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Natural Gamma Ray Borehole Logging Technique for Estimating Radiogenic Heat Production in Basaltic Environment, Case study from Kodana region, Southern Syria

Jamal Asfahani[1*]

Resumen

Con el propósito de evaluar la producción de calor radiactivo (HP, por sus siglas en inglés) se han utilizado dos técnicas nucleares en un entorno basáltico de Kodana, en el sur de Siria. Estos son: sondeo de pozos para el registro de rayos gamma de origen natural (Ra) y espectrometría de rayos gamma. Las medidas de Ra se convierten a valores HP con base a la relación de Bucker y Rybach. La subestimación de los valores HP en el caso de estudio del sondo de pozos en Kodana señala la necesidad de una modificación de las constantes de la relación de Bucker y Rybach (0.0158 y 0.8). Por ello se propone establecer una nueva ecuación de la siguiente forma: HP(μW/m^3)= 0.037 (Ra(API)+ 4.35, más adecuada para caracterizar HP en ambientes basálticos continentales. Además, su eficacia se ha validado con la estimación y análisis del HP en tres pozos adicionales en la región de estudio. El análisis de 377 puntos medidos a lo largo del pozo Kodana muestra que el Ra varía entre 4.93API y 9.31API, con un valor promedio de 6.83API, mientras que el HP corregido y calibrado varía entre 0.32 y 0.51 μW/m^3, con un valor promedio de 0.42 μW/m^3.

Utilizando multifractales número-concentración y gráficas log-log se distinguen cuatro rangos de valores de HP calibrados en la región de estudio. El primer rango (<0.354μW/m^3) está relacionado con basalto denso y masivo; el segundo (0.354–0.41μW/m^3) con basalto sólido; el tercero (0.41–0.44μW/m^3) con basalto piroclástico, y el cuarto (>0.44μW/m^3) con productos de alteración del basalto y arcillas.

Palabras Clave: Producción de calor radiactivo, Técnica de registro de pozos de rayos gamma naturales, Basalto en el sur de Siria

Abstract

Two nuclear techniques are used to evaluate the radioactive heat production (HP) in a basaltic environment in the Kodana region, Southern Syria: natural gamma ray borehole logging (Ra) and spectrometry gamma ray. The Ra measurements are converted into (HP) values based on the Bucker and Rybach relationship. The underestimated HP values obtained in this case study of Kodana well require therefore a modification of the Bucker and Rybach relationship constants (0.0158 and 0.8). A new equation is thereafter established and proposed as follows: HP (μW/m^3) = 0.037* Ra(API) + 4.35. This equation is more suited to characterize HP in continental basaltic environments. The proposed equation is validated and has proven its efficacy through estimating and analyzing the HP in three additional boreholes in the study region. The analysis of 377 measured points along the Kodana borehole shows that Ra varies between 4.93API and 9.31API, with an average value of 6.83API, while the corrected and calibrated HP varies between 0.32 and 0.51 μW/m^3, with an average value of 0.42 μW/m^3.

Four calibrated HP ranges were isolated in the study region using the multi-fractal concentration number and log-log graphs. The first range (<0.354 μW/m^3) is related to hard massive basalt, the second (0.354 - 0.41 μW/m^3) is related to hard basalt, the third (0.41 - 0.44 μW/m^3) is related to pyroclastic basalt, and the fourth (> 0.44 μW/m^3) is related to basalt alteration products and clay.

Keywords: Radioactive heat production, Natural gamma ray borehole logging technique, Basalt Southern Syria

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* Corresponding author: Jamal Asfahani

[1] Geology Department, Atomic Energy Commission of Syria, P.O.Box. 6091, Damascus- Syria.

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1. Introduction

The radiogenic heat production (HP), an important parameter, is produced in the rocks through the decay of radioactive elements such as uranium, thorium and potassium. The heat production rate of a given rock can be therefore computed based on the concentrations of those radioactive elements and the density rocks (Rybach, 1988). The HP parameter has a considerable effect on the temperature distribution (Black Well and Steele, 1989), where its importance is evident in the modeling of deep sedimentary basins and in the heat-flow studies (e.g. Deming *et al.*, 1990). The heat-flow variations within a sedimentary basin are essentially due to the changes in radiogenic heat production of the underlying basement.

This paper deals with the characterization and identification of the radiogenic heat production in basaltic environments by using two different nuclear techniques, particularly, the natural gamma ray borehole logging, based on the use of Bucker and Rybach relationship, 1996, and the gamma ray spectrometry techniques.

Bucker and Rybach relationship, 1996, directly relates the gamma ray log records with the radioactive heat production. Asfahani, 2018, and 2022 evaluated the heat production in Area-1 and Area-2 in Syria respectively, applying the aerial spectrometry gamma ray technique. Asfahani (2019a) also applied the spectrometry gamma ray technique on 748 rock samples taken from Syrian territory to estimate their heat production and to map its spatial distribution on a constructed map. Asfahani, 2019-b, used the natural gamma ray well logging technique to evaluate the heat production in the phosphatic Khneifis deposit in Syria. Asfahani *et al.*, 2021, applied also this technique to characterize laterally and vertically the radioactivity (Ra) and the heat production in Banting district, SW of Malaysia, based on the Bucker and Rybach relationship. They explained that the high radioactivity and heat production ranges are mainly related to the silty clay layers, bearing uranium and thorium.

Prior to this research work, no available data on radiogenic heat production existed for the basaltic environments in Syria. Thus, it is timely to get the order of magnitude of this radioactive heat production parameter for different basaltic litho-types. The data reported here may also be useful for future thermal studies in neighboring areas.

The main objective of this paper is therefore to evaluate the radioactive heat production parameter (HP) in the study region, as a function of depth, concentrating mainly on the available Kodana borehole.

