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Radiogenic Heat Variation with Lithology in Clastic Sediments Deduced from WellLogs: An Implication for Hydrocarbon Generation ATG-Field, Niger Delta Basin

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ABSTRACT. This study investigates the variation in radiogenic heat production (RHP) from four sets of well logs, namely ATG-10, ATG-11, ATG-7, and ATG-5, recorded in clastic sediments of the Benin, Agbada, and Akata formations in the ATG field, shallow offshore Niger Delta. The primary lithologies identified in the gamma-ray log were sand, shale, and shale-sand intercalations. The variations of radiogenic heat production (RHP) were computed using the total gamma ray count (GR) combined with density logs (RHOB) using the Bucker and Rybach linear methods. Heat production rates calculated were found to vary from 0.23–2.24 μWm^{-3} ± 0.08 for ATG 10, and 0.22–2.25 μWm^{-3} ± 0.08 for ATG 11, then 0.31–2.35 μWm^{-3} ± 0.08 for ATG 7 and 0.34–2.33 μWm^{-3} ± 0.08 for ATG 5. The average radiogenic heat production ranges from 0.9 μWm^{-3} to 2.29 μWm^{-3}. High values of radiogenic heat production were observed in the shale lithology of the Akata Formation, attributed to the high concentrations of radioelements (uranium, thorium, and potassium) in the sediment. Conversely, low RHP values were found in the sand lithology of the Benin Formation due to the lower concentrations of these radioelements. The magnitudes of RHP calculated in this study can produce enough heat, which may affect the hydrocarbon potential in the clastic sediments of the Niger Delta and may also classify the thermal regime and contribute to the maturation of Kerogen into hydrocarbon in the Niger Delta. Depth versus RHP cross plots showed heat production tends to increase with depth since the basin is underlain by the Akata formation, which is mainly marine shale. Where spectral gamma-ray data are not available, the relationship between RHP Gamma-ray and density log established in this study may be used in any part of the Niger Delta to calculate RHP.

Keywords: Radiogenic heat · Radioelements · Gamma-ray · RHP.

1 INTRODUCTION

Understanding the thermal history and present thermal state of the subsurface is fundamental to hydrocarbon maturation studies, particularly in the context of sedimentary basin modelling and continental evolution (Turcotte & Ahern, 1977; Keen, 1979; Royden *et al.*, 1980; Angevine & Turcotte, 1981). A key factor affecting these thermal characteristics is the quantity and distribution of heat generated by the radioactive decay of isotopes in the Earth's crust (Babalola, 1984). This is especially significant in petroleum systems analysis, as it aids in estimating the maturation state of organic matter within sedi-

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mentary sequences, thereby helping predict the potential for hydrocarbon generation, thermal evolution of sedimentary basins and by extension, the maturation of source rocks and the quality of reservoir rocks is governed by temperature variations within the Earth's interior (McKenna & Sharp, 1998). Consequently, geoscientists utilize geothermal data extensively to reconstruct basin thermal histories and to understand the broader thermal architecture of the lithosphere. Organic matter maturation, primarily the transformation of kerogen into hydrocarbons, is driven by geothermal heating processes acting on sedimentary sequences (Beardsmore & Cull, 2001; Emujakporue & Godwin, 2016).Temperature distribution in sedimentary basins is controlled by three primary components: (1) radiogenic heat production (RHP) within the sediments, (2) RHP from the underlying crystalline crust, and (3) mantle-derived heat, often referred to as primordial heat (Hokstad *et al.*, 2017). Heat sources within these systems are diverse and include deep mantle heat, exothermic chemical reactions within the basin, radiogenic decay of isotopes in sediments, and solar radiation at the Earth's surface (Lowrie, 1997).

The study area is located in the shallow offshore region of the Niger Delta Basin, Nigeria (Figure 1), between latitudes 3°N and 6°N, and longitudes 5°E and 8°E. Situated in the Gulf of Guinea off the coast of Equatorial West Africa, it is part of one of the world's most prolific hydrocarbon provinces. Radiogenic heat production (RHP) is a fundamental scalar petrophysical property that remains independent of insitu temperature, pressure, and chemical environment (Rybach, 1982). It is defined as the amount of heat released per unit time and per unit volume of rock due to the decay of unstable radioactive isotopes, typically expressed in microwatts per cubic meter (μW m^{-3}) (Christoph, 2020). The dominant contributors to RHP in crustal rocks are three naturally occurring radioactive elements: uranium (U), thorium (Th), and potassium (K). These isotopes possess long half-lives comparable to the Earth's age and are sufficiently abundant in the crust, making their heat contribution geologically significant (Brown & Mussett, 1993).

During radioactive decay, mass is converted into energy, with alpha, beta, and gamma radiation released as decay products. While neutrinos and antineutrinos escape the Earth without interaction, the kinetic energy of other particles is absorbed by the surrounding rock and converted into heat (Hamza & Beck, 1972; Rybach, 1986). The decay energy of uranium isotopes, especially ^{238}U, is significantly higher than that of thorium and potassium, yet their relative heat contributions are of similar magnitudes due to differences in crustal abundance (Turcotte & Schubert, 2002).

Radiogenic heat constitutes a major internal source of terrestrial heat and is a crucial component of the continental heat budget. Therefore, accurate heat flow modeling in sedimentary basins must incorporate RHP to properly constrain the thermal regime (Bücker & Rybach, 1996). Although other heat sources-such as frictional heating from fault movements, oxidation of sulfides, and exothermic metamorphic or diagenetic reactions exist, they are generally considered negligible in comparison to radiogenic contributions (Jessop, 1990; Slagstad, 2008). The vertical distribution of radiogenic heat sources within the continental crust significantly influences the thermal structure of the lithosphere and the amount of mantle-derived heat reaching the base of the crust. This distribution has profound implications for understanding geodynamic processes, lithospheric rheology, and hydrocarbon maturation. As such, it forms a key constraint in geochemical, petrological, and tectonic models of crustal evolution (Turcotte & Oxburgh, 1972; Albarède, 1975; Buntebarth, 1976; Gosnold, 1987; Beaumont *et al.*, 2001).

