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ACQUISITION OF SPECTRAL GAMMA-RAY DATA FROM CUTTINGS, WITH APPLICATION IN THE PALEOENVIRONMENTAL INTERPRETATION OF THE CABEÇAS FORMATION, PARNAÍBA BASIN, BRAZIL

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ABSTRACT. The use of spectral gamma-ray (SGR) logs helps in the interpretation of depositional environments and in paleoenvironmental reconstitution. To obtain SGR data in wells where they were not originally acquired, a low-cost methodology for acquiring them using cuttings was developed. For this study, we used a portable gamma spectrometer, cuttings of 5 wells and logs of 10 wells that crossed the Cabeças Formation of the Parnaíba Basin. The use of Th/U and U/K ratios allowed for a better correlation between the laboratory curves and those acquired by wireline. The intervals with Th/U>7 were interpreted as sedimentary inputs, a characteristic of fluvial floods and oxidizing conditions, typical of the continental environment, weathered soils and shallow marine environments. Based on the frequency of these contributions, the Cabeças Formation was subdivided in three intervals. The intermediate interval has a higher frequency of the intense discharge of these rivers and was interpreted as having been deposited in the most proximal environment. The other intervals, lower and upper, in general, show prevalent incursions with a Th/U<7 and were interpreted as a more distal environment. This work methodology can be performed on cuttings from any well or basin, providing better refinement to sedimentological and stratigraphic studies, optimizing oil exploration and production.

Keywords: paleoenvironmental reconstitution; well correlation; Th/U ratio; U/K ratio; well log.

RESUMO. A utilização de perfis de raios gama espectrais (SGR) auxilia na interpretação dos ambientes deposicionais e na reconstituição paleoambiental. Para obter os dados SGR em poços onde não foram originalmente adquiridos, foi desenvolvida uma metodologia econômica de aquisição utilizando amostras de calha. Neste estudo, utilizamos um gamaespectrômetro portátil, amostras de cinco poços e dados de perfis de dez poços, obtidos em poços que atravessaram a Formação Cabeças, Bacia do Parnaíba. A utilização das razões Th/U e U/K permitiu uma melhor correlação entre as curvas de laboratório e as adquiridas em perfilagens. Interpretaram-se os intervalos com a razão Th/U>7 como aportes sedimentares resultantes de inundações catastróficas, condição oxidante, típica do ambiente continental, solos intemperizados e ambiente marinho raso. Com base nas frequências desses aportes dividimos a Fm. Cabeças em três intervalos. O intervalo intermediário, que apresenta maior frequência dessas incursões fluviais, foi interpretado como tendo sido depositado em ambiente mais proximal. Os outros intervalos, inferior e superior, em geral, apresentam predominantemente incursões com razão Th/U<7, tendo sido interpretados como ambiente mais distal. Esta metodologia pode ser realizada em amostras de calha de qualquer poço ou bacia, proporcionando melhor refinamento aos estudos sedimentológicos e estratigráficos, otimizando a exploração e produção de petróleo.

Palavras-chave: reconstituição paleoambiental; correlação de poços; razão Th/U; razão U/K; perfilagem de poços.

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INTRODUCTION

Gamma-ray logging was introduced in the late 1930s and it was immediately useful for distinguishing shaly from clean formations (Ellis & Singer, 2007). The use of spectral gamma-ray (SGR) records aids in the interpretation of depositional environments. However, this type of investigation, during logging surveys, is not carried out systematically in all drilled wells, due to the higher cost of the SGR when compared to the conventional GR log. This study proposes the acquisition of SGR data from cuttings, thus enabling the construction of laboratory logs. For this purpose, cuttings from five wells and data from other five wells were used, where the SGR tools were run in boreholes, for the comparison of signatures between wells and the validation of the results. Unfortunately, SGR measurements were not performed in all wells. The SGR was run in a single borehole, not allowing an ideal comparison between these measurements for a more accurate calibration.

In addition to the SGR logs, this work used other electrical logs from the ten wells to make the stratigraphic correlations. Analyzing the trends of the Th/U, U/K ratios and the total gamma-ray curves, it was possible to perform a higher resolution stratigraphic slicing based on wells that cross the Cabeças Formation.

METHODS

Theoretical Foundation

The natural gamma-ray spectrometry tool detects naturally occurring gamma-rays of various energies emitted from a formation. Amounts and types of elements present are determined by how the formation was deposited and what has happened to it since deposition. Thorium, uranium and potassium (^{232}Th, ^{238}U and ^{40}K) are primarily responsible for the energy spectrum observed by the tool. The individual contributions of the three elements in relation to the total formation weight are calculated from the energy spectra. Elemental concentrations thus calculated showed correlation to depositional environment, geomorphic and diagenetic processes, clay type, and clay volume (Serra et al. 1980).

The tool measures gamma-rays with energies ranging from below 0.5 to well above 2.5 MeV, and presents the individual spectra for the three-decay series responsible for most natural radiation. The various series are due to the parent elements ^{232}Th, ^{238}U and ^{40}K. Thorium is associated only with detrital sediments, never with purely chemical sediments, while uranium is associated with both detrital and chemical sediments and the potassium is mainly associated with the formation of clays (Serra et al., 1980) (Table 1).

Radioactive isotopes initially contained mainly in acidic igneous rocks are transported due to geological processes to the sediments where they usually accumulate in a clayey substance. Typically, high gamma-ray response indicates the presence of fine-grained deposits or clay-rich rock formations, such as shale, claystone, mudstone, while the relatively low gamma radiation indicates the presence of coarser-grained clean sandstones and carbonate rocks. However, the main feature of SGR is the ability to distinguish gamma emissions from K, U and Th (Klaja & Dudek, 2016).

The recognition of radioactive minerals, especially the clay minerals present in the rocks, and the understanding of the oxidizing and reducing conditions of the depositional environment through the measurement of uranium (oxidizing environments are free of uranium while reducing environments are rich) allow a better determination of the mineralogical aspects. When combined with the vertical distribution of lithologies and grain sizes, it helps to reconstruct the depositional environment more accurately (Hassan et al., 1976).

