Modeling and inversion of gamma-ray logs: estimation of radionuclide concentrations

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Abstract

The natural radionuclide concentrations (U, Th and K) present in crustal rocks are usually estimated from rocks samples treated in labs. Investigations have assessed the rate of radiogenic heat production in the studied area. However, it is sometimes impossible to have samples to assess them in laboratory. Here, we propose a methodology to estimate natural radionuclide concentrations (i.e, C_U, C_{Th} and C_K) by inversion of gamma-ray logs. Below we present the methodology to achieve this goal by using a robust physical model for gamma-ray measurements in sedimentary basins. The result of the estimations of radionuclide concentrations was then applied in the radiogenic heat and gamma-ray equation and compared with the initial values proposed in a lithologic model. The methodology will be used in sedimentary basins real to know the radionuclide concentration, uranium, thorium and potassium elements.

Introduction

The natural radionuclide concentrations (C_U, C_{Th} and C_K) present in crustal rocks are usually estimated from rocks samples treated in labs. This is necessary to local lithology study. The minerals have proportional concentration of natural radionuclide that emit radiation because the radioactive decay. These radiations are detected in downhole logging, through detectors generating gamma-ray emissions, in API units. Consequently, there are heat production that make possible the production of hydrocarbon through a process known for kerogen thermal maturation (Roque & Ribeiro, 1997). Investigations have been carried out in different sedimentary basins for estimations of radionuclide concentrations (Conceição & Bonotto, 2006; Ferreira, 2008). Further investigations have assessed the rate of radiogenic heat production in the studied area (Sapucaia et al., 2005). The estimative of radionuclide concentrations and the rate of radiogenic heat production are additional information to geothermal studies. However, it is sometimes impossible to have samples to assess them in laboratory. A linear relation between radiogenic heat and gamma-ray were proposed by Bucker & Ryback in 10 distinct sedimentary basins (Bucker & Ryback, 1996). Here, we propose a methodology to estimate natural radionuclide concentrations (i.e, C_U, C_{Th} and C_K) by inversion of gamma-ray logs. Below we present the methodology to achieve this goal.

Methodology

The physical model that represents the variation of radiogenic heat production is (Bucker & Ryback, 1996)

$$A = 10^{-5}\,\rho\,(9.52C_U + 2.56C_{Th} + 3.48C_K), \qquad (1)$$

where the radiogenic heat production (A) is given in μW/m^3 and the bulk density is in g/cm^3. In this work, we used the linear relation between the radiogenic heat production and the gamma ray counts (Bucker & Ryback, 1996)

$$A(\mu W/m^3) = 0.0158(GR(API) - 0.8), \qquad (2)$$

in order to derive the physical model for gamma ray counts as a function of the radionuclide concentrations, i.e., GR $\equiv$ GR(ρ,C_U,C_{Th},C_k) as follows:

$$\text{GR} = \rho\,(a_u C_U + a_{th} C_{Th} + a_k C_K) + a_{gr}. \qquad (3)$$

where the constants a_u, a_{th} (m^3/Kg/ppm) and a_k (m^3/Kg/%) take values in agreement with linear equation (2), and $a_{gr} = 0.8$ unidades API. The equation 3 below is used for construction of the objective function which allows inverting the concentrations C_U, C_{Th} and C_k. We applied the software MATLAB (script `linprog`) in order to invert the obtained objective function. The `linprog` script is based on the simplex algorithm, allowing the use of inequalities for constraining the estimations.

Results

We applied the `linprog` inversion to a numerical model simulating the following lithologies: sandstones, shales and calcilutite (Weng & Lin) (see Figure 1). The sandstones are formed by quartz, K-feldspar and silt minerals. The shales are formed by kaolinite and illite minerals. The mixture of silt and calcite forms the calcilutite. In Figure 2, we plotted the simulated bulk density, radiogenic heat production and the gamma-ray logs. To construct the radiogenic heat production and the gamma-ray logs, we used equations 1 and 3, respectively. The radionuclide concentration logs were inputs for applying the equation 3 (see Figure 2). In the following, we used `linprog` script in order to recover the radionuclide concentrations from the GR log (see Figure 2c), incorporating specific constrains to the inversion process.

The application of the `linprog` script returned the estimations in Figure 3 (see figure captions). For the whole set of radionuclide concentrations, the `linprog` script returned good results in the modelled sandstones, while high variations for the shales and the calcilutite. Table 1 exhibits statistical measures for the absolute errors.

We then applied the estimations of radionuclide concentrations C_U^{est}, C_{Th}^{est} and C_K^{est} in the radiogenic

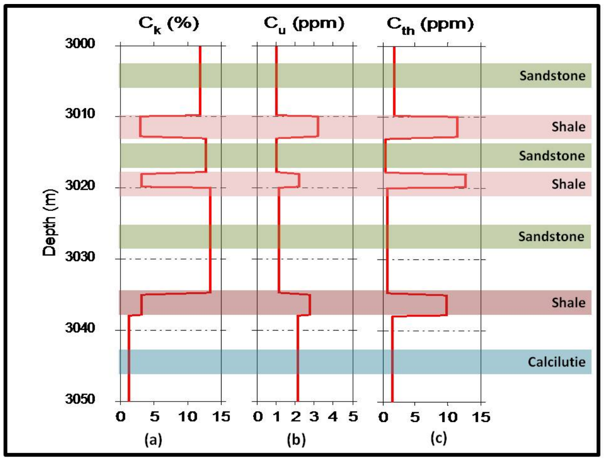

Figure 1: Lithology model and corresponding radionuclide concentrations: (a) C_K in %; (b) C_U in ppm; and (c) C_{Th} in ppm. The model simulates radioactive sandstones, shales and a calcilutite.