Radiogenic heat production (RHP) plays a crucial role in the formation and accumulation of hydrocarbons and other mineral resources. Despite its significance, RHP within sedimentary basins remains poorly constrained, largely due to the complexity of the subsurface and variability in measurement techniques. However, available data demonstrate a wide range of RHP values, varying over several orders of magnitude.

In the Niger Delta, heat production estimated from gamma-ray logs ranges from approximately 0.24 μWm^{-3} to 2.0 μWm^{-3}, with average values between 0.3 and 1.93 μWm^{-3} (Emujakporue, 2016). Similarly, in the Chad

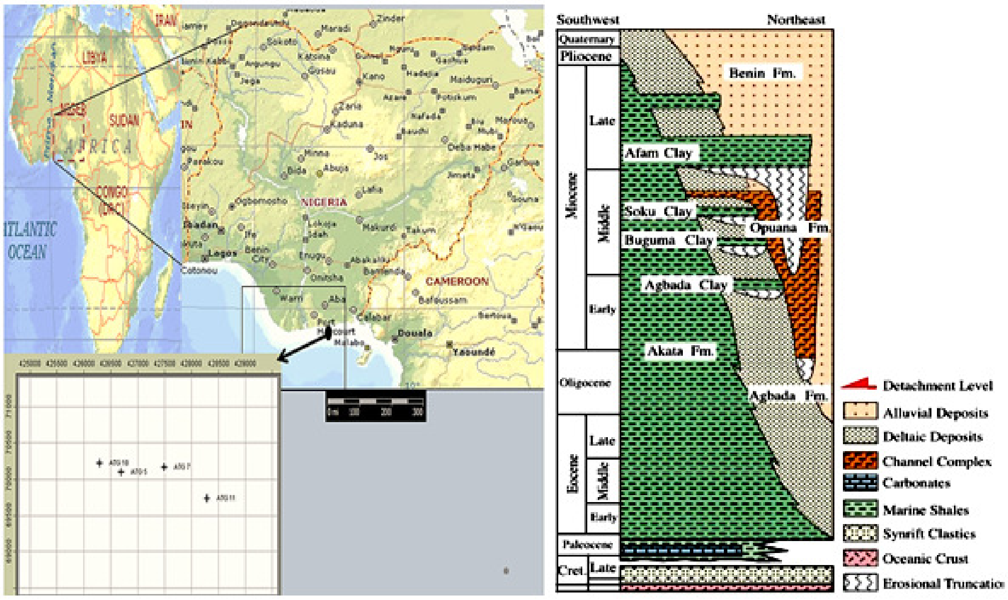

FIGURE 1. Study area in the Niger Delta Sedimentary basin in the Gulf of Guinea and Stratigraphic Column of the Niger Delta (Doust & Omatsola, 1990).

Basin of northeastern Nigeria, RHP derived from spectral gamma-ray logs varies from 0.1 to 1.9 μWm^{-3}, with averages typically between 0.1 and 0.9 μWm^{-3} (Ali & Orazulike, 2010). For comparison, sediments along the continental margins of eastern North America show heat production values ranging from 0.3 μWm^{-3} for limestones to between 1.4 and 1.8 μWm^{-3} for shales (Keen & Lewis, 1982).

In contrast, Precambrian crystalline rocks of the West African Craton display RHP values ranging from 0.9 to 1.8 μWm^{-3}, which are slightly lower than those recorded in East Africa, where RHP values range from 1.0 to 3.6 μWm^{-3} (Chapman & Pollack, 1975). Generally, sediments exhibit wider RHP variability than cratonic rocks, with a decreasing trend observed from shales to mudstones, sandstones, coals, carbonates, and evaporites (Epp *et al.*, 1970; Keen & Lewis, 1982; Rybach, 1986; Zhang, 1993; McKenna & Sharp, 1998).The estimation of RHP in sediments is commonly achieved through well-log data, particularly using natural gamma spectrometry (NGS) or gamma-ray logs. NGS tools measure the total count and spectral distribution of gamma radiation to estimate the concentrations of key radiogenic elements uranium (URAN, in ppm), thorium (THOR, in ppm), and potassium (POTA, in %). The gamma-ray energy spectrum of a rock is a composite of the characteristic emissions from each of these isotopes, enabling the estimation of RHP based on their individual contributions.

In the context of petroleum exploration, this data is indispensable. RHP can be estimated either directly from spectral gamma-ray logs or via empirical relationships involving total gamma-ray counts integrated with bulk density logs. This approach has been applied effectively in parts of the Niger Delta sedimentary basin to characterize heat generation within the subsurface and inform models of organic matter maturation and thermal evolution.

