Using geophysical density logging to estimate the thickness and density of coal seams in the Southern region of Brazil

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Abstract

This study shows the usefulness of borehole geophysical logging of density in the identification of coal seams, in relation to other lithologies present in a coal deposit located in the south of Brazil. Four drillholes were studied. The geological descriptions of the core samples recovered from these holes were the main information used as a control parameter in comparison with the geophysical logs. A threshold of density (2.0 g/cm^3) was established in the gamma-gamma log analysis for identifying the coal seams with economic value. Also due to the economic and operational aspects related to the coal industry, the coal seams must be at least 0.4 meters thick. Once the coal seams were identified by density logs, a verification of the accuracy in the determination of the thicknesses and densities of the coal seams was performed. The coal seam thicknesses and densities determined by borehole logging were close to the observed values in the borehole core samples. As a result of the comparison between the geological and density log data, an average value difference of 0.03 m and -0.01 g/cm^3 was reached for thickness and density, respectively. Due to the results and valuable information obtained, it was also possible to indicate and determine which areas of the deposit should be mined in relation to the drillholes studied and threshold parameters established. In conclusion, the importance of this evaluation is emphasized, mainly with respect to the thickness of the coal seams, which aids in the development of effective mine planning.

Keywords: borehole logging, coal, density.

1. Introduction

The evaluation process of a mineral deposit consists of several steps to ensure the accuracy of the data obtained directly or indirectly for the subsequent delimitation of the ore body's geometry and the estimation of the mineral resources. The most common direct sampling technique in the mineral industry is rotary diamond drilling with core sample recovery. The wide dissemination of this sampling methodology is due to the analyses that can be performed using the physical data, which ranges from delimitation of existing lithologies and strata thickness, to laboratory analyses that aims to provide geochemical classification data of the rocks in a deposit, as well as the relationship between the ore and existing waste lithologies (Webber, 2008).

In coal deposit exploration, an important indirect method of investigation applied in drillholes is the borehole geophysical logging (Hoffman *et al.*, 1982; Kayal & Christoffel, 1989; Afonso, 2014).

This method has been used due to its versatility, low cost and ease of application. In addition, the technique can provide the identification of lithologies, stratigraphic correlations and correlations between the rock properties and strata of interest (Ellis & Singer, 2007; Hearst *et al*., 2000). Among the borehole geophysical logging methods, gamma-gamma (density log) is one of the most recommended technics for the discrimination of coal strata from waste materials and it is the subject of this study.

Basically, the gamma–gamma probe comprises two parts: a radioactive emission source (usually Cs-137), sending the gamma radiation that will interact with the geological formations, and scintillometers that read the returning radiation after the gamma rays are backscattered by the geological interaction. The backscattered gamma rays are used to determine the specific gravity of the geologic formations. A detailed description of gamma–gamma probes is shown in Ellis & Singer (2007). A typical relationship between the density of the material surveyed and the backscattered radiation in a density log probe is shown in Figure 1. A mathematical model can be adjusted for formations with specific gravities above 1 g/cm^3 using a negative exponential function. This method, when applied in coal deposits, allows for a better visualization of the existing seams and their thicknesses. In this type of deposit, coal seams are often associated with sedimentary rocks, but coal has a lower density when compared to the other existing lithologies. Using gamma-gamma logging, it's possible to obtain important coal properties, such as ash content and heating power (Webber *et al*., 2009; Afonso, 2015).