The Th/U and U/K ratios can be used for paleoenvironmental interpretation and depending on the values they can point to continental, shallow marine, marine or anoxic environments and even to the types of clays found in the samples (Fertl, 1979; Klaja & Dudek, 2016). Table 2 presents a summary of these ratios.

Geology of the Study Area

The study area is in the center-north region of the Parnaíba Basin, Brazil. The study and correlation of the evaluated wells were limited to the Cabeças Formation.

Table 1 - Characteristics, associations and occurrence of the elements K, Th and U, (based on Serra et al., 1980).

Element	Characteristics	Association	Occurrence
Potassium (^{40}K)	One of the basic components of shale rocks. Presence indicator of feldspars and micas. Mainly occurs in oxidized form K2O.	Clay and shales. Arkosic conglomerate, arkose and graywacke.	Tectonically active areas undergoing rapid erosion. Terrigenous sediments with a low chemical maturity. Potassium feldspars and micas, alteration products: kaolinite, sericite and chlorite. Evaporites.
Thorium (^{232}Th)	Insoluble in water. Usually associated with shales; may give information on the clay type. Combined with heavy minerals in igneous rocks.	Detrital sediments. Never with purely chemical sediments.	Heavy minerals, which are more abundant in the silty fraction Residual sediments like bauxite, kaolinite and smectite
Uranium (^{238}U)	Usually associated with organic matter (anoxic environment)	Detrital and chemical sediments. Organic matter. Shales	Absorbed by clay minerals, being associated with organic matter Heavy minerals. Uranium is fundamentally associated with reduction of organic matter/ anoxic environments. Precipitation in high permeability intervals, natural fissure and fracture systems, fault zones, etc.

Table 2 - Geological Significance of Spectralog Ratio Values (adapted from Fertl, 1979).

Ratios	Geological Significance
Th/U	• Varies with depositional environment. Baseline and shoreline variations. • (Th/U > 7) continental, oxidizing environment, weathered soils, etc. • (Th/U < 7) marine deposits, gray and green shales, graywackes. • (Th/U < 2) marine black shales, phosphates. • Stratigraphic correlations, transgression x regression, oxidation x reduction regimes, etc. • Source rock potential estimates of argillaceous sediments (shales). • In igneous rocks, high Th/U indicative of oxidizing conditions by magma before crystallization and/or extensive leaching during postcrystatlization history.
U/K	• Evaluation of the organic matter content in clay sediments. • Stratigraphic correlations. • Source rock potential of argillaceous sediments

The Devonian Cabeças Formation (Plummer, 1948, apud Caputo, 1984) consists of about 100 to 400 m of medium to coarse-grained, hard, cross-bedded to massive, light gray to white sandstone beds with some conglomerate and pebbly sandstone interbeds (Caputo, 1984). Diamictites eventually occur, mainly in the upper part. The dominant sedimentary structures in the sandstones are the tabular and trough cross-bedding. Features of glacial origin occur at the top of the formation. Tempestites occur at the base of the formation (Della Fávera, 1990). According to Della Fávera (2001), the Cabeças Formation represents the delta front region of fluvio-deltaic systems dominated by catastrophic floods, whose prodelta would be represented by the previous muddier unit, the Pimenteiras Formation (Fig. 1).

Acquisition of SGR data from cuttings

The portable gamma-spectrometer Radiation Solutions Inc. model RS-230 BGO Super-SPEC Handheld Gamma-Ray Spectrometer and a 2 mm thick lead mesh, 1 m long and 10 cm high walls, were used for acquisition of data in the laboratory (Fig. 2).