2 GEOLOGY OF THE NIGER DELTA

The study area is situated within the shallow offshore region of the Niger Delta Basin, Nigeria (Figure 1), between latitudes 3°N and 6°N, and longitudes 5°E and 8°E. It lies in the Gulf of Guinea, off Equatorial West Africa, forming part of one of the world's most prolific hydrocarbon provinces. The Niger Delta is an arcuate-shaped delta characterized by sedimentary sequences exceeding 12 km in thickness, and it constitutes a major petroleum-producing basin (Evamy *et al.*, 1978). Geological and geophysical evidence suggests that the Niger Delta developed after the formation of the Benue Trough and Anambra Basin. Numerous studies indicate that the Niger Delta is the thickest sedimentary basin in Nigeria and is structurally defined by growth faults and roll-over anticlines, which dominate its tectonic framework (Hospers, 1965; Corredor, 2005; Okiwelu *et al.*, 2012, 2013). Stratigraphically, the Tertiary Niger Delta is commonly divided into three major formations, reflecting a prograding depositional system. These units are primarily distinguished by their sand-to-shale ratios and depositional environments, as highlighted by various researchers (Short & Stauble, 1965; Avbovbo, 1978; Doust & Omatsola, 1989; Whitman, 1982; Reijers, 1996; Evamy *et al.*, 1978). At the bottom of the stratigraphic sequence undelay the Akata Formation, a prodelta marine unit deposited from the Paleocene to the present. It is primarily composed of thick shale sequences interspersed with turbiditic sands, along with minor clay and silt deposits. This formation is interpreted as a deep marine deposit formed during periods of low sea levels, when terrestrial organic matter and clay-rich sediments were transported into anoxic, low-energy environments (Stacher, 1995). The Akata Formation is the main source rock in the basin. Overlying the Akata Formation is the Agbada Formation, which spans from the Eocene to Recent. This unit represents the main petroleum-bearing interval of the Niger Delta and comprises paralicsiliciclastic sediments. It features alternating layers of sandstones and shales, with more sand-dominant deposits in the upper intervals and a more balanced shale-sand mix at the base (Avbovbo, 1978; Reijers, 1997; Burke, 1972). The uppermost unit is the Benin Formation, made up of coastal plain sands (Figure 2). Deposited from the Late Eocene to Recent, this formation consists of massive, unconsolidated continental sands and gravels of fluvial origin, primarily deposited in an upper delta plain setting. The Benin Formation is also an important aquifer system, known for its high freshwater yield.

3 MATERIALS AND METHODS

The ATG Field is located in the shallow offshore region of the Niger Delta Hydrocarbon Province. The study area encompasses four wells, each equipped with a suite of well logs, including gamma-ray, density, compressional velocity (V_p), resistivity, and porosity logs. Radiogenic heat generation within rocks is principally governed by the abundance of radioactive isotopes, their respective decay rates, and the energy released during particle emission. These factors, decay rate and energy output,are unique to each radioactive isotope, and the absolute concentration of these isotopes in a rock ultimately dictates the total rate of heat production (Table 1). Representative radiogenic heat production (RHP) values for various lithologies are presented in (Table 2). Approximately 98% of the geothermal heat attributed to radiogenic processes originates from the decay of three primary isotopes: Uranium (^{238}U), Thorium (^{232}Th), and (^{40}K) Potassium, which possess both the longevity and energy emission properties necessary to contribute significantly to the Earth's heat budget (Turcotte, 1980; Emsley, 1989; Jessop, 1990).

3.1 Lithology discrimination and volume of shale

The Gamma-ray index method was utilized to estimate the proportions of shale and sand lithologies within the study area. This involved identifying the clean sand line from Gamma-ray log responses. The calculation of the Gamma-ray index represents the initial step in determining the volume of shale, as outlined by Schlumberger (1974) and presented in Equation 1. Lithological differentiation was based on Gamma-ray values, where readings below 75 API (typically represented in yellow) were interpreted as sand, while values above 75 API (typically shown in grey) were classified as shale. This approach was applied to the Gamma-ray logs of wells ATG-10, ATG-5, ATG-11, and ATG-7, reflecting the alternating sand and shale sequence characteristic of the study area subsurface geology.

$$IGR = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \tag{1}$$

3.2 Methods of calculating radiogenic heat and radioactive decay

Heat generation in rocks occurs primarily through the radioactive decay of unstable isotopes, notably Uranium (^{238}U), Thorium (^{232}Th), and Potassium (^{40}K). This decay process releases energy in the form of alpha (α) particles, beta (β) particles, gamma (γ) rays, neutrinos (ν), and antineutrinos ($\dot{\nu}$), as illustrated in Equations 2, 3, and 4 (Beardsmore &

