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Modification of radiogenic heat production equation due to radioactive disequilibrium in rock samples from Gamma-Ray spectrometry

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ABSTRACT

Accurate Radioactive Heat Production (RHP) estimation is essential for determining geothermal potential and exploration. However, a mass defect due to Uranium Series Decay (USD) is a serious problem that has yet to be considered by previous RHP models in computing accurate RHP. The RHP is a petro-physical property that quantifies the heat generated by the decay of radioactive isotopes within rocks. However, there is a mass defect in the process due to series disequilibrium in U decay called Uranium Series Decay (USD) that affects the accurate estimation of the RHP, which was not considered by the two previous RHP models, established by Birch and Rybach in 1954 and 1976 respectively. This work aims to determine the performance level of the previous RHP models and consider the effect of USD on establishing an improved new RHP model with a better performance level for accurate estimation of RHP.

A revised data from gamma-ray spectrometry was used to compute the Beta and Alpha energies ($E_{\beta max}$) of decay schemes, mass defect ($E_{\Delta m}$) of radioelements, total absorbed energy (E_{abs}) per atom, numerical constants (B_i) and converted to the accepted RHP unit (μWm^{-3}) for each radionuclide. The modified RHP model (A_3) was evaluated and validated using error metrics like the Sum of Squared Error (SSE), Mean Absolute Error (MAE), Coefficient of Determination (R^2), and Root Mean Squared Error (RMSE) and radiometric data from seven different regions of Nigeria (Southwest-SW, Southeast-SE, Southsouth-SS, Northwest-NW, Northeast-NE, Northcentral-NC) and India. The performance of the improved model (A_3) was compared with Birch's (A_1) and Rybach's (A_2) RHP models.

The A_3 RHP model obtained was $RHP(\mu Wm^{-3}) = \rho(0.103C_U + 0.029C_{Th} + 0.061C_K)$, where C_U, C_{Th} and C_K are the concentration of U, Th and K in part per million (ppm) and ρ is the density of the rock sample(kgm^{-3}). It was observed that the A_1, A_2, and A_3 models have 47.8, 45.2, and 54.6 percent performance levels, respectively, which indicates that the A_3 model has better performance value than the A_1 and A_2 models. A_3 also returned a lower measure of errors in SSE, MAE, and RMSE than the A_1 and A_2 models in all the regions considered and this showed that the A_3 model performed better in the metrics analysis for all the regions.

The performance level of the existing models, used to estimate RHP by researchers in the geosciences was determined and a more accurate model with better performance was obtained by considering mass defect due to Uranium Series Decay (USD) in the RHP estimation using data from Nigeria and outside Nigeria.

Keywords: Radiogenic Heat Production, Uranium disequilibrium effect, Geological formation, Gamma-ray spectrometry, Performance metrics, Birch and Rybach heat production models

INTRODUCTION

Radioactive heat production (RHP) is a petro-physical property which quantifies the quantity of heat produced by the decay of radioactive isotopes within the rocks and minerals (Asfahani, 2018). It can be expressed in μWm^{-3} and depends on the amounts of radioelements of interest, which are potassium (K), uranium (U) and thorium (Th) contained in rocks and are relevant to internal terrestrial heat sources since they add to the heat created during the process of radioactive decay in rocks, which also reflects the geochemical conditions during rock formation (Asfahani, 2018; Fall et al., 2018). The space-time distribution of radionuclide has a large influence on the Earth's internal temperature field, and sometimes 30 to 40% of the ground heat flow density is generated by radionuclide. RHP is an important parameter for detailing the geothermal history of different geotectonic locations (Tabod et al., 1992; Valković, 2019). The origin of the heat sources differs for each region, and high heat flow regions show different heat transfer modes (Plomerova et al., 1993).

Birch (1954) formulated an empirical formula to calculate the RHP in rocks, which is generally conventional and widely used in many research works, and the equation is written as:

$$A_1(\mu Wm^{-3}) = \rho(0.097C_U + 0.035C_K + 0.026C_{Th}) \quad (1)$$

Rybach (1976) observed that since 1954, some factors like decay patterns, half-lives and mass alterations and differences had been reviewed based on data from the works of Hyde et al. (1964) and Brunee and Voshage (1964) which called for the review of the constants of the heat production after twenty two years of existence of the Birch's equation. The Birch formula was revised by Rybach (1976) who proposed the new expression as:

$$A_2(\mu Wm^{-3}) = \rho(0.0952C_U + 0.0348C_K + 0.0256C_{Th}) \quad (2)$$

where: ρ = dry density of rock (kg/m^3), C_K, C_U, C_{Th} = concentrations of K in %, uranium and thorium in ppm respectively. Rybach determined the decay energy $E_{\Delta m}$ from the mass changes of uranium and thorium from the initial radioisotopes and stable end products by considering the quantity of radiated α-particles (He^4).