The API unit is required to be used for the gamma ray intensity in the Bücker and Rybach relationship. The counts per second (cps) unit of the measured natural gamma ray borehole logging records must be therefore converted into API units.

A new adapted equation is established and proposed in this paper to estimate the heat production in basaltic environments, where the use of Bücker and Rybach (1996) equation gives underestimated values of the heat production HP for such basaltic environments.

The log-log graph related to the concentration-number (C-N) model is used to identify the different ranges of both, the measured natural gamma ray (Ra) and the computed (HP) parameters in the Kodana study region. Those Ra and HP ranges reflect the vertical boundaries of the different lithologies traversed by the study borehole.

The following is achieved in this paper:

1. Evaluating the radioactive heat production (HP) as a function of depths along the study boreholes in the Kodana region by using the available natural gamma ray logs.
2. Evaluating the radioactive heat production (HP) of the rock samples taken from different depths of the Kodana borehole, applying the gamma ray spectrometry technique in laboratory.
3. Validating and proving the accuracy of the new equation proposed for HP estimation in three additional boreholes available in the study region.
4. Determining the main statistical characteristics of the measured natural gamma ray borehole logging records and the computed radioactive heat production in the analyzed boreholes, particularly the Kodana one (Min, Max, Mean, and standard deviation σ).
5. Assessing the different population ranges of both, the measured natural gamma ray logging records, and the computed HP parameters in the Kodana region through a fractal approach.

2. Field work

Nuclear and electrical borehole logging techniques were used to log four drilled boreholes of depths varying between 190 and 300m in Southern Syria; their locations are shown in the Figure 1. A Digital Robertson geology borehole logging station was used for executing and acquiring the borehole logging records.

The present paper focuses mainly on the results obtained at the Kodana borehole, as similar borehole logging results have been obtained in the other three boreholes.

Figure 2 shows the different logs obtained in the Kodana borehole. Those logs include the natural gamma ray (cps), the density LSD log (g/cm^3), the porosity (%), and the short and long normal resistivity (Ohm-m) (Asfahani, 2011). The logs shown in Figure 2 cover only the saturated Neogene basalt aquifer from a depth of 110m. The water level and the interface between the saturated and non-saturated zones were already determined by neutron-porosity logs (Asfahani, 2011), as shown in Figure 3. The lithological description of the traversed layers in the saturated basaltic zone, shown in the right side of Figure 2 was established according to the different mentioned borehole logging results and their statistical treatment (Asfahani, 2011).

Four kinds of basalts have been identified in the study region based on the adapted threshold concepts and the above-mentioned nuclear and electrical logs (Asfahani, 2011). Those basalt types are as follows:

- Hard massive basalt.
- Hard basalt.
- Pyroclastic basalt.
- Alteration basalt products, clay.

3. Nuclear techniques for estimating heat production

Two nuclear techniques are used in this paper to evaluate the radioactive heat production in a basaltic environment (Richardson and Killeen, 1980; Thompson *et al.*, 1996; Bücker and Rybach, 1996; Salem *et al.*, 2005; Asfahani 2018; Asfahani, 2019a, and Asfahani, 2019b). The first one is the natural gamma ray borehole logging technique, and the second is the gamma ray spectrometry applied on basaltic rock samples.

3.1 Natural gamma ray borehole logging technique- Ra and API unit

The natural gamma ray (Ra) log is a continuous measurement of the natural radioactivity radiated from the lithological formations traversed by the logged borehole. This radioactivity is due to the presence of the potassium-40, uranium, and thorium (K40, eU, eTh). The used sensitive detectors were able to count the number of gamma rays per unit of time. The equipment used to record the (Ra) logs is a RG PC-logger system II. The length of the winch is 500 m. The gamma probe dimensions are 2.4 m length and 4.4 cm diameter. The gamma detector is the sodium iodide (Thallium doped) scintillation crystal, with a dead time of 4 micro seconds (Robertson geo-logging, 1993).

It is to mention that the location of the drilled Kodana well of GPS coordinates (E: 3589614, N: 3301961 and Z: 770m) was determined by the author (Asfahani, 2022a).

The gamma-ray intensity was measured by the unit of count per second (cps). The American Petroleum Institute has already adopted the "API" as a gamma ray unit to obtain a standard unit for gamma ray log measurements. One API Gamma ray unit is determined as 1/200 of the difference between the low and high gamma ray radiation values measured in (cps) in the calibrated pit. The calibration relationship between cps and API is written as follows (Lashin, 2005):

$$\text{API} = 1/200 * \Delta\,(\text{high- low (cps)}) \qquad (1)$$

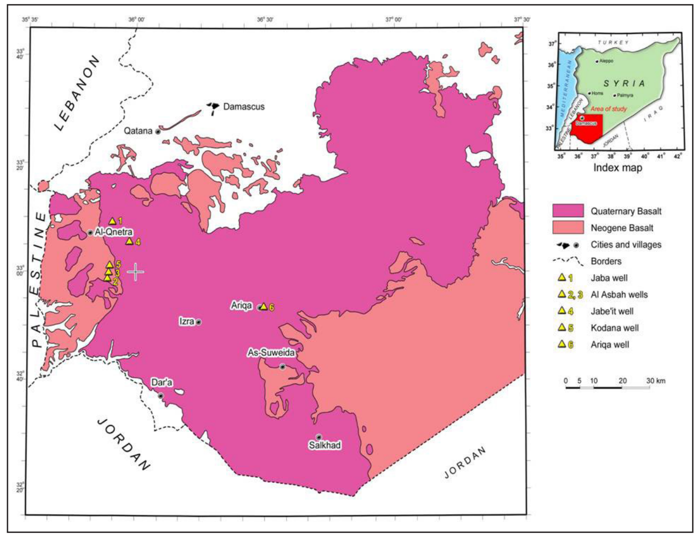

Figure 1. Geology of the study region and the location of the drilled boreholes.