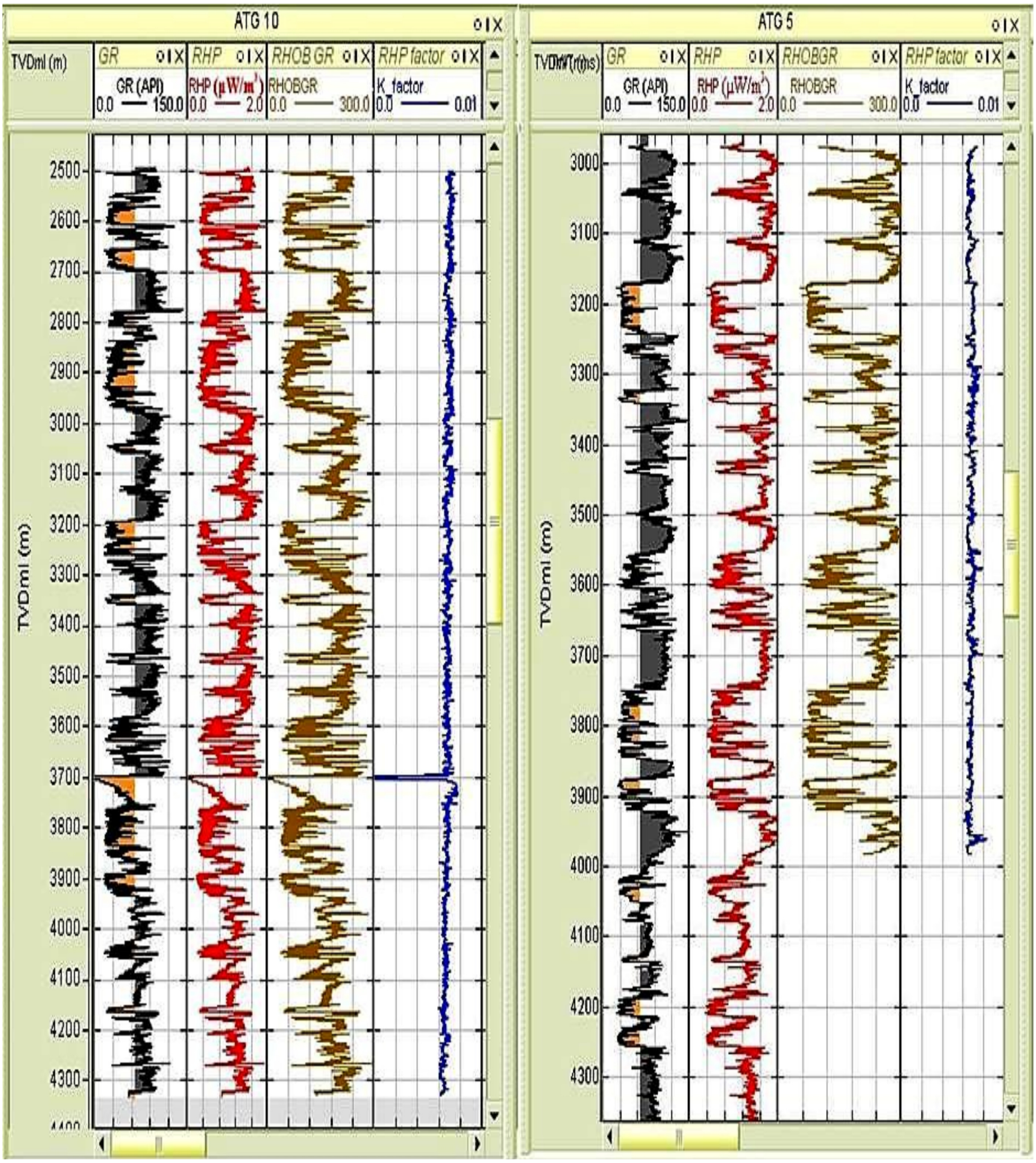

FIGURE 2. Radiogenic heat production derived from well logs measured in ATG-10 and ATG-5, with Gamma ray logs indicating lithology Shales (Grey) and sands (Redish brown), and radiogenic heat factor (K) blue.

TABLE 1. Major heat-generating elements in rocks (Emsley, 1989; Jessop, 1990).

Element	Heat Generation (µW/kg)	Average Crustal Abundance, n (w/w)	A'×n (µW/kg)
Uranium	96.7	2.3 ppm	2.22×10-4
Thorium	26.3	8.1 ppm	2.13×10-4
Potassium	0.0035	1.84 %	6.44×10-5

TABLE 2. Radiogenic heat (A) of different rocks calculated by different authors.

Lithology	A (µW/m³)	Remarks
Sandstone, average	0.73	Funnell and others (1996)
Sandstone, wacke	0.99	Rybach (1986)
Sandstone, arkose	0.84	Rybach (1986)
Sandstone, subarkose	0.6	Estimated
Sandstone, quartzite	0.32	Rybach (1986)
Siltstone	1.3	Funnell and others (1996)
Shale, <2% TOC	1.86	Carmichael (1984)
Shale, black	5.5	Rybach (1986)
Limestone, <1% TOC	0.62	Rybach (1986)
Chalk	0.1	Balling and others (1981)
Dolomite	0.36	Rybach (1986)
Anhydrite	0.09	Rybach (1986)
Halite	0.012	Rybach (1986)
Chert	0.5	Calculated from gamma-ray logs in Watney *et al.* (2001)
Coal	0.46	Ahmad and Finlay (1987) and Bartow and Ledgar (1984)
Tuff, felsic	1.6	Mareschal and others (1999)
Tuff, basaltic	0.4	Average of values from Pimentel and others (1991)

Cull, 2001). The rate of radiogenic heat production in rocks is governed by the concentration of radioactive isotopes, their respective decay rates, and the energy associated with the emitted particles. These parameters vary depending on the specific isotope involved. Consequently, the absolute abundance of each radioactive isotope within a rock directly determines its total heat production. During decay, a portion of the emitted energy is lost to space, while the remainder is absorbed by the surrounding rock matrix, contributing to subsurface thermal regimes (Hamza & Beck, 1972).

$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + \gamma \quad (2)$$

$$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + \beta + \gamma \quad (3)$$

$$^{40}K \rightarrow {}^{40}Ca + \beta^{-} + \dot{\nu} + \gamma \quad (4)$$

Where α, β, γ, ν, and $\dot{\nu}$ alpha, beta particles, gamma ray, neutrino and anti-neutrino, respectively. However, the surrounding rocks absorb the kinetic energy of the emitted particles, which leads to heat production. The contribution to heat production of each of the relevant radioactive elements is summed by the individual heat contributed by each radioactive element to obtain the total radiogenic heat production either for an area or for sample Equations 5 and 6. This sum is given as:

$$A = A_U + A_{Th} + A_K \quad (5)$$

$$A = \rho\left(C_U A_U + C_{Th} A_{Th} + C_K + A_K\right) \quad (6)$$

Where, A = total RHP (in µWm^{-3}), A_U (contributed by Uranium), A_{Th} (contributed by Thorium), A_K (contributed by Potassium), ρ is the rock density, C is the heat generation rate per mass and concentration of the corresponding element in the rock.

3.3 Radiogenic heat production methods

If the rock's density (ρ) and the concentrations of Uranium (C_U), Thorium (C_{Th}), and Potassium (C_K) are known, its radiogenic heat generation rate (A) can be calculated. By substituting the values provided by Rybach (1988), as shown in Table 1, into Equation 7, the heat generation rate can be determined as follows:

$$A = \rho \times 10^{-5}\left(9.52C_U + 2.56C_{Th} + 3.48C_K\right) \quad (7)$$

TABLE 3. Relative Gamma Uranium, Relative Thorium and Potassium (Adams & Weaver, 1958; Emsley1989).

