) equation, which incorporates the weight concentrations (in parts per million, ppm) of uranium, thorium, and the percentage of potassium, along with the rock density. The concentrations of these elements are derived from spectral gamma-ray tools, while the density is obtained from the density log. However, spectral gamma-ray tools are not always available in all wells, and even when they are, they rarely provide comprehensive coverage of the entire well section.

To mitigate this limitation, the study employed conventional gamma-ray logs, which are commonly present in the logging records of most oil wells. By analyzing thousands of spectral gamma-ray tool readings, a novel equation was developed to estimate heat generation from rocks based on gamma-ray log readings, which provided satisfactory results.

The study collected over 6,000 data points for uranium (U), thorium (Th), and potassium (K), with 2,000 readings for each element using the NGS log tool. Additionally, 2,000 data points for density were obtained using the density log. These measurements were gathered from a 1,000-meter section of a well, with two readings per meter for each element. Using Equation (1), the heat produced per cubic meter (A) was calculated, as described by Burrus et al. (1986).

$$A\ (\mu W/m^3) = 10^{-5}\ D\ (9.52\ U.c + 2.56\ Th.c + 3.48\ K.c) \quad (1)$$

Where D = Density of rocks kg/m^3, U.c, and Th.c = Uranium and Thorium concentration in weight ppm, from NGS Log, and K.c = Potassium concentration in weight%.

The calculated heat production values were then plotted against gamma-ray (GR) readings from the same well section to establish the relationship between gamma-ray emissions and the heat produced by the radioactive elements. This analysis, as depicted in Figure 3, led to the formulation of an empirical equation to estimate radioactive heat generation (A) from GR log readings in API units. Although the R-squared value was 0.69, the results were promising.

$$A\ (\mu W/m^3) = 0.0246 \times GR\ (API) + 0.2088 \quad (2)$$

5. Results and Discussion

The reasonably good linearity of the GR-A relationship results (Figure 3) from the fact that both heat generation and total gamma radioactivity are a sum of contributions from U, Th, and K.

In this study, a rock column with a thickness exceeding 3,000 meters was selected to assess the amount of radioactive heat generation (RHG) using Equation (2) This thickness encompassed all Cretaceous and Jurassic deposits in the chosen section, covering more than 15 rock formations (Table 1). Specifically, the column included 2,264 meters of Cretaceous formations (including approximately 500 meters of Early Tertiary deposits) and over 800 meters of Jurassic deposits. The heat generated in the Cretaceous formations ranged from a low of 0.83 μW/m³ in the Kometan Formation to a high of 3.84 μW/m³ in the Chia Gara Formation (Figure 4a). In contrast, the heat generation rate in the Jurassic formations ranged from a low of 1.53 μW/m³ in the upper part of the Butmah Formation to a high of 4.43 μW/m³ in the Naokelekan Formation (Figure 4b).

Table 1. Summary of average and total radioactive heat generation in Cretaceous and Jurassic successions.

Age	Formations	Thickness m	Average RHG μW/m³	Total RHF μW/m²
Cretaceous	Kolosh	559	1.07	598.13
	Tanjero	209	1.27	265.43
	Shiranish	483	1.08	521.64
	Kometan	20	0.83	16.6
	Qamchuqa	581	0.84	488.04
	Sarmord	305	1.79	545.95
	Chia Gara	107	3.84	410.88
Total		**2264m**		**2846.67 μW/m²**
Jurassic	Barsarin/ Gutniah	41	2.12	86.92
	Naokelekan	26	4.43	115.18
	Sargelu	106	3.99	422.94
	Alan	63	2.93	184.59
	Mus	23	2.45	56.35
	Adaiyah	58	1.64	95.12
	Butmah Upper	135	1.53	206.55
	Butmah Lower	415	2.48	1029.2
Total		**867m**		**2196.85 μW/m²**

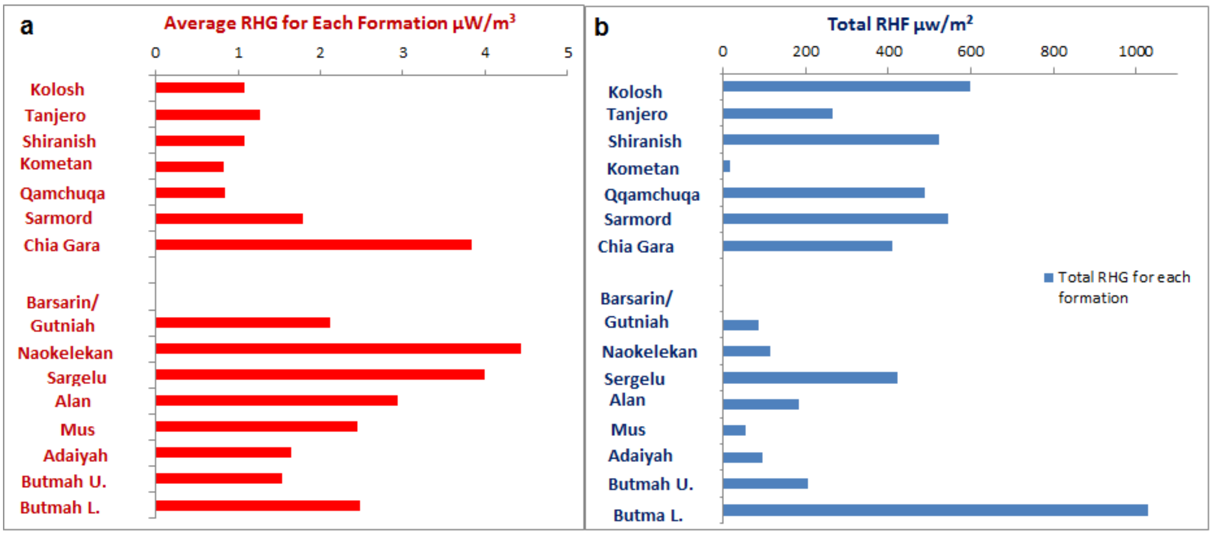

Figure 4. a) Average radioactive heat generation per formation. b) Total heat flow across each formation.