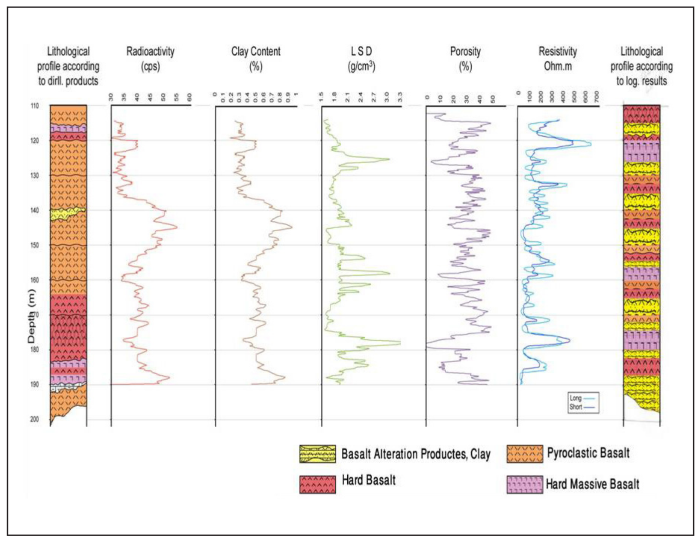

Figure 2. Nuclear and electrical logging records with lithological description of the Kodana borehole.

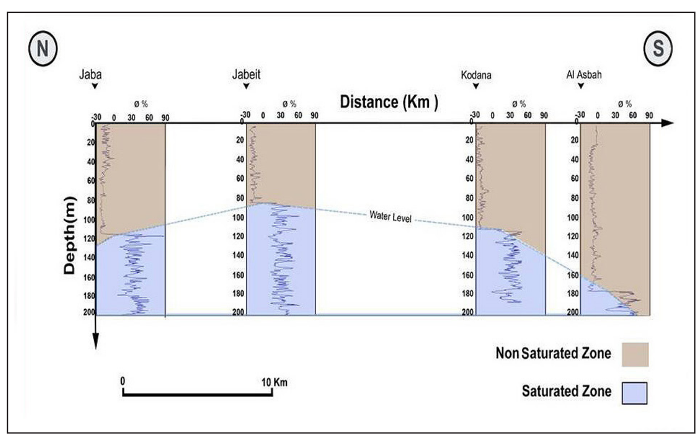

Figure 3. The water level and the interface between saturated and non-saturated zones in the study region, Southern Syria (Asfahani, 2011).

The high measured value in the analyzed Kodana well is 56 cps, the low measured value is 20 cps. Using these numbers in equation (1), 0.18 cps is about 1 API.

3.2 Spectrometric gamma ray technique

The gamma spectrometer consisted of a 12.5% relative efficiency Ge detector, with an energy resolution of 1.8keV at 1.333MeV, coupled to an S-100 spectroscopy system with an 8192 ADC card. The gamma ray measurements were realized in a 10 cm thick lead shield covered internally with a 1 mm thick copper sheet. The calibration of the gamma spectrometer for U, Th, and K analysis was achieved with the use of the standard reference materials RGTh and RGU related to IAEA, which were counted under the same conditions as ore samples (AQCS, 1995). The GaNAAS (Gamma and Neutron Activation Analysis Spectrum) PC program was used to analyze the gamma spectra (Nuclear Analysis Software, 1991). This is an indirect spectrometric gamma counting technique that gives U analysis as eU analysis. The term eU is widely used to indicate an equivalent uranium, and is equal to the true uranium only if the rock sample analyzed is in a radioactive equilibrium state, (Asfahani, 2002). Nineteen rock samples taken from different depths of the Kodana borehole were analyzed using this technique to determine U, Th and K contents of the studied basaltic section. Four basaltic rock samples were used for computing the radioactive heat production (the other fifteen rock samples were not used, being located in the unsaturated basaltic aquifer above 110m).

The evaluation of the radioactive heat production (HP) on the rock samples requires the knowledge of the concentrations of the radioelements (eU, eTh, and K%) (Fernandez *et al.*, 1998) and the density of the rock samples (ρ) (Asfahani, 2019a), where the following empirical equation is used (Rybach, 1976):

$$HP\ (\mu w/m^3) = \rho * Y \qquad (2)$$

Where Y= (0.0952 eU+ 0.0256 eTh + 0.0348 K%)

In which, ρ (g/cm^3) in equation (2) is the dry density of the sample rock, eU (ppm), eTh (ppm), and K (%) are the concentrations of uranium, thorium, and potassium respectively.

Equation (2) gives the energy released during alpha, beta, and gamma decay of the radioelements (Rybach, 1976; Rybach, 1976a; and Birch, 1954). The alpha decay of the uranium is the main source of radioactive heat production (Birch, 1954), unlike thorium and potassium that have only a limited contribution.

The natural gamma spectrometry tool (NGS) and the density tool (LTD) can be also used together to estimate the radioactive heat production along the boreholes. The knowledge of the (eU, eTh, K%) and the density (ρ) allows consequently to compute the radioactive heat production from equation (2).

However, the gamma spectrometry borehole logging tool is not always available, while the natural gamma-ray logging tool (Ra) is available and can be used in a huge number of exploration boreholes over the world. The natural gamma ray (Ra) log reflects generally the sum of uranium, thorium, and potassium existed at a given depth in the study borehole, as represented by Y in equation (2).