γ-Producing element	Relative γ-Activity A	Average Abundance n (%)	$A \times n$
Uranium	3600	0.00023	828
Thorium	1300	0.00081	1025
Potassium	1	1.84	1.84

Where, A = radiogenic heat production (µW m⁻³), C_U = concentration of Uranium in ppm, C_{Th} = concentration of thorium in ppm, C_K = concentration of potassium in percent (%), ρ = density (kgm⁻³).

To apply Equation 7, it is crucial to determine the rock's density (ρ) and the concentrations of the radioactive elements Uranium (U), Thorium (Th), and Potassium (K). Radiogenic heat production has been estimated using laboratory-measured concentrations of these radioelements (Fernández *et al.*, 1998), as well as directly from gamma-ray logs (Bücker & Rybach, 1996). Furthermore, airborne gamma-ray spectrometry has been employed to estimate radioactive heat production over large regions (Richardson & Killeen, 1980; Thompson *et al.*, 1996). Alternatively, Issler and Beaumont (1989) established an empirical relationship between the fractional proportion of quartz (FQ) in a rock matrix and radiogenic heat production, based on measurements from sedimentary rocks in the Labrador Shelf. This relationship is represented by Equation 8 as:

$$A = -0.96\,(FQ) + 1.29 \tag{8}$$

Where, FQ = fractional proportion of quartz in a matrix.

Where electric well logs are available, Rybach (1986) derived a simple relationship between heat generation and the natural gamma log, GR, in Equation 9 as follows:

$$A = 0.0145\,(GR - 5.0) \tag{9}$$

Equation 9 was revised because of limited data and was revised by Biicker & Rybach (1996), and arrived at Equation 10.

$$A = 0.0158\,(GR - 0.8) \tag{10}$$

3.4 Determination of radiogenic heat from spectral gamma ray logs

The gamma-ray (GR) log measures the total gamma radiation emitted by the primary radioactive elements: Uranium (C_U), Thorium (C_{Th}), and Potassium (C_K).The relationship includes a coefficient (X) that varies depending on the radius of sensitivity of the logging tool, which itself is influenced by factors such as the energy of the emitted radiation, the rock density, and the specific type of logging tool used (Serra, 1984). By combining Equations 6 and 10, radiogenic heat production (A) can be related to the GR response. Although this relationship is influenced by various factors, particularly rock density, the sensitivity radius usually stays within a few decimeters and can be treated as constant for a given borehole (Beardsmore & Cull, 2001).

$$GR \propto POTA + 0.13 \times THOR + 0.36 \times URAN \tag{11}$$

$$GR = X \times [POTA + 0.13 \times THOR + 0.36 \times URAN] \tag{12}$$

$$\frac{A}{GR} = \frac{RHOB \times 10^{-3} \times [35.0 \times POTA + 26.3 \times THOR + 96.7 \times URAN]}{X \times [POTA + 0.13 \times THOR + 0.36 \times URAN]} \tag{13}$$

$$A = \frac{3.5 \times 10^{-2}}{X} \times RHOB \times GR \times \left[\frac{POTA + 0.751 \times THOR + 2.76 \times URAN}{POTA + 0.13 \times THOR + 0.36 \times URAN}\right] \tag{14}$$

$$A = 3.5 \times 10^{-2} \times RHOB \times GR \times \frac{Y}{X} \tag{15}$$

$$Y = \left[\frac{POTA + 0.751 \times THOR + 2.76 \times URAN}{POTA + 0.13 \times THOR + 0.36 \times URAN}\right] \tag{16}$$

Y = Radiogenic factor

$$X = \frac{GR}{[POTA + 0.13 \times THOR + 0.36 \times URAN]} \tag{17}$$

$$\frac{A}{GR \times \rho} = 3.5 \times 10^{-2} \frac{Y}{X} \tag{18}$$

$$K = 3.5 \times 10^{-2} \frac{Y}{X} \tag{19}$$

$$A = K \times GR \times \rho \tag{20}$$

$$K = \frac{A}{GR \times \rho} \tag{21}$$

In this study, radiogenic heat production was estimated using the approach developed by Bücker and Rybach, as expressed in Equation 10, which establishes a linear relationship between natural total gamma-ray log readings measured in API units from industrial exploration data (Anonymous, 1974).

4 Results and Discussion

To understand the thermal state of a sedimentary basin and the organic maturation of sediments into hydrocarbons, it is crucial to calculate and quantify the heat generated by the radioactive decay of elements present in the sediments. In this study, gamma-ray and density logs were utilized over a depth between 2500 m and 4350 m. The gamma-ray logs were employed to distinguish the shale-sand lithology, as shown in Figures 2 and 3 for wells ATG 10, 5, 11, and 7, respectively. The primary lithologies observed in the gamma-ray logs included shale, sand, and shale-sand intercalations. Variations of radiogenic heat production with lithology were computed using the total gamma ray count (GR) combined with density logs (RHOB) using the Bucker and Rybach linear methods, Equation 10, Figure 4 for ATG 10 & 5 and Figure 5 for ATG 11 and 7, respectively. Heat production rates vary from 0.23–2.24 μWm^{-3} ± 0.08 for ATG 10, and 0.22–2.25 μWm^{-3} ± 0.08 for ATG 11, then 0.31–2.35 μWm^{-3} ± 0.08 for ATG 7 and 0.34–2.33 μWm^{-3} ± 0.08 for ATG 5. The highest average radiogenic heat production in shale lithology was calculated to range from 0.9 μWm^{-3} to 2.29 μWm^{-3}, with elevated values observed in the shale of the Akata Formation. This may be attributed to the fact that shales typically emit more gamma radiation compared to other sedimentary rocks, such as sandstone. This is primarily due to the higher clay content in shales, which contains significant amounts of radioactive potassium. Additionally, the cation exchange capacity of clay minerals facilitates the absorption of uranium and thorium, further contributing to the elevated gamma-ray emissions. Low values of RHP of 0.2 μWm^{-3} – 0.9 μWm^{-3} were observed in the sand lithology of the Benin formation, and it was due to low concentrations of radio elements in the sandstones. Alternate low values and high values of RHP were observed in the shale sand intercalations of the Agbada Formations. The high values of RHP were due to the contributions from shales, and the low values were due to the contributions from sands Tables 4, 5, 6, and 7 for ATG 10, 11, 7 and 5, respectively. Equation 21 was derived from Equations 11–20 and is called the radiogenic heat factor (K). A cross plot of K-factor with depth shows a constant average value of 0.006 in Figures 2 & 3 for ATG 10, 5, 11, and 7, respectively. The constant value of K implies that plotting radiogenic heat production against the product of gamma ray and density should yield an approximately straight line with an average slope of 0.006. This slope, representing RHP versus RHOB × GR, is influenced solely by the relative abundances of uranium, thorium, and potassium in the Niger Delta basin sediments. In addition to staying constant with depth, the gradient is expected to remain consistent across regions where sediments share a common source. Accordingly, the cross-plot of RHP (A) versus $RHOB \times GR$ for the Niger Delta, Figures 4 & 5, showed that the gradient