It is noted that the heat generation rates in the Jurassic formations are generally higher than those in the Cretaceous formations. However, when calculating the cumulative amounts of heat, although the average heat generated per unit volume in the Jurassic is higher than in the Cretaceous (Figure 5a), the overall heat generated from all the Cretaceous layers is greater than that from the Jurassic layers. This is due to the greater overall thickness of the Cretaceous deposits compared to the Jurassic deposits. Specifically, the total heat generated in the Cretaceous rock column amounts to 2,846 $\mu W/m^2$, whereas the total heat generated in the Jurassic rock column is 2,196 $\mu W/m^2$ (Figure 5b).

The importance of this method lies in calculating the amount of radioactive heat generated within sedimentary basins; it helps to measure subsurface temperature at any depth (Tz) more accurately by incorporating data on the thermal conductivity of rock beds (K), which varies from one type of rock to another, and the heat originating from the Earth's interior (qb) according to Equation 3 (Allen & Allen, 2005). Unlike the traditional method, which relies solely on the geothermal thermal gradient.

$$\mathrm{T(z)} = To + \frac{(qb+AL)Z}{K} - \frac{AZ^2}{2K} \qquad (3)$$

Where Z = any depth. M, T_o = Surface temperature c°, qb = Basal heat flow mW/ m^2, A = Internal heat generation mW/m^3, L = Thickness of the Basin. M and K = Thermal conductivity of the rock. mW/ m.c°

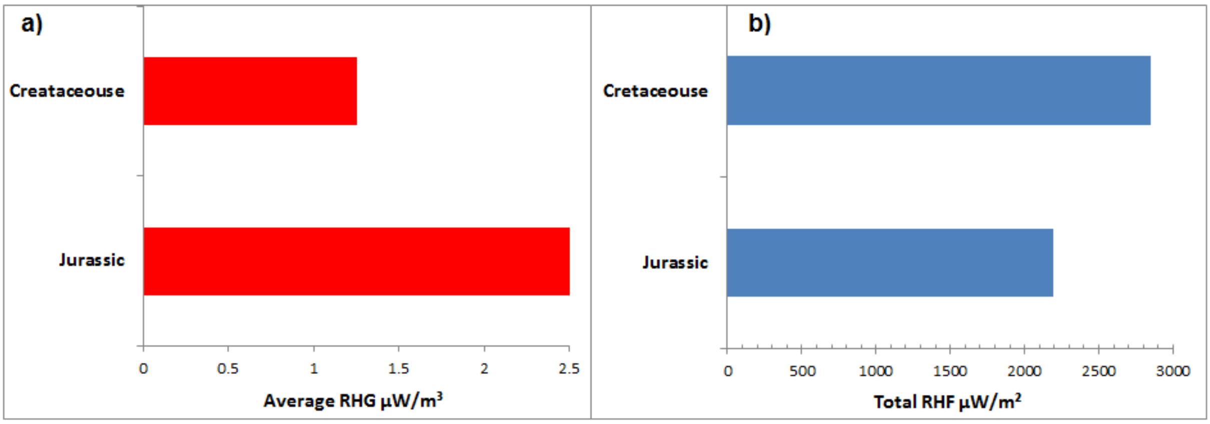

Figure 5. a) Average radioactive heat generation for each of the Cretaceous and Jurassic rocks. b) Total heat flow for each of the Cretaceous and Jurassic rock columns.

6. Conclusions

This study examines a 3,000-meter-thick well section in northeastern Iraq encompassing formations from the Cretaceous and Jurassic ages to calculate radioactive heat generation. In the absence of Natural Gamma Ray Spectroscopy (NGS), the Normal Gamma log (GR) can effectively estimate the heat generated by radioactive elements like uranium, thorium, and potassium by utilizing mathematical relationships derived from prior NGS data. In addition, the heat production within the Cretaceous rocks ranges from 0.83 $\mu W/m^3$ in the Kometan Formation to 3.84 $\mu W/m^3$ in the Chia Gara Formation. Moreover, heat generation is significantly higher in the Jurassic formations, ranging from 1.53 µW/m^3 in the upper Butmah Formation to 4.43 µW/m^3 in the Naokelakan Formation. Also, despite higher heat generation rates in the Jurassic formations, the overall heat generated in the Cretaceous layers is greater due to their greater thickness, totaling 2,846 µW/m^2 compared to 2,196 µW/m^2 in the Jurassic. Finally, the cumulative heat generation across the 3000-meter section for the Cretaceous and Jurassic ages totals 5043.52 µW/m^2 (5.034 mW/m^2) heat flows. Considering the estimated thickness of the sedimentary basin in the region exceeds 10,000 meters, the total heat generation is approximately 16,811 µW/m^2 (≈17 mW/m^2). This represents more than 25% of the total subsurface heat flow, estimated at 40 – 60 mW/m^2.

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