Bücker and Rybach in 1996 already established an empirical direct linear relationship between the logging (Ra) intensity evaluated in API unit, and the radioactive heat production (HP) (μw/m^3), as follows:

$$HP\ (\mu W/m^3) = 0.0158\ (Ra\ (API) - 0.8) \qquad (3)$$

Equation (3) was established and derived through a collected data set from the research boreholes Sancerre-Couy/F, Soultz/F, BALAZUC-I/F, KTB/D, ODP 834B (Ocean Drilling Program), and three different NAGRA-holes/CH (Bücker and Rybach, 1996). It is applicable only for a radioactivity range of 0 to less than 350 API. It is often suitable to be applied in different sedimentological and geological environments, and gives reasonable results within an error of less than 10% (Bücker and Rybach, 1996). As much as the K/eU and eTh/eU ratios are closer to the mean characteristics values of the continental crust, as much as the error is lower (Bücker and Rybach, 1996).

The radioactive heat production HP is evaluated in the Kodana borehole study, based on equation (3). HP is also evaluated in three additional available boreholes in the study region (Jaba, Jabeit, and Al-Asbah), using a new proposed equation more suitable for characterizing the continental basalt than the one of Bücker and Rybach, 1996.

3.3. Fractal technique and concentration number mode (C-N)

A log-log graph with the concentration-number (C-N) multifractal model is used to determine the straight line segments and the break thresholds points, that we use as vertical boundaries to separate between different anomalous ranges (Afzal *et al.*, 2010; Zuo 2011; Wang *et al.*, 2011, Mohammadi *et al.*, 2013). This technique is applied herein on the measured natural gamma ray logs (Ra), and on the related computed corrected radioactive heat production (CHP) parameters for the Kodana region to distinguish different ranges of Ra and HP anomalies.

The equation describing the concentration-number (C-N) fractal model is as follows:

$$N(\geq\mu) = F\ \mu^{-D} \qquad (4)$$

Where μ is the treated geophysical parameter values, which are in this paper the (Ra) in API unit, and the corrected radioactive heat production (CHP) (μW/m³). N(≥μ) is the cumulative number of the analyzed geophysical data, which are the cumulative number of the measured natural gamma ray logs (CNRa), and the cumulative number of the computed radioactive heat production (CNCHP), with the geophysical parameter values greater than or equal to μ; D is the scaling exponent or fractal dimension of the distribution of geophysical parameter values and F is a constant.

4. Results and Discussion

Natural gamma ray borehole logging technique was applied on the available four drilled boreholes in the Kodana region (Asfahani, 2011). The cps unit of the natural gamma ray records (Ra) presented for Kodana well, shown in Figure 2 is converted in this paper to API units. Figure 4 shows the variation of Ra along the Kodana borehole.

It is clear from Figure 4 that Ra intensity varies between 4.93 and 9.31 API with an average value of 6.83 API.

The quation (3) of Bücker and Rybach, 1996, presented above, is used to evaluate the radioactive heat production HP along the Kodana studied borehole. Figure 5 shows therefore a representative example on the radioactive heat production variations log (LHP) obtained along the Kodana borehole.

The main and high (LHP) layer is concentrated at depths between 140 and 155m, due to the presence of a basalt alteration products, and clay at this range of depths.

The (LHP) values obtained with the Bücker and Rybach technique (1996) shown in Figure 5 are underestimated in comparison with the literature HP values obtained in similar continental basalt areas particularly in the Northeast of German basin (where the HP for the basaltoides is ranged between 0.1 and 0.7μW/m³) (Ben Norden and Forster, 2006); Hasterok *et al.*, 2018; and Asfahani, 2019a.

Abady *et al.*, 2004 has already reported the mean radioactive heat production of 0.11 μW/m³ for the basalt of Eastern desert, Egypt, and compared also with other published data such as 0.80 μW/m³ for the basalt from Japan, and 0.39 μW/m³ for the basalt former USSR.

The (LHP) underestimation in this specific case study of Kodana well can be explained by the considerable radioactive difference between the continental rock samples basalt of the study region, and those used for the calibration of Bücker and Rybach technique, 1996. Those authors

declared that as much the K/eU and eTh/eU ratios of the analyzed rock samples are closer to the mean characteristic values of the continental crust, as much the error in evaluating the radioactive heat production is lower (Bücker and Rybach, 1996).

The radioactive heat production (HP) is also computed on four different basaltic rock samples taken from different depths of the Kodana borehole, to get the real and corrected heat production (CHP) of the basaltic layers in the study region. The results of those four rock samples analysis are shown in Table 1. The values of (CHP) for those rock samples

Table 1. Corrected radioactive heat production (CHP) of the basaltic rock samples taken from Kodana borehole.

Number	Depth (m)	eU (ppm)	eTh (ppm)	K%	Density (g/cm³)	CHP μW/m³	LHP μW/m³
1	110	1.48	2.11	0.49	1.55	0.33	0.07
2	115	1.35	3.4	0.55	1.57	0.37	0.076
3	130	1.29	2.45	0.71	1.818	0.38	0.079
4	170	1.75	2.85	0.67	1.6	0.42	0.098

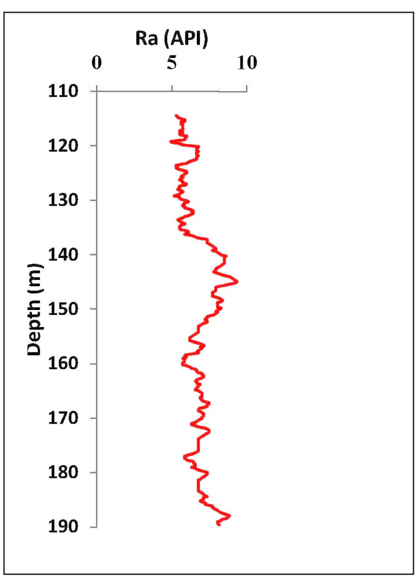

Figure 4. Natural gamma ray log Ra along the Kodana borehole.