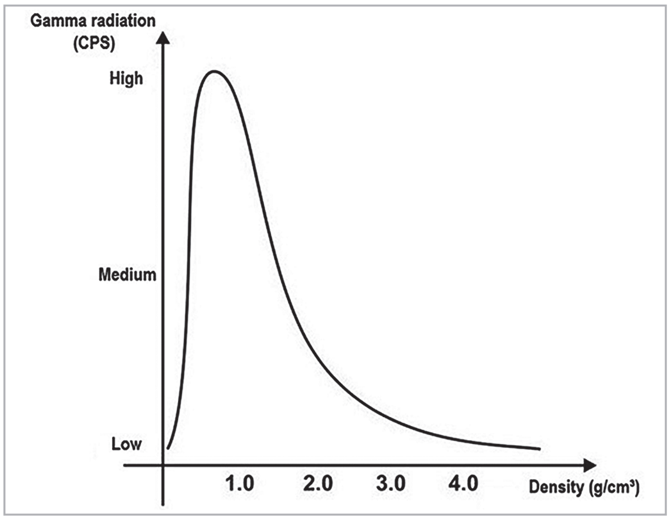

Figure 1 - Relationship between density and backscattered radiation in a density log probe (adapted from Hoffman, 1982).

This article has two main goals: (**1**) verify if gamma-gamma logging is able to identify the coal seams present in four drillholes in the B3 area, as well as the thickness of the coal seam based on a previously chosen density threshold value; (**2**) compare the density and thickness data obtained in the laboratory analyzes and geological survey respectively with the same data type obtained by the gamma-gamma method and finally trying to determine the degree of accuracy of the gamma-gamma method.

2. Location of the study area

The exploration drillholes are located in the B3 area, which is situated near the city of Butiá, 86 km from Porto Alegre, capital of Rio Grande do Sul, Brazil (Fig. 2).

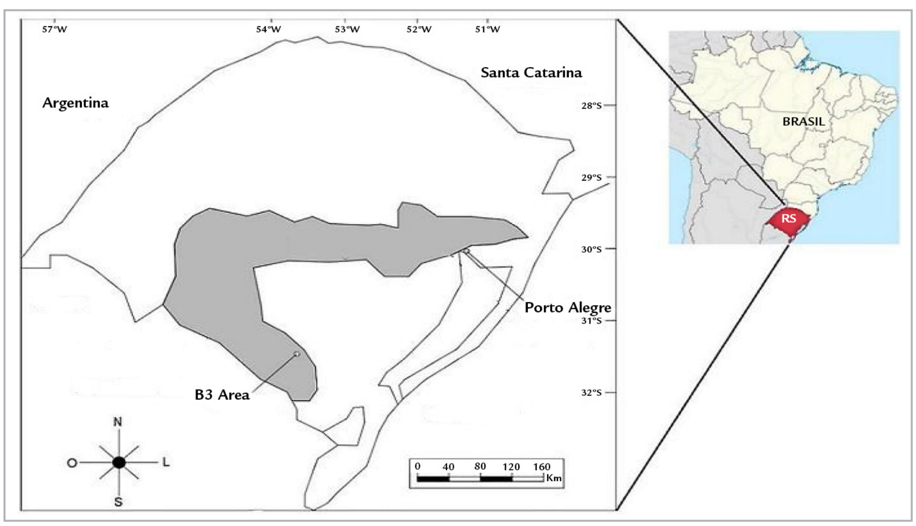

Figure 2 – Location map of B3 area in Candiota, Rio Grande do Sul.

2.1 Geological description of the region

The main Brazilian coal deposits are in the Paraná Basin, which is an intracratonic basin, with sediment depositions starting in the Ordovician period and ending in the Cretaceous period. The B3 area belongs to the Parana Basin (Fig. 3) and is in the Rio Bonito formation, inside the unity called Guatá group which is composed of sandstones, mudstones, shales and coal developments related to a deltaic-coastal environment. Specifically, in the B3 area, the geology is characterized by siltstones, claystones, sandstones and conglomerates with several coal seams between them (Webber *et al.*, 2013).