(m = 0.006) was fairly uniform across all wells. As a result, the heat generation equation for the ATG field can be expressed using Equation 3, rather than the more general Equation 2.

$$RHP = 0.0064\,(RHOB \times GR) + 0.35 \quad (22)$$

$$RHP = 0.0064\,(RHOB \times GR) + 0.59 \quad (23)$$

$$RHP = 0.0065\,(RHOB \times GR) + 0.41 \quad (24)$$

$$RHP = 0.0064\,(RHOB \times GR) + 0.30 \quad (25)$$

The values of radiogenic heat production (RHP) calculated in this study are consistent with other RHP values reported for the Niger Delta and for sedimentary basins worldwide. In the Niger Delta sedimentary basin, Emujakporue and Godwin (2016) computed average RHP values from well logs in shale horizons, ranging from 0.8 to 2.0 $\mu W/m^3$, a range similar to that found by McKenna and Sharp (1998) in the Gulf Coast region of Texas. In South Texas, heat production rates vary across different formations: clean Stuart City (Lower Cretaceous) limestones show the lowest values at $0.07 \pm 0.01\,\mu W/m^3$, while Frio (Oligocene) mudrocks exhibit the highest at $2.21 \pm 0.24\,\mu W/m^3$. Average heat production rates were measured at 0.88 $\mu W/m^3$ for Wilcox (Eocene) sandstones, 1.19 $\mu W/m^3$ for Frio sandstones, 1.50 $\mu W/m^3$ for Wilcox mudrocks, and 1.72 $\mu W/m^3$ for Frio mudrocks. Likewise, Chapman and Polack (1975) reported radiogenic heat production values between 0.96 and 1.8 $\mu W/m^3$ in Precambrian rocks of the exposed West African Craton. In comparison, Cenozoic and Mesozoic lacustrine sediments from Chinese basins showed RHP values ranging from 1.02 to 3.28 $\mu W/m^3$ (Zhang, 1993). Keen and Lewis (1982) found that sediment heat generation along the eastern North American continental margin varies from 0.3 $\mu W/m^3$ in limestone to between 1.4 and 1.8 $\mu W/m^3$ in shale. In the Bahariya Formation, radiogenic heat production (RHP) varies from low values of 3.96 $\mu W/m^3$ to higher values ranging from 7.48 $\mu W/m^3$ to 9.09 $\mu W/m^3$. Ali and Orazulike (2010) also utilized spectral well log data to estimate radiogenic heat production in the Chad Basin, reporting values ranging from 0.17 to 1.90 $\mu W/m^3$, with an average of 0.90 $\mu W/m^3$.

5 CONCLUSION

Radiogenic heat production in the clastic sediments in Benin, Agbada and Akata shale of the Niger Delta varies consistently with lithology. RHP tends to increase with increasing depth, and this is due to an increase in shaleness of the Akata formation. The average range of radiogenic heat production falls between 0.9 µWm-3- 2.29µWm-3, with High values of RHP corresponding to the shale lithology, while Low RHP values correspond to the sandstones of the Agbada formation Figures 3 and 4. While alternate values of RHP were observed in the shale-sand intercalations of the Agbada formation, Tables 4, 5, 6, and 7. The estimated radiogenic heat production could generate sufficient heat to influence the hydrocarbon potential and the maturation of organic matter in the clastic sedimentary formations of the Niger Delta. From the results in Tables 4, 5, 6, and 7, the values of radiogenic heat calculated from gamma-ray logs can be used to calibrate the hydrocarbon field to mark reservoir rocks and source rocks, since radiogenic heat increases with shaleness, indicating hydrocarbon source rock. It may also be used to predict petrophysical properties of a formation, such as lithology and sediment thickness. It is essential to consider other thermal properties of the sediments before making reliable predictions about organic maturation and the timing of oil generation. This study's findings show that radiogenic heat production is a key factor in accurately assessing the thermal maturity of sediments. Therefore, it should be incorporated into future thermal models for sedimentary basins. Radiogenic heat production, derived from gamma-ray log data in the clastic sediments of the Niger Delta margin, significantly influences heat flow, thermal history, and organic matter maturation. Incorporating these values into basin evolution models is essential for aligning predictions with observed data like heat flow, organic maturity, and geothermal gradients. Nevertheless, these measurements represent just the first step in collecting the data needed to fully understand the thermal evolution of sediments and hydrocarbon maturation.