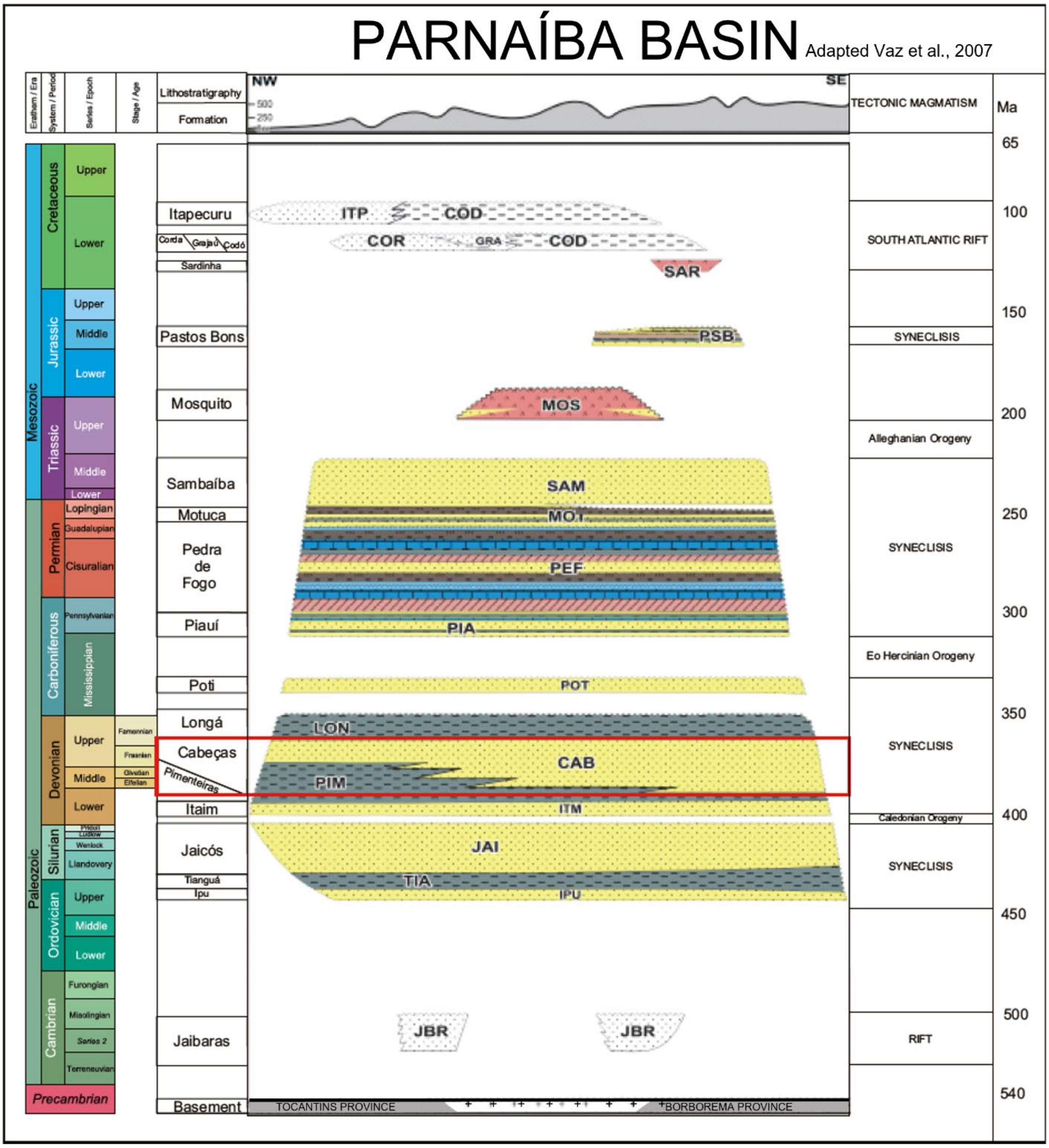

Figure 1 - Stratigraphy chart of Parnaíba Basin (adapted from Vaz et al., 2007) highlighting Cabeças Formation.

The log correlation was done with the SIGEO3 geological interpretation software, owned by Petrobras. Drill cuttings are part of the material cut by the drill while drilling. This material is separated by sieves, collected and stored in tnt (non-woven biodegradable) bags and represents the lithology of the sampled interval. The spacing must be defined according to the need of the study. The cuttings are used for the lithological description of the area of interest of the borehole, where the spacing interval of 3 meters is generally used, as it was used in this work. Cuttings can be influenced by some factors, such as: (a) collapses of material inside the borehole, rocks from upper intervals that may fall downhole during maneuvers in the drilling column, (b) error in the calculation of the return time of the samples, caused mainly by variations in the diameter of the wellbore, widening and expansion of the clays, or even by the great depth of the borehole, (c) losses or contamination with material collapsed in the shale shakers.

The acquisition of data logs in wells, including SGR, is carried out in wireline campaigns in oil, water, or other mineral deposits. After drilling the

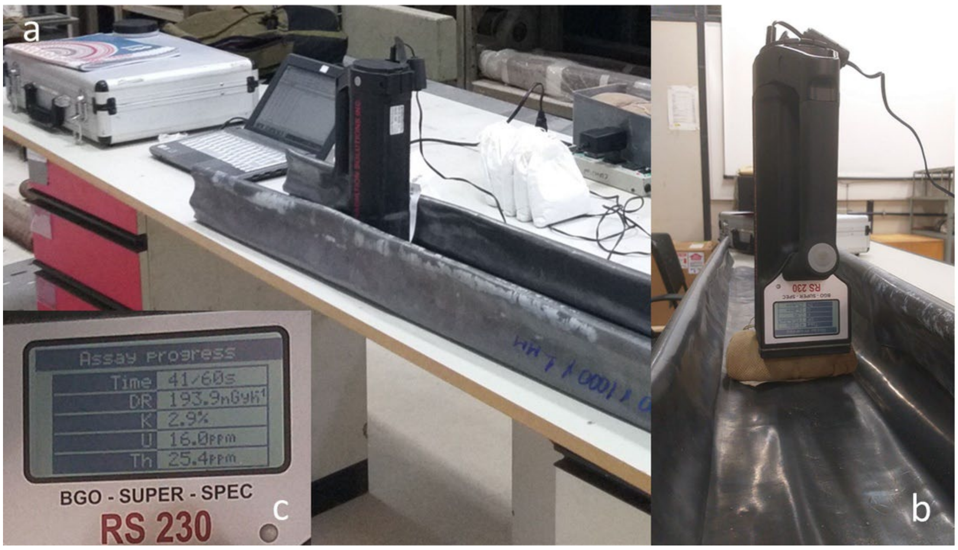

Figure 2 - a) and b) Acquisition of full and spectral gamma-ray data, from drill cuttings, in a tnt bag, with the portable RS-230 gamma spectrometer, on the lead mesh, at the UFF laboratory. c) Detail of the equipment display (Pereira, 2020).

phases of interest, tubular tools containing different sensors are introduced into the well without coating, go down to the base of the research interval, and then are pulled by an electric cable, recording the log data of the interval during the ascent. In the case of gamma spectrometry, the tool is a radiation meter for scintillation. As the tool moves up the well, different data as the depth, gamma-ray, SGR, resistivity, sonic, density, neutron and other data are recorded on the surface, at a wireline unity. These data can be made digitally available in file-format Log ASCII Standard (LAS).

The wells considered in this work were: 1-OGX-16-MA, 1-OGX-34-MA, 3-OGX-38-MA, 3-OGX-46D-MA, 4-OGX-49-MA, 1-OGX-77-MA, 1-OGX-93-MA, 1-OGX-101-MA, 1-OGX-110-MA and 3-PGN-5-MA. The open hole logs used were gamma-ray, spectral gamma-ray (only wells 1-OGX-16-MA, 1-OGX-34-MA, 3-OGX-38-MA, 3-OGX-46D-MA and 1-OGX-77-MA), caliper, resistivity, density, neutron and sonic. Total and spectral gamma-ray measurements, using cuttings, on the wells 4-OGX-49-MA, 1-OGX-101-MA, 1-OGX-110-MA, 1-OGX-93-MA and 3-PGN-5-MA were carried out to build laboratory SGR logs.