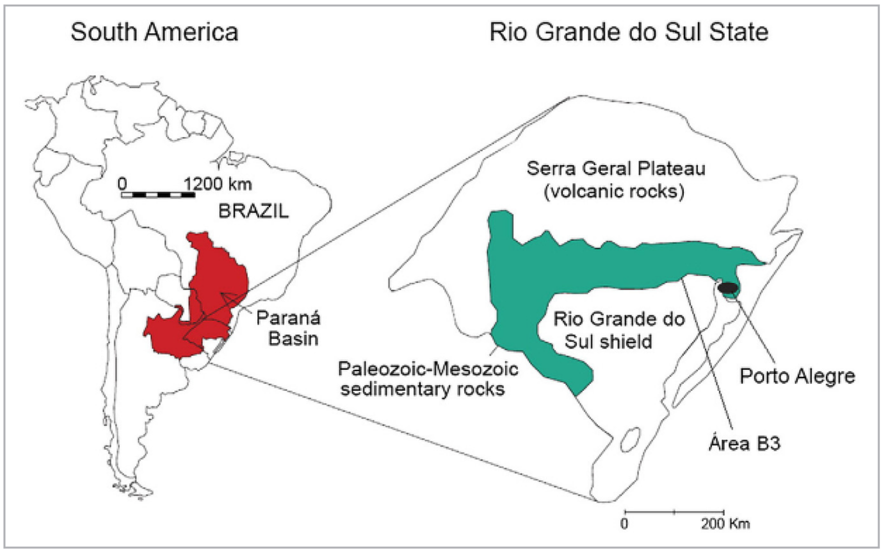

Figure 3 - Map depicting Paraná Basin and the B3 Area (from Webber *et al.*, 2013).

According to Webber *et al*., (2013), the general stratigraphic column of the deposit is composed of 1 m of topsoil, followed by 10 m of siltstone with sandstone layers, which belong to the Palermo Formation, and gray siltstones that belong to the Rio Bonito Formation. The coal seams in the deposit are named as A, S, M1, M2, M3, I1 and I2 (Webber, 2008), with some local variations (Fig. 4). However in this study, only the following seams were taken into consideration in the data analyzed, and have the following geological descriptions as stated: (**1**) S coal seam which presents an average thickness of 0.98 m and characterized by bright coal with a high concentration of vitrinite and a few layers of waste material composed of carbonaceous siltstones; (**2**) M1 and M2 seams, which are very closely spaced and have a total average thickness of 1.58 m, where M1 is generally composed of layers of bright coal and carbonaceous siltstones and M2 is composed of bright coal without partings; (**3**) I1 seam is mostly composed of siltstones and paraconglomerates, having an average thickness of 1.2 m; (**4**) According to Webber (2008), the I2 seam is the last seam of the lithological sequence and is composed of siltstones interspersed with conglomerates and coal; however, the continuity of this layer needs further investigation.

Herein, four drillholes are analyzed and they exhibit a different combination of coal seams, depending on the specific position in the mineral deposit. The following coal seams that can be seen in each respective drillhole are (Fig. 5): (**1**) B3-03 the layers S+M1 and M2; (**2**) B3-12 the layers S, M1, M2; (**3**) B3-13 the S + S3, M1+ M2, I1S and I1I; (**4**) B3-18 the layers S, M1, M2, I1I, I1S and I2ST. The general information about these holes is available in Webber (2008).