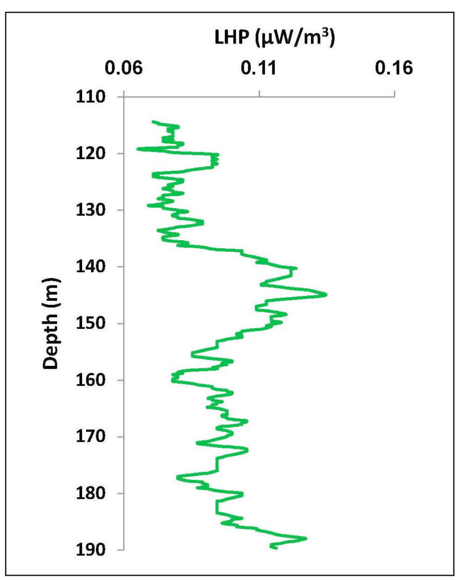

Figure 5. Radioactive heat production log (LHP) along the Kodana borehole.

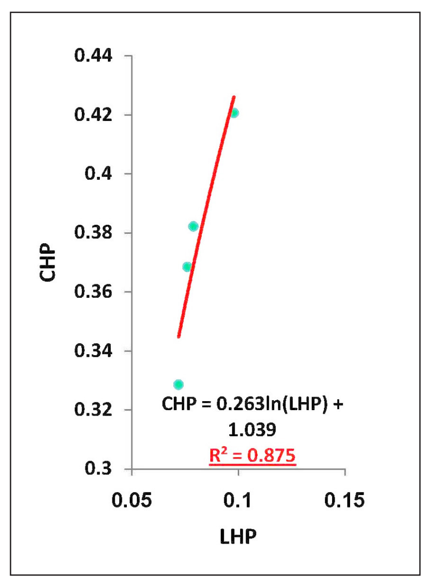

Figure 6. Regression equation between (CHP) and (LHP).

vary between 0.32 and 0.42 μW/m^3, and are in agreements, particularly with the range (HP) values of the basalt of German basin (Ben Norden and Forster, 2006, Abady *et al.*, 2004; Hasterok *et al.*, 2018; and Asfahani, 2019a.

A regression analysis is done between the corrected radioactive heat production values of the rock samples (CHP), and those values computed (LHP) in the Kodana borehole by Bücker and Rybach technique, 1996 at the same depths of rock samples locations, Table 1. The regression line between (CHP) and LHP is shown in Figure 6.

The regression equation between (CHP) and (LHP) has the following form:

$$CHP = 0.26 * \ln(LHP) + 1.039 \quad (5)$$

with a regression coefficient R^2= 0.875.

Since R^2 is high and acceptable, equation (5) is applied therefore to correct and calibrate the measured radioactive heat production (LHP) along Kodana borehole as shown in Figure 7.

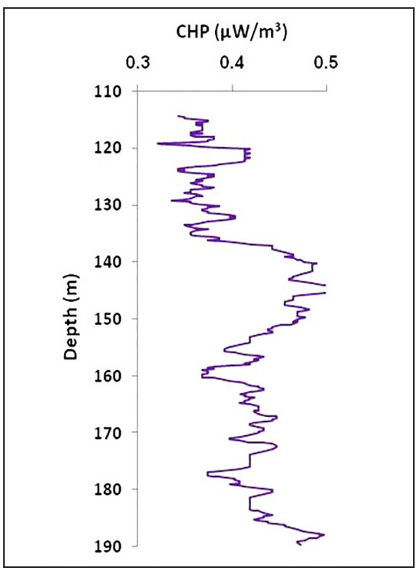

Figure 7. corrected and calibrated (CHP) along Kodana borehole.

Table 2. Statistical characteristics of Ra (API) and CHP (μW/m^3) in the Kodana borehole

	Ra (API)	HP (μW/m^3)
No of measured points	377	377
Min	4.93	0.32
Max	9.31	0.51
Average	6.83	0.42
Standard deviation	0.94	0.041

The corrected (CHP) along the Kodana borehole varies between a minimum of 0.32 and 0.51 μW/m^3 with an average of 0.42μW/m^3 as shown in Table 2. The frequency distributions of both (Ra) and (CHP) shown in Figure 8 (a and b) reflect normal distributions.

The obtained corrected (CHP) values are in close agreement with those of the basalt of the Northeast German basin (Ben Norden and Forster, 2006), Abady *et al.*, 2004; Hasterok *et al.*, 2018, and Asfahani, 2019a.

Based on the corrected radioactive heat production log discussed above, the empirical equation (3) of Bücker and Rybach (1996) must be necessarily modified to be more suitable and applicable in continental basalt environments. The two constants of 0.0158 and 0.8 reported in the equation (3) must be therefore changed and modified to be as 0.037 and -4.35 respectively.

The new established equation has accordingly the following form:

$$HP\ (\mu W/m^3) = 0.037\ (Ra\ (API) - (-4.35)) \quad (6)$$

Figure 9 confirms the excellent agreement between the corrected radioactive heat production results (CHP) discussed above and those (CHP-1) obtained by applying the new proposed modified equation (6). The R^2 regression coefficient

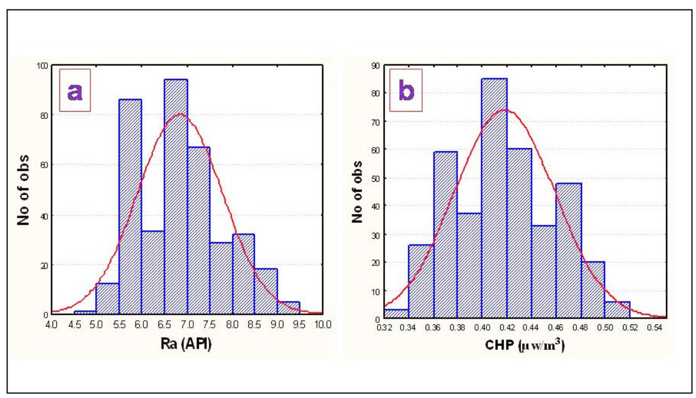

Figure 8. Frequency distribution of a): Radioactivity (Ra) and b): Corrected radioactive heat production (CHP).