RESULTS AND DISCUSSION

Before starting the data collection in the laboratory, a series of tests was carried out to determine the ideal conditions for acquisition. By configuring the RS-230 gamma-spectrometer in ASSAY mode, each Total GR measurement (radiation dose value) is obtained, in nano Gray per hour (nGy/h)–the values of K (%), Th (ppm) and U (ppm) (RS-125/230 User Manual, 2015). A set of 35 cutting bags, from well 3-PGN-5-MA, was selected and the natural radiation was measured at different exposure times, 30, 60 and 90 seconds, to determine which was the best exposure time, considering the needs and work compatibility. The curves Total GR (nGy/h) were plot above the open hole GR (gAPI, gamma-ray log international unity). The software Trace K2 was used for this comparison, which allowed us to identify that the best-fit curve was the 60-second exposure, considering the wireline tool curve as a standard. Data acquisitions were always carried out at the same place in the laboratory, where the sample bags were placed individually on the center of the lead mesh (Fig. 3).

The cuttings used in the study are from wells where the SGR tool was not used in a borehole, so it was not possible to make comparisons between the K (%), U (ppm) and Th (ppm) curves. It was considered that these curves behave differently, proportional to the GR curve.

To observe the quality of the laboratory measurements, a standard sample was created, in resin, containing monazitic sand (rich in thorium). This sample was measured repeatedly under the same conditions as the cuttings to monitor data

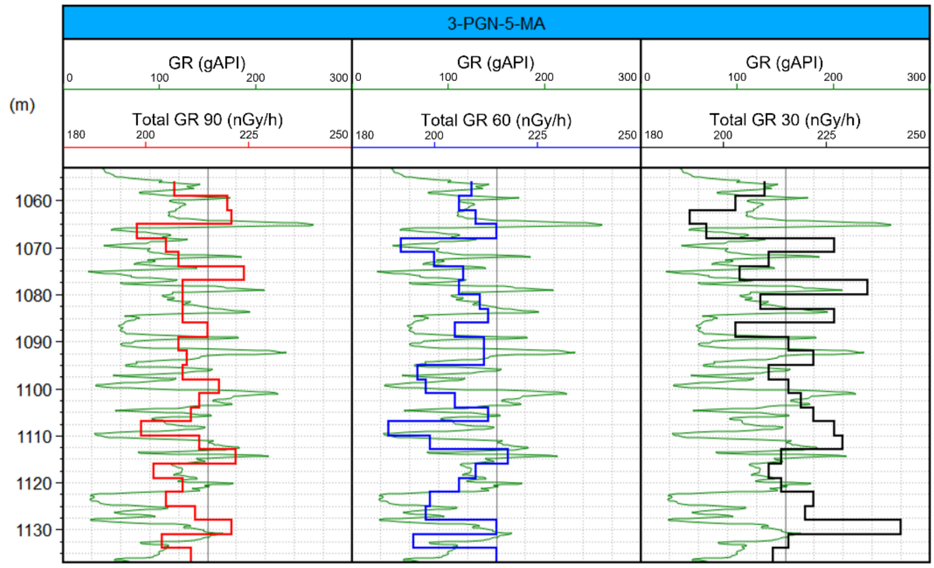

Figure 3 - Total gamma-ray curves. Wireline green, gAPI; red, blue and black Total GR curves, laboratory measurements, nGy/h, 90, 60 and 30 seconds of exposure to the RS-230 gamma spectrometer, respectively (Nobre, 2019).

dispersion. To reduce the background influence on the measurements, it was necessary to isolate these samples from other radioactive sources (rock samples and other cuttings), using the lead mesh. In the tests, it was observed that, with the use of this lead mesh, there was a significant reduction in the background influences, mainly in the U, Th and Total GR measures. Scatter plots with the results of these tests are shown in Figure 4, where values of the measurements made on the test sample, inside and outside the lead mesh, and the background inside the lead mesh were plotted.

Figure 5 shows two graphs of measurement histograms in Cabeças Formation. The first with the median values of K (%), U (ppm) and Th (ppm), where large variations in the values of the three elements are observed when comparing the wells where the gamma spectrometry was acquired in the laboratory in relation to those acquired by the wireline tool. The second graph shows the median of the values of the Th/U, U/K (10^{-4}) ratios, where the ratios present similar values.

Well Correlation

Different log curves as Gamma-ray (GR), Caliper (CAL), Resistivity (RES), Neutron (NPHI) and Density (RHOB) in crossover, Sonic (DTC), PEF (photoelectric), interpreted lithology, well and laboratory logs K and U, Th in crossover and the calculated ratios Th/U and U/K were used to correlate wells. However, for better viewing, it was necessary to prepare a specific track layout, containing seven tracks (Fig. 6).

The first track shows the zones defined for this article. The second track presents the elevation, the GR log varying from 0 to 200 API and CAL varying from 6 to 16 inches.

Based on the relationship presented by Fertl (1979) and Klaja & Dudek (2016), the log of the Th/U (dimensionless) ratio was plotted, varying from 0 to 10 in the third track, with cutoff lines in Th/U < 2, filled in black (indicating anoxic environments); Th/U > 7, filled in yellow (indicating oxidizing environments, with greater continental inputs); and the interval with Th/U between 2 and 7 (indicating transitional environment), filled in blue.

Klaja & Dudek (2016) also suggested grouping the U/K and Th/U curves into a single track, as these curves are inversely proportional and the change associated with the uranium content causes the curves to vary in opposite directions, that is, when there is an increase in the values of the U/K curve, with simultaneous decrease in Th/U values, the cause is an increase in uranium, the reverse is caused by an increase in thorium. This crossover of logs was plotted on the fourth track, with the Th/U ranging from 0.1 to 10 and the U/K (dimensionless x 10^{-4}) ranging from 0.3 to 10, with padding to the left of the log U/K in blue and to the right in yellow.