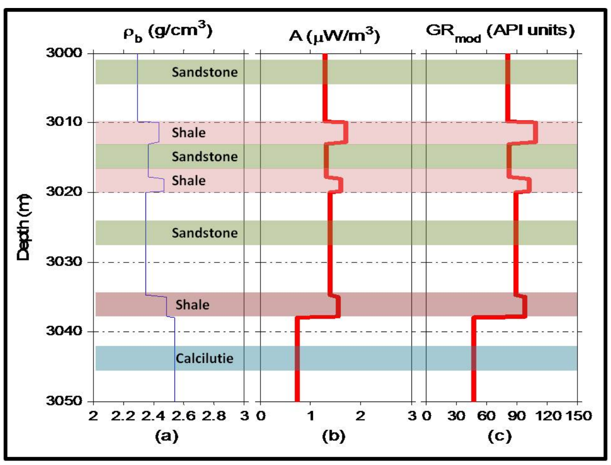

Figure 2: Result of the simulation of bulk density (a), radiogenic heat production (b) and gamma-ray log (c).

heat production and in the gamma ray model (i.e., equations (1) and (3), respectively) and compared with the corresponding logs in figure2. Both logs coincide (see figure 4), showing the good performance of the inversion technique. The statistical values are showed in the table, where we can to see small variation of error between uranium concentration radionuclide model and uranium concentration radionuclide estimate.

Table 1: Statistical measures for the absolute errors between the model and the predictions (see figure 4). Units for the mean, standard deviation σ and variance σ^2 apply accordingly.

	$\| C_U^{mod} - C_U^{est} \|$	$\| C_{Th}^{mod} - C_{Th}^{est} \|$	$\| C_K^{mod} - C_K^{est} \|$
Mean	0.329	1.100	1.419
σ	0.347	1.748	1.468
σ^2	0.120	3.055	2.156

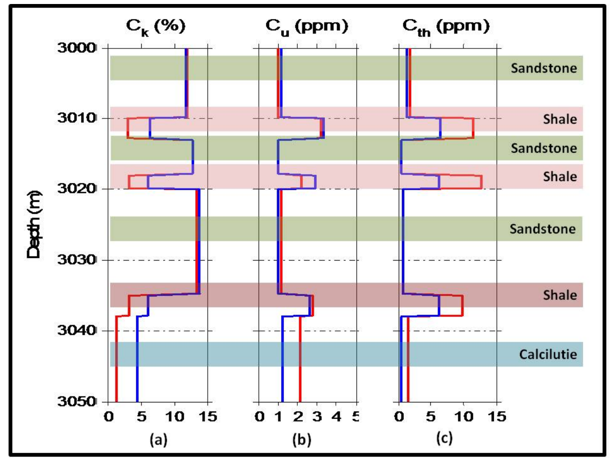

Figure 3: Results of the gamma-ray log inversion for the radionuclide concentrations. Red color shows the model; blue color represents the inversion results.

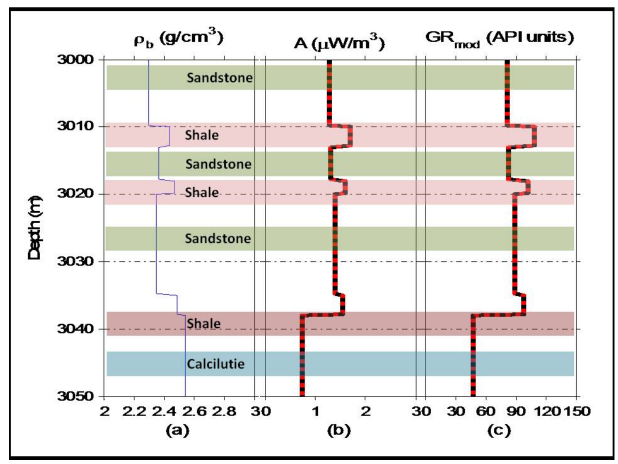

Figure 4: Results of the application of the radiogenic heat production and the gamma-ray models after the inversion (the dots in black color).

Conclusions

The model equations for radiogenic heat production and gamma-ray variations used in this work yield consistent values found in sedimentary basins. Thus, use of such models for inverting radionuclide concentrations from gamma-ray logs is physically possible. This is demonstrated by the results of the modeling exercise above. The simplex algorithm must be used with caution, because robust constraints are necessary for small uncertainty in the predictions. In our case, we shall design constraints specifically for the upper Macaé formation (i.e., Namorado reservoir) from which gamma-ray logs are to used for estimation of radionuclide concentrations.

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