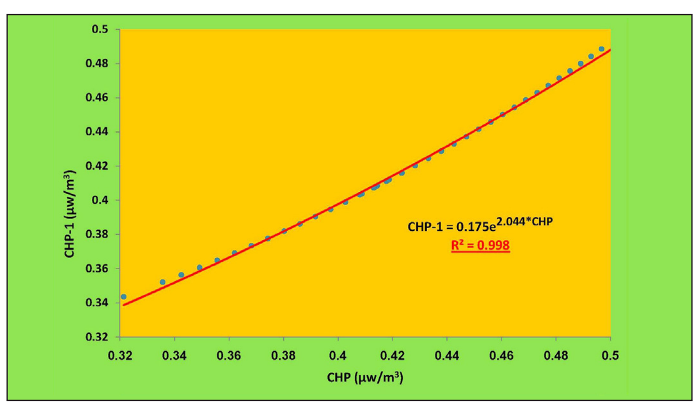

Figure 9. Correlation curve between (CHP) and (CHP-1).

between (CHP) and (CHP-1) is 0.998. The absolute and relative errors between (CHP) and (CHP-1) do not exceed 0.0221 and 6.87% respectively.

With the values of both the (CHP) log and the density log being known at the Kodana borehole, one can easily get the variations of the parameter (Y) included in equation (2) along the Kodana borehole as shown in Figure 10.

The "Y" parameter includes the sum of radioelements (eU, eTh, and K%) that contribute to the heat production. It seems that the vertical resolution of the (Y) is better than that of the Ra log shown in Figure 4. The variations of (Y) log give insights on the basalt deposition and its geological conditions, and show also a successive of poor and rich radioactive contents (eU, eTh, and K%).

Figure 11 shows a positive correlation statistical relationship between (Y) and (CHP) with $R^2 = 0.384$. The low R^2 is due to two factors. The first is that uranium is the main radioactive element

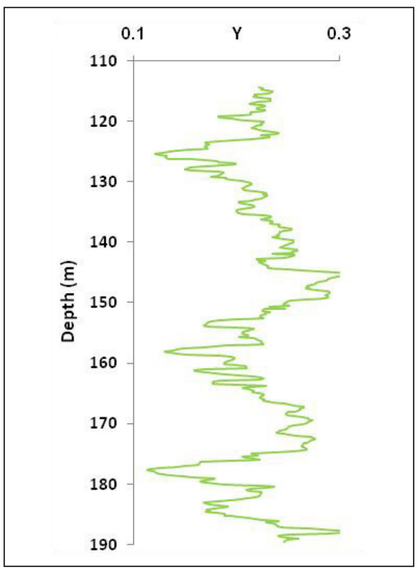

Figure 10. Variation of "Y" along Kodana borehole.

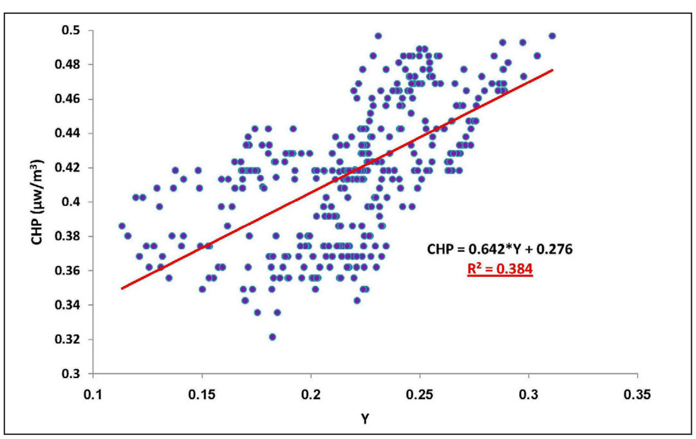

Figure 11. Correlation relationship between (Y) and (CHP).

in producing heat, compared with eTh and K%, which have just a limited role in such a radioactive heat production. The second is the density parameter that relies (Y) and (CHP), and its variations along the Kodana borehole.

Fractal concentration-number (C-N) model and log-log plots are applied to characterize the variations of both Ra (API) and CHP ($\mu W/m^3$) parameters related to 377 points measured along the Kodana borehole in the study region.

The log-log graphs show different break points (C1, C2, and C3) that can be used as thresholds and lithological boundaries in the study Kodana borehole. Different lithological populations of (Ra) and (CHP) are consequently differentiated according to those determined break-points. The three C1, C2, and C3 threshold break points are shown on the C-N log-log plot of (Ra) at the locations of 0.823, 0.907, and 0.933 respectively as presented in Figure 12. Those three locations on the log (Ra) indicate a natural gamma ray intensity of 6.65, 8.07, and 8.57 API respectively. The three break points correspond to four straight line segments with different slopes $-D$, corresponding to different population ranges on the log–log plots of $N(\geq\mu)$ versus μ (Ra).

The four Ra ranges are as follows: The first range is less than 6.65 API, the second range is between 6.65 and 8.07 API, the third range is between 8.07 and 8.57 API, and the fourth range is bigger than 8.57 API.