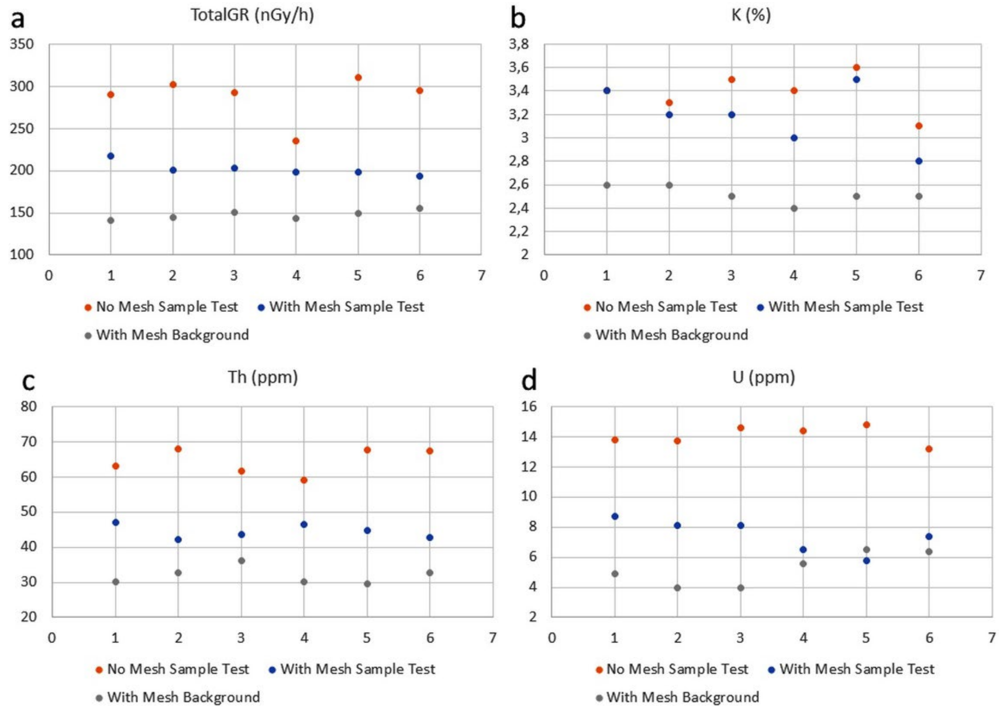

Figure 4 - Scatter plots of measurements–on the y-axis the values of Total GR, K, U and Th, (a, b, c and d, respectively)–of the test sample and the background. In red, the test sample, outside the mesh; in blue, the test sample inside the mesh; and in green, the background inside the mesh. The x-axis shows the number of measurements (Pereira, 2020).

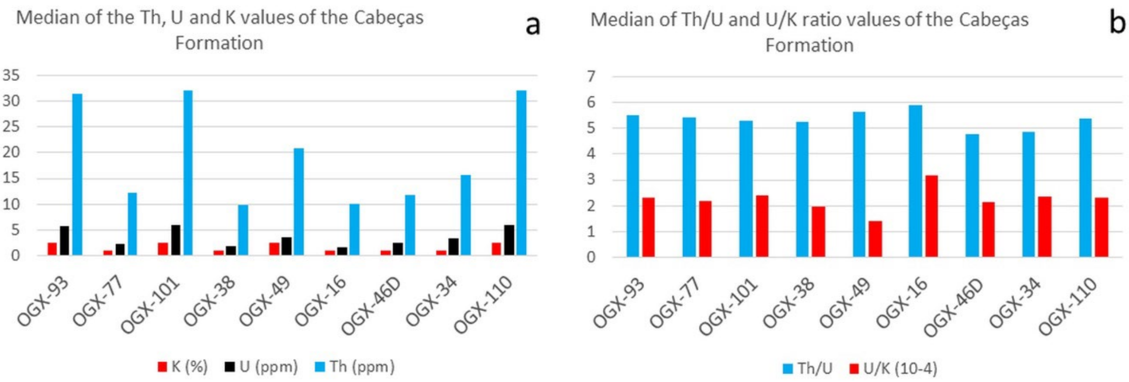

Figure 5 - Histogram graphs (a) of the median values of K (%) (red), U (ppm) (black), and Th (ppm) (blue); and (b) of the Th/U (blue), U/K (10^{-4}) (red) in the Cabeças Formation. (a) Large variations in the values of the three elements are observed when comparing the wells where gamma spectrometry was acquired in the laboratory (1-OGX-93-MA, 1-OGX-101-MA, 4-OGX-49-MA and 1-OGX-110-MA) in relation to those acquired in Wireline (1-OGX-77-MA, 3-GX-38-MA, 1-OGX-16-MA, 3-OGX-46D-MA and 1-OGX-34-MA); and (b) It is observed that the acquisition ratios by wireline and laboratory have similar median values.

In the fifth track, logs of the U and Th values were plotted, with inverse scales, to identify possible intervals with sandstones (higher thorium) and clays (higher uranium values). The values of uranium range between -2 and 10 ppm. Thorium ranges from 40 to 5 ppm in wells where the data were acquired by wireline and from 43 to 26 ppm in wells where the data were acquired in the laboratory. This difference in the scale was necessary due to the small variation in the values acquired in the laboratory. This track was filled to the left of the uranium log in green and to the right in yellow.

The sixth track presents the interpreted lithology of the wells. The seventh track presents the logs on an inverse density scale, ranging from 2 to 3 g/cm^3 and the neutron ranging from 45 to −15%, filled to the left of the density log in green and to the right in yellow.