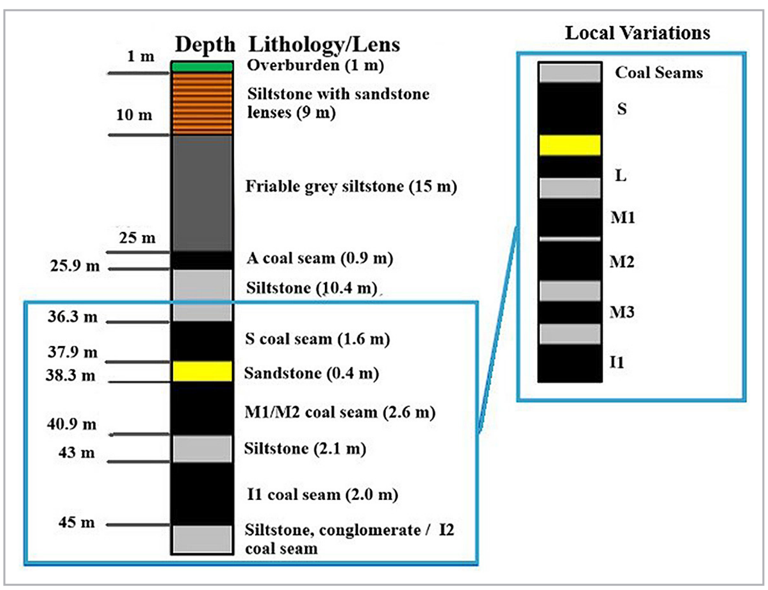

Figure 4 –Stratigraphic column of the B3 deposit and on the right the local variations between coal and partings (from Webber *et al.*, 2013).

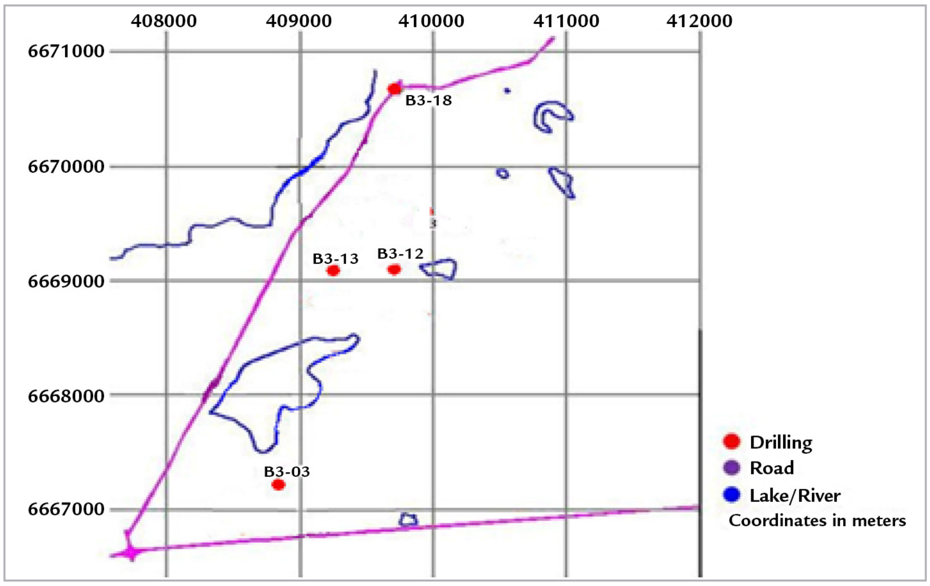

Figure 5 – Localization of the drillholes (adapted from Webber, 2008).

3. Materials and methods

The field work required the application of geophysical logging in several drillholes in the B3 area. Four vertical exploration drillholes were chosen for this investigation with varying depths between 35 to 75 m. The gamma-gamma probe used for the data acquisition was the Sidewall Density Sonde (SWDS), manufactured by Robertson Geologging Ltd (UK). Density logging is always performed from the bottom of the drillhole to the top, performing the data recordings until the sonde reaches the surface. The geologist's recognition of the lithologies of the core samples recovered is based on visual analysis of the texture, structure and composition of these samples. In the case of coal samples, the qualitative features are described in detail, such as the vitrinite content, in accordance with the patterns of the Standards Association of Australia (ANON, 1993). The choice for the LSD sensor is due to the investigation ratio, and by consequence, the larger investigation volume of the sensor, in order to be able to capture information related to coal layers with a thickness equal to or greater than 0.4 m, which attends the coal industry standards.

After data acquisition and processing, the information obtained is displayed and visually interpreted through the software WellCAD™. For comparative purposes, the core recovery referring to the drillholes (B3-03, B3-12, B3-13 and B3-18) which is also part of the focus of this research, is almost 100%. Before the interpretation step, the parameters for analysis were established. According to Afonso (2014), a simple method to mark the geologic contacts (roof and floor depths) of coal is to choose a threshold of about 2.0 g/cm^3 for the LSD sensor which was calibrated to register the rock densities.