The three C1, C2, and C3 threshold break points are shown on the C-N log-log plot of CHP at the locations of -0.451, -0.387, and -0.355 respectively as presented in Figure 13. Those three locations on the log (CHP) indicate a corrected radioactive heat production CHP of 0.354, 0.41, and 0.44 $\mu W/m^3$ respectively. The three break points correspond to four straight line segments with different slopes $-D$,

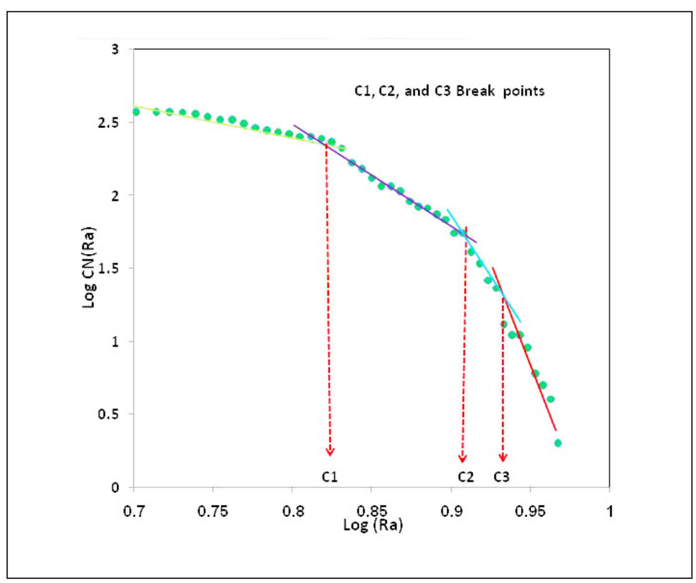

Figure 12. Log-log plot for the Ra (API) parameter in the Kodana borehole.

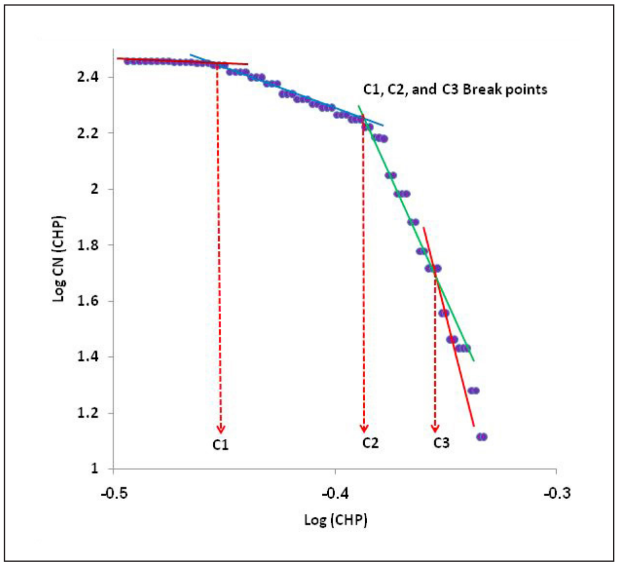

Figure 13. Log-log plot for the computed CHP parameter in the Kodana borehole.

corresponding to different population ranges on the log–log plots of N(≥μ) versus μ (CHP).

The four (CHP) ranges are as follows: The first range is less than 0.354 μW/m^3, the second range is between 0.354 and 0.41 μW/m^3, the third range is between 0.41 and 0.44 μW/m^3, and the fourth range is bigger than 0.44 μW/m^3.

The lithological rock types corresponding to the four ranges of (Ra) and (HP) determined by the fractal technique discussed above are shown in Table 3.

The new corrected radioactive heat production data gathered through benefiting from the available natural gamma ray logging records are important for the geothermal research in the near future in the study region.

5. Verification and validation of the new proposed equation

The new proposed equation 6 for estimating the heat production in basaltic environments is verified and validated through its additional application in other three drilled wells (Jaba, Jabeit, and Al-Asbah) in the study region. The locations of those three wells are shown in Figure 2. The natural gamma rays logs (Ra) in cps for those wells cover only the saturated Neogene basalt aquifer in the study region as shown in Figure 3, and are converted into API unit (Figure 14) as done for Kodana well.

The heat production logs (HP) are computed for those wells, according to the proposed equation 6 as shown in Figure 15.

The main statistical results obtained for Ra and HP for those three wells are presented in Table 4.

Comparable HP results with those discussed above for Kodana well are obtained by applying equation 6.

The range of the heat production obtained in the four studied wells (0.165-0.5 μW/m^3) by using the new proposed equation is in agreement with the one reported (0.1- 0.7μW/m^3) by Ben Norden and Forster, 2006 for the the basaltoides of Northeast of German basin. This attests to the

validity of the new proposed equation 6 for characterizing the heat production (HP) of the continental basalt, by using the natural gamma ray well logging technique.

Table 3. Rock types related to the Ra (API) and CHP (μW/m^3) in the study area.

Ra (API)	**HP (μW/m^3)**	**Rock Type**
< 6.65	< 0.354	Hard massive basalt
6.65-8.07	0.354-0.41	Hard basalt
8.07-8.57	0.41-0.44	Pyroclastic basalt
> 8.57	> 0.44	Alteration basalt products, clay

Table 4. Statistical of Ra and HP in the Jaba, Jabeit, and Al-Asbah wells.