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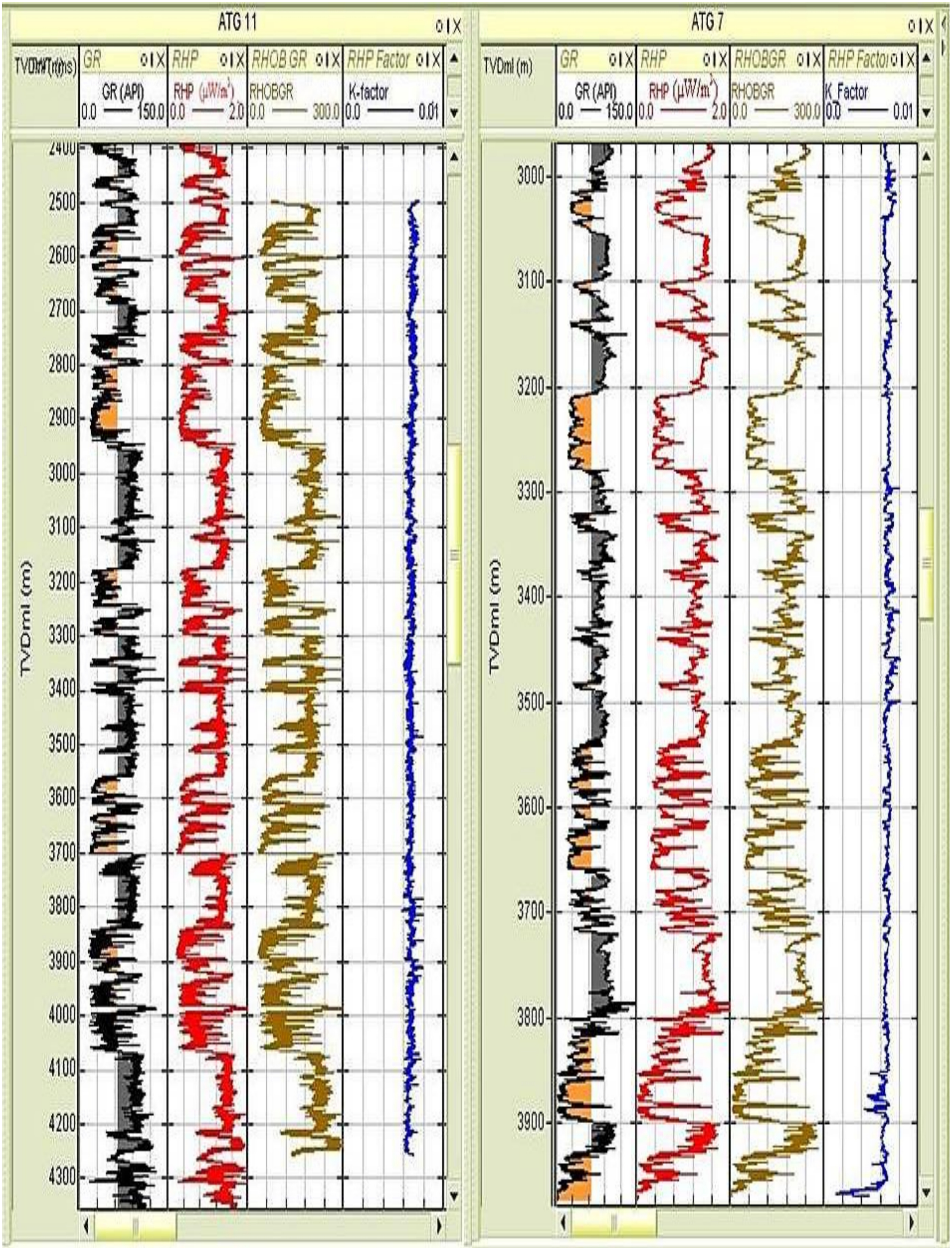

FIGURE 3. Radiogenic heat production derived from well logs measured in ATG-11 and ATG-7, With Gamma ray logs indicating lithology, shales (Grey) and sands (Redish brown), and Radiogenic heat factor (K) Blue.

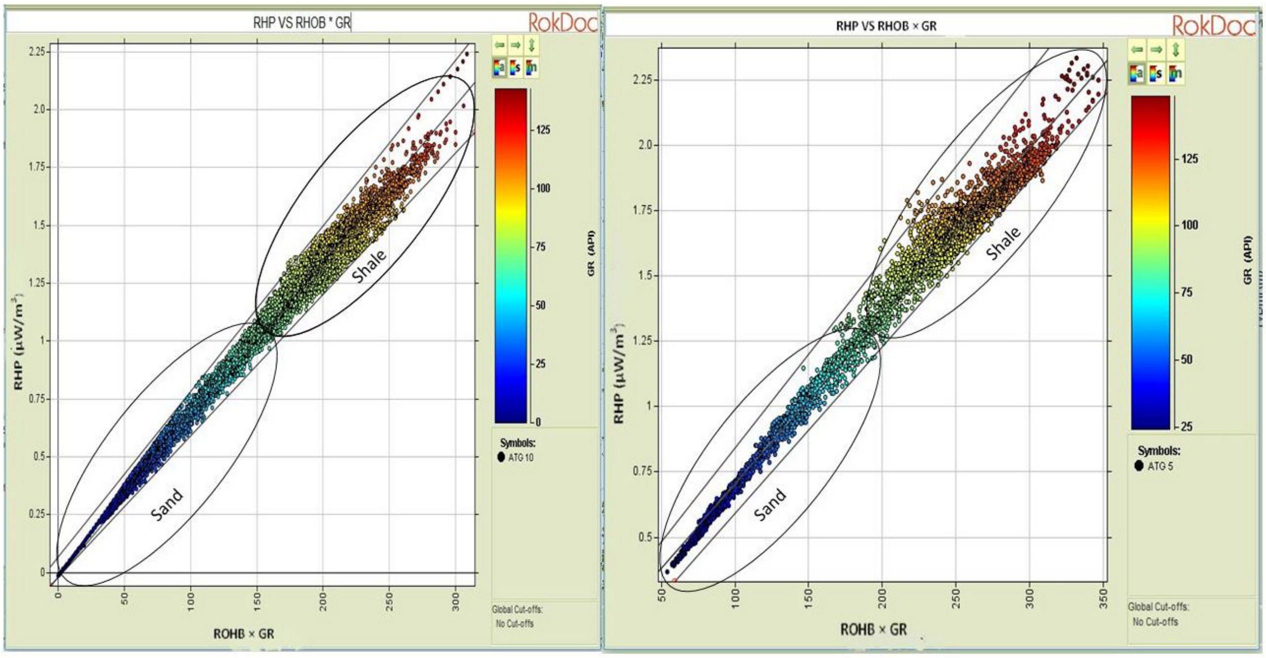

FIGURE 4. Radiogenic heat production determined from gamma-ray logs versus RHOB (density log) × Gamma Ray Logs (GR) for well ATG-10and ATG-5.