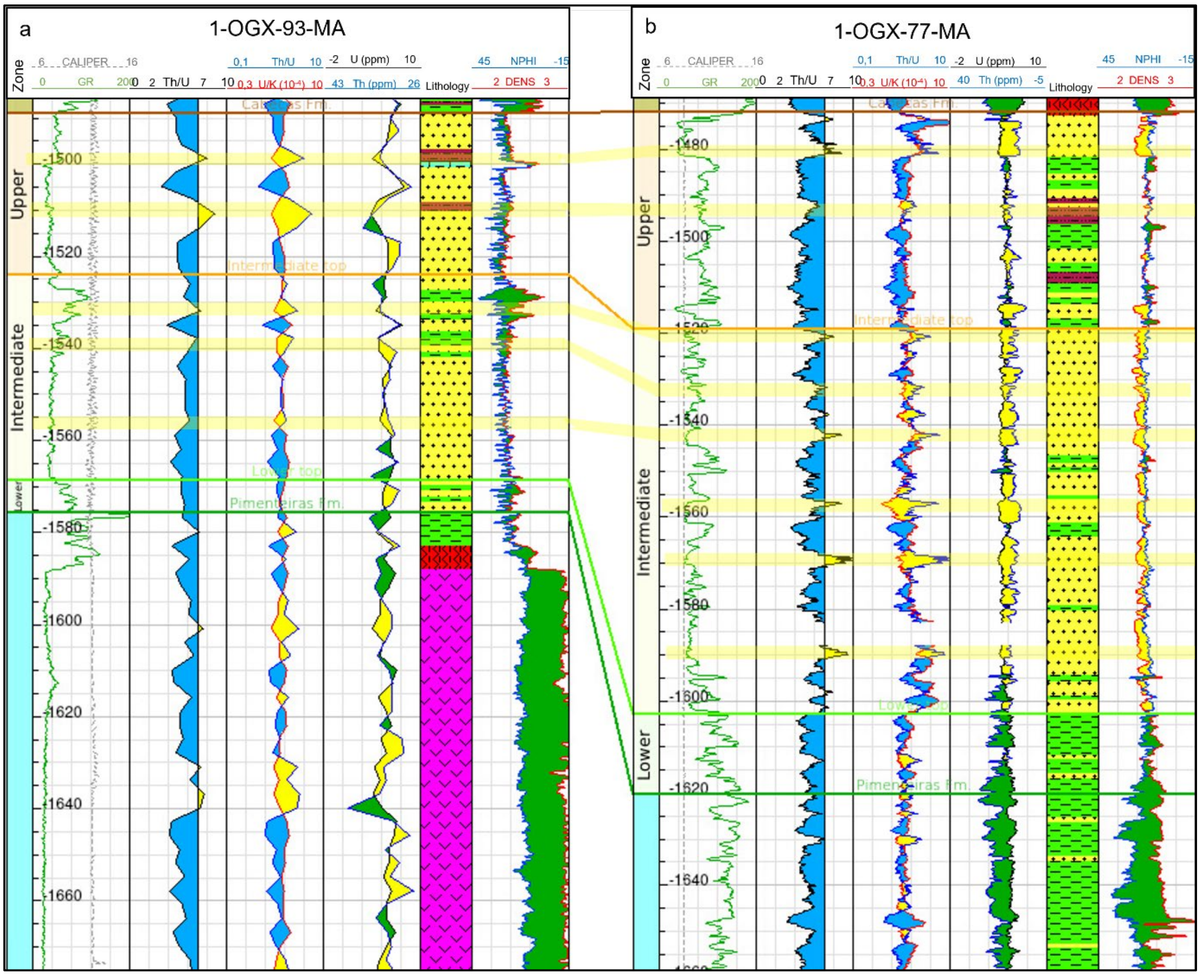

Figure 6 - Wells 1-OGX-93-MA (a) and 1-OGX-77-MA (b) in elevation, with electrics logs, GR (gamma-ray), CALIPER (caliper), NPHI (neutrons) and density, U and Th, in addition to the calculated ratios Th/U and U/K. Division of the Cabeças Formation–the intermediate interval, between the top intermediate markers (orange line) and the lower top (green line) markers, with the three intervals identified in the Cabeças Formation. Note that, in the upper interval, the Th/U ratio falls while the U/K ratio increases in the lower and upper intervals (intervals highlighted in yellow), thus interpreting continental contributions possibly due to the melting of ice sheets. The gamma spectrometry of well 1-OGX-93-MA was raised in the laboratory, while that of 1-OGX-77-MA was raised based on wireline (Pereira, 2020).

The use of Th/U and U/K ratio curves allows a better visualization to perform correlations between wells with SGR data from different sources, since the ratio between curves minimizes differences in the reading scales and background interferences. With the wells plotted in an arbitrary section (Fig. 7) identified, which characterizes a shallow marine environment, with less continental input than the intermediate interval. These results corroborate the description presented by Caputo (1984) for the base of this formation, the clasts, from sand-grain size up to 1 mm in diameter comprise gneiss, schist, phyllite, siltstone, and iron oolite fragments from the underlying Pimenteiras Formation, presenting higher amounts of uranium values (Fig. 6).

and analyzing the shape of the Th/U, Th/U x U/K and full gamma-ray logs, it was possible to divide the Cabeças Formation into three intervals.

The lower interval shows the highest median of the total gamma-ray values when compared to the intermediate interval. A low Th/U ratio <7 was also

The intermediate interval has lower median values of total gamma-ray when compared to the other intervals. In this interval there are also the highest median values of the Th/U ratio, with many values greater than seven, characterizing that the continental inflow was greater in it than in the other intervals, perhaps due to large inflows of continental material by cause of fluvial systems fed by the melting of glaciers. Tunnel valley deposits, also