In the present study, the probe calibration procedures and definition of the density log response function were carried out using several samples taken from drilling cores. Around 30 samples were used, representing coal densities, and also waste lithologies, such as siltstones and sandstones, with a full range of densities approximately between 1.4 and 2.4 g/cm^3. Samples densities were determined by direct laboratory tests. The samples used in the calibration represented intervals in depth generally greater than 0.4 meters, where the density recorded remained reasonably constant. All holes considered here have the same nominal drilling diameter (NW), and the caliper register is very constant throughout the holes (close to the nominal diameter), which is a feature easily observed in the logs. The caliper was acquired simultaneously to the counts of the sensors (scintillometers) recording backscattered gamma rays. Likewise, all holes were logged during the same year, which practically eliminates variations in readings caused by decay of the Cs-137 source, whose half-life is approximately 33 years. Finally, LSD sensor records at corresponding depths of core samples were correlated with the densities obtained in the laboratory, and the response function (a negative exponential, shown in Figure 1 was used to model the response of the density probe.

The threshold mentioned above, used to identify coal, is a value largely based on the results of laboratory analyses performed on drilling samples, which show that densities equal or below 2.0 g/cm^3 are normally related to samples classified as coal during visual identification and tactile assessment made by the geologist, during the activity of describing the drilling samples. Above this threshold value, the material is classified as waste. In this study, the main interest is in coal seams that are at least 0.4 meters thick, due to the economic and operational aspects related to the coal industry, and the vertical resolution of the LSD sensor from density log, which is also around 0.4 m. In conclusion, a visual and comparative analysis was carried out between the gamma-gamma density data and lithological description performed by the geologist. Additionally, another comparative analysis was performed to verify if the density data obtained for the drillholes in the B3 area by the gamma-gamma method corresponds to the density values obtained by the laboratory analysis.

4. Results

Using the gamma-gamma method, it was possible to determine the contact positions and density of the coal seams present along the drillholes when making comparisons between their values and the lithological descriptions of the core samples.

Observing specifically the coal seams, it was possible to correlate the seams with a higher percentage of vitrinite, which has low densities, with the acquired values measured by the long-spaced sensor. Considering the parameters used in the coal industry, several seams of coal were analyzed in the drill holes (B3-03, B3-12, B3-13 and B3-18), whose main geological features are repeated in the area of interest. Figures 6, 7, 8 and 9 present the most important parts of the density data acquired in the holes through the gamma-gamma method, including a column showing the lithological descriptions. However, not all coal seams are thick enough and have high quality (low ash content) to be detected by density logging or other methods in general. Also, some coal seams did not meet the pre-established threshold parameters. For example, in B3-03, M1 seam did not meet the necessary thickness required (Fig. 6) which was confirmed by the lithological description. However, the limits between the S layer and M1 seam are not clear in the density log, and in a hypothetical situation, the S layer will be mined to reach the M1 seam; from a geological and economic point of view, the two layers can be combined and mined. A similar situation occurred in the B3-13 drillhole, where the seams M1 and M2 cannot be separated because the parting PM1-M2 (carbonaceous siltstone with vitrenium) is not seen clearly in the density log (Fig. 8) and also in the B3-18 drillhole with the layers I2ST, I2SB and I2I (Fig. 9). In those situations, the density of two or more coal layers is calculated through the average weighted by the length of the geological strata, taking into account the total thickness of the packages and their densities, in order to obtain the value of the combined package. After that, the comparison between hard and soft data is performed.

Once the main coal seams could be satisfactorily recognized in the logging data of the drillholes available in this study, the values of thickness and density extracted from the logging data were compared with the same information coming from the geological description of the drill core samples that can be seen in Table 1.

Regarding the drillhole diameter, it generally remains constant, as can be seen in the Figures 6, 7, 8 and 9, so it does not have a crucial impact on the study.