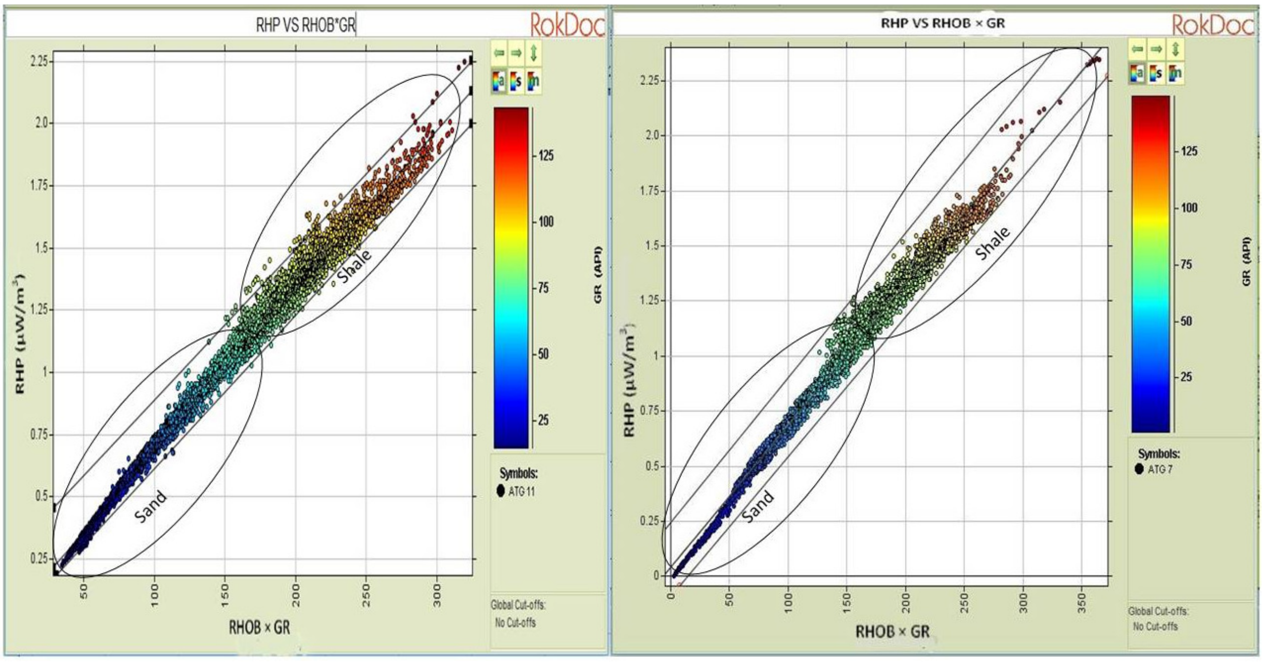

FIGURE 5. Radiogenic heat production determined from gamma-ray logs versus RHOB (density log) × Gamma Ray Logs (GR) for well ATG 11 and ATG-7.

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TABLE 4. RHP data for sediments from well ATG-10.

ATG-10				
Thickness (m)	Lithology	Gamma-ray (API)	Density (RHOB, g/cm^3)	Average Radiogenic Heat (μWm^{-3})
2499.20 – 2573.27	Shaly-Sand	73.77	2.21	1.15
2573.42 – 2607.41	Sand	30.8	2.19	0.47
2607.56 – 2654.96	Shaly-Sand	74.61	2.23	1.16
2655.11 – 2699.91	Sand	35.2	2.17	0.54
2700.07 – 2779.01	Shale	93.51	2.3	1.46
2779.16 – 2979.42	Sand	44.31	2.2	0.68
2979.57 – 3193.54	Shale	84.66	2.2	1.32
3193.69 – 3261.66	Sand	32.69	2.33	0.51
3359.04 – 3580.33	Shale	85.57	2.32	1.33
3580.48 – 3697.83	Shaly-Sand	60.72	2.28	0.94
3697.98 – 3723.39	ND	ND	ND	ND
3723.58 – 3936.64	Sand	44.01	2.27	0.68
3936.79 – 4324.98	Shaly-Sand	71.78	2.4	1.12

TABLE 5. RHP data for sediments from well ATG-5.

Well ATG-5				
Thickness (m)	Lithology	Gamma-ray (API)	Density (RHOB, g/cm^3)	Average Radiogenic Heat (μWm^{-3})
2979.15 – 3170.98	Shale	105.18	2.36	1.64
3171.13 – 3239.41	Sand	40.17	2.22	0.62
3239.56 – 3272.02	Shaly-Sand	80.55	2.28	1.26
3272.18 – 3323.69	Shale	100.32	2.23	1.57
3323.84 – 3341.98	Sand	41.86	2.2	0.64
3341.99 – 3558.84	Shale	100.36	2.32	1.57
3558.99 – 3664.76	Shaly-Sand	68.42	2.27	1.06
3664.95 – 3750.25	Shale	104.77	2.3	1.64
3750.41 – 3847.18	Sand	46.23	2.28	0.71
3847.49 – 3920.94	Shaly-Sand	71.84	2.33	1.12

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