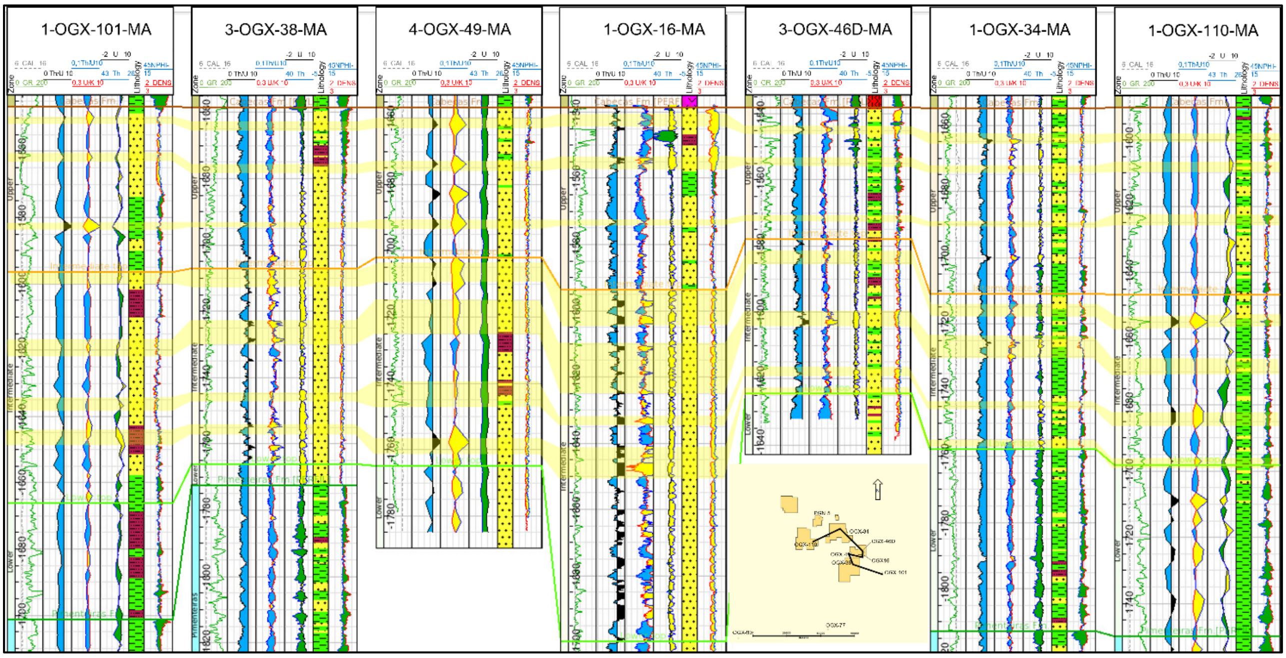

Figure 7 - Geological section of the wells in elevation, top datum of the Cabeças Formation. Intermediate and superior intervals of the Cabeças Formation. Continental inputs (river dischage) interpreted in yellow.

associated with glacier melting, are characterized by pebbly diamictites (sandstone, mudstone and volcanic pebbles) and deformational features, such as intraformational breccia, clastic dykes and sills of diamictites. All these features represent the first evidence of the Famennian glaciation in the basin, recording an advance–retreat cycle of a glacier (Miranda et al. 2018). Della Fávera (2001) interpreted it as prodelta deposits of a fluvio-deltaic system dominated by catastrophic floods. Caputo (1984) described these sandstones as cross bedded medium-to coarse-grained, poor-to well sorted with angular grains, kaolinitic matrix, and micromicaceous (Fig. 6).

The upper interval shows an increase of the gamma-ray log towards the top. Cores from this interval were described by Miranda et al. (2018), recognizing the strongly laminated nature of these tidal influenced deposits. There is a reduction in the Th/U ratio in relation to the intermediate interval and, in some wells, the median of the total gamma-ray values is higher than in the intermediate interval. Probably this tidal influenced environment with the presence of estuaries was no longer affected, or had a small contribution, from the catastrophic floods mentioned by Della Fávera (2001); and the deposits are dominated by fine to very fine-grained micaceous sandstone locally with coarse quartz grains (Caputo, 1984) (Fig. 6).

Two histogram plots were designed using the medians of the values of the total gamma-ray and the Th/U ratio per interval. The first histogram for the full gamma-ray data, where it is possible to identify higher values for the lower and upper intervals. The second one, for the Th/U ratio, displays higher values in the intermediate interval when compared to the lower and upper intervals of the Cabeças Formation (Fig. 8).

The continental inflows were interpreted when the intervals presented a low U/K ratio and a high Th/U ratio, consequently an increase in thorium concentrations compared to the uranium concentrations (Fig. 6).

CONCLUSIONS

The Total GR curve acquired in the laboratory showed a behavior similar to that acquired in the well, even observing increasing and decreasing cycles of radiation. In some intervals, the poor correlation can be interpreted as being caused by the miscalculation of the return time of the samples, which can displace the curve in relation to the original, as well as the sampling represents a larger interval of cut rock. Therefore, the comparison between the acquisition methods must be made in a qualitative way, since the acquisition in the laboratory refers to the average of a 3m interval,

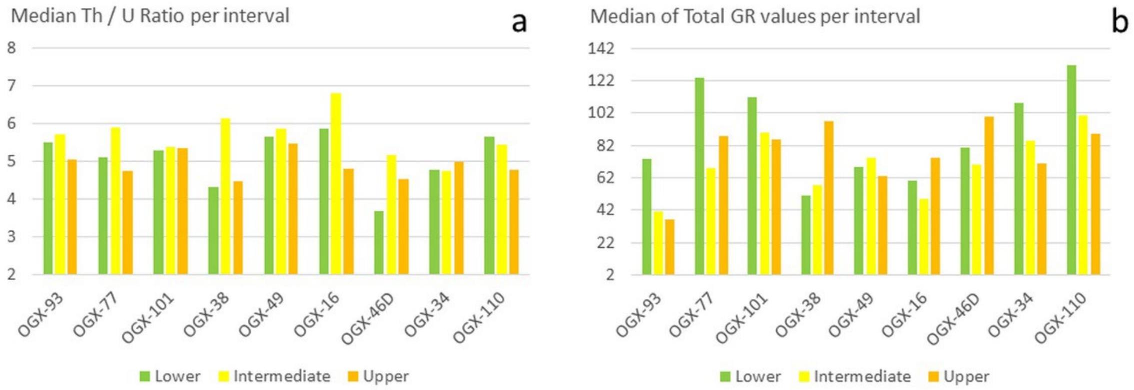

Figure 8 - (a) Histogram graph of the median of the Total GR values by interval, where the lower range has higher values than the intermediate range. (b) Histogram graph of the median of the Th/U ratio by interval, where the intermediate interval in general presents higher values than the lower and upper intervals, denoting a greater influx of continental sediments (Pereira, 2020).

while the acquisition in a well has a much higher resolution and refers to a point to be at every 0.15m.