	(Jaba well) **Ra (API)**	(Jaba well) **HP** (μW/m^3)	(Jabeit well) **Ra (API)**	(Jabeit well) **HP** (μW/m^3)	(Al-Asbah well) **Ra (API)**	(Al-Asbah well) **HP** (μW/m^3)
Min	0.123	0.165	1.13	0.20	0.94	0.195
Max	0.31	0.172	2.88	0.27	3.78	0.30
Average	0.229	0.169	1.87	0.23	1.91	0.23

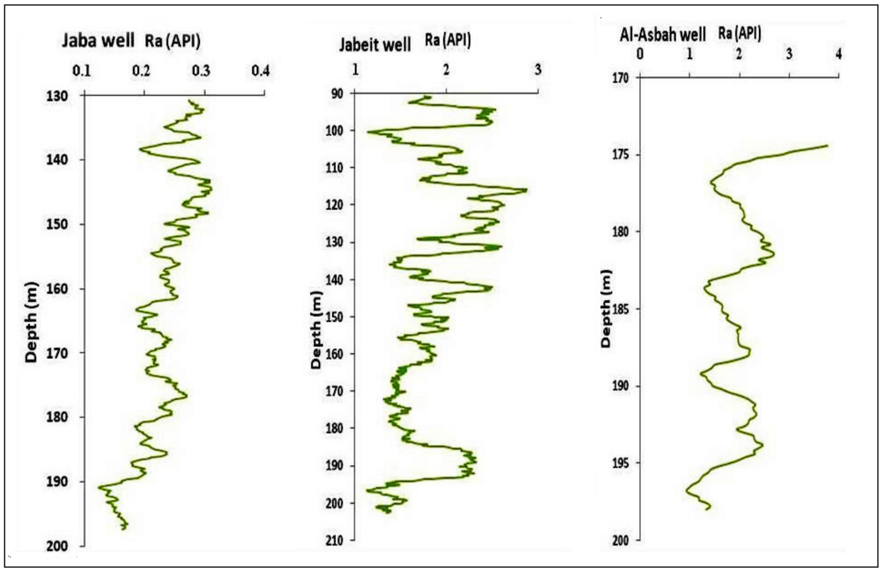

Figure 14. Natural gamma ray logs (Ra) in Jaba, Jabeit, and Al-Asbah wells.

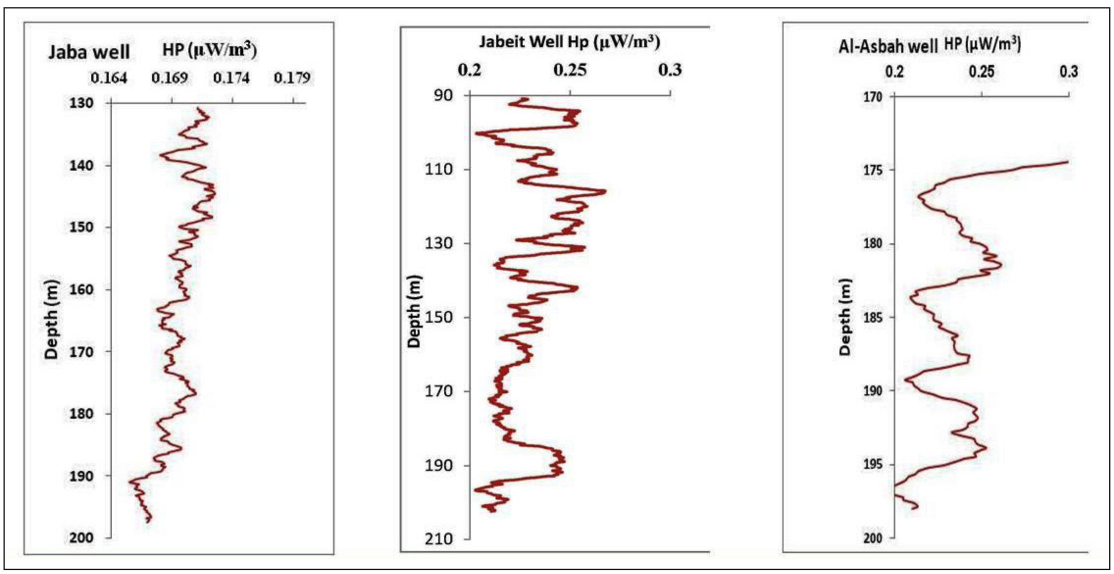

Figure 15. Heat production logs (HP) computed according to equation.6 in Jaba, Jabeit, and Al-Asbah wells.

6. Conclusion

The direct method proposed by Bücker and Rybach (1996) is applied to convert the natural gamma ray logs (Ra) to radioactive heat production logs (LHP). The application of this technique on the (Ra) of Kodana borehole gives underestimated (LHP) values. This underestimation is due to the considerable difference between the radioactive content of the continental basalt (eU, eTh, and K%) related to the study region and that of the basaltic rock samples used for the calibration of the empirical relationship of Bücker and Rybach. The constants of equation (3) of Bücker and Rybach, 1996 are accordingly modified, where a new relationship is established and proposed between natural radioactivity (Ra) log values and radioactive heat production (HP). The new proposed equation is more suitable as demonstrated and proven in this present case study to be applied for characterizing the radioactive heat production in continental basaltic environments. This new equation is also verified and validated on other additional three drilled wells in the study region, where the different HP results obtained through those wells demonstrate a clear consistency between them.

The radioactive heat production values (CHP) obtained through the basalt rock samples are accurately determined, and agree with those obtained in the literature worldwide. The regression analysis done between (LHP) and (CHP) enables us to establish the corrected radioactive heat production (CHP) log along the Kodana borehole, where the high (CHP) values are related to the basalt alteration product and clay. The use of the concentration-number (C-N) fractal model with the log-log graphs allows to distinguish different radioactivity and corrected radioactive heat production ranges related to different kinds of basalt. The new (CHP) log data of the Kodana region are required for analyzing and characterizing the temperature distribution modeling and the thermal evolution of the study region.

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8. Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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