The performance of the gamma spectrometry on cuttings proved to be efficient for acquiring data for correlations between wells, even when comparing with wells where the gamma spectrometric record was obtained through a running tool in the borehole wireline campaigns. It was possible to distinguish more proximal facies, presenting the Th/U > 7 ratio, which can contribute to paleoenvironmental reconstructions.

To perform correlations between wells with different sources of gamma spectral data, the use of Th/U and U/K ratio curves allowed for a better visualization between laboratory and wireline curves, as the relationship between curves minimized differences in reading scales, as well as background radiation interference.

The analysis of the trends of Th/U, U/K and full gamma-ray curves allowed the subdivision of the Cabeças Formation into three depositional stages. In the lower interval there is a gradual drop in gamma-ray values to the top and the Th/U ratio is generally below 7. In the intermediate interval, there is a higher frequency of high values of the Th/U ratio, as well as a drop in the gamma-ray log, that remains low in most wells. In the upper interval, the full gamma-ray log values rise again, and the Th/U ratio also remains lower, as in the previous interval. This type of analysis shows that the gamma spectrometry tool, both in wireline and in the laboratory, helps in stratigraphic refining.

The delta front region of a fluvio-deltaic system dominated by catastrophic floods for Cabeças Formation is interpreted, in this work, as intervals with Th/U ratio greater than seven, indicating an oxidizing condition, typical of the continental environment, weathered soils, and shallow marine environments. The intermediate interval presents a higher frequency of these floods and was deposited in a more proximal environment than the Lower and the Upper intervals. Powerful flows reach more distal regions in the basin, resulting in inflows with higher values of the Th/U ratio than those in the lower and upper intervals of the Cabeças Formation.

The workflow carried out in the laboratory showed that gamma spectrometry measurement on cuttings, in the laboratory or while drilling, is a powerful tool and can be used mainly in wells where spectral gamma-ray curves were not recorded in wireline. This work proposes an effective work methodology, using a tool of relatively low operational cost, to perform refined stratigraphic interpretations, favoring correlations between wells and stratigraphic zoning.

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REFERENCES

CAPUTO, M.V. 1984. Stratigraphy, tectonics, paleoclimatology and paleogeography of Northern Basins of Brazil. Thesis (Doctorate) - University of California, Santa Barbara. 586 pp.

DELLA FÁVERA, J.C. 1990. Tempestitos da Bacia do Parnaíba: um ensaio holístico. Doctorate Thesis in Geology. IG-UFRGS, Porto Alegre, RS, Brazil. 243 pp.

DELLA FÁVERA, J.C. 2001. Fundamentos de Estratigrafia Moderna. Rio de Janeiro, RJ, Brazil EdUERJ. 264 pp.

ELLIS, DV. & SINGER, JM. 2007. Gamma-ray Devices, In: ELLIS, DV. & SINGER, JM. Well Logging for Earth Scientists. chapter 11 p. 267–288. 10.1007/978-1-4020-4602-5_11.

FERTL, W.H. 1979. Gamma-ray Spectral Data Assists in Complex Formation Evaluation in: Trans., SPWLA Sixth European Formation Evaluation Symposium, London, March 1979; also Dresser Atlas publication No. 3335, 61.

HASSAN, M., HOSSIN, A., & COMBAZ, A. 1976. January 1. Fundamentals of the Differential Gamma-ray Log - Interpretation Technique -. Society of Petrophysicists and Well-Log Analysts.

KLAJA, J.; DUDEK, L. 2016. Geological interpretation of spectral gamma-ray (SGR) logging in selected boreholes. Nafta-Gaz. 72. 3–14. 10.18668/NG2016.01.01.

MIRANDA, F.S.; VETORAZZI, A.L.S.; CUNHA, P.R.C.; ARAGÃO, F.B.; MICHELON, D; CALDEIRA, J.L.; PORSCHE, E.; MARTINS, C.; RIBEIRO, R.B.; VILELA, A.F.; CORRÊA, J.R.; SILVEIRA, L.S.; ANDREOLA, K. 2018. Atypical igneous-sedimentary petroleum systems of the Parnaíba Basin, Brazil: seismic, well logs and cores. Geological Society, London, Special Publications, 472, 341–360, http://sp.lyellcollection.org

NOBRE, J.A. 2019. Interpretação paleodeposicional das formações Poti e Cabeças com base em dados gamaespectrais, obtidos em amostras de calha de poços da área do Parque dos Gaviões, Bacia do Parnaíba. Universidade Federal Fluminense, Niterói, RJ, Brazil. 71 pp.

PEREIRA, R.M. 2020. Interpretação paleodeposicional da Formação Cabeças a partir de dados gamaespectrais de poços da área do Parque dos Gaviões, Bacia do Parnaíba. Master Dissertation - Universidade Federal Fluminense, Niterói, RJ, Brazil, 122 pp.

RS-125/230. 2015. User Manual, Revision 1.05 Radiation Solutions Inc. Ontario, Canada. December 2015.

SERRA, O., BALDWIN, J., QUIREIN, J. 1980. Theory, Interpretation, and Practical Applications of Natural Gamma-ray Spectroscopy. In: SPWLA 21st Annual Logging Symposium, Lafayette, Louisiana, USA.

VAZ P.T., REZENDE V.G.A.M., WANDERLEY FILHO J.R., TRAVASSOS W.A.S. 2007. Bacia do Parnaíba. Boletim de Geociências da Petrobras, 15(2): 253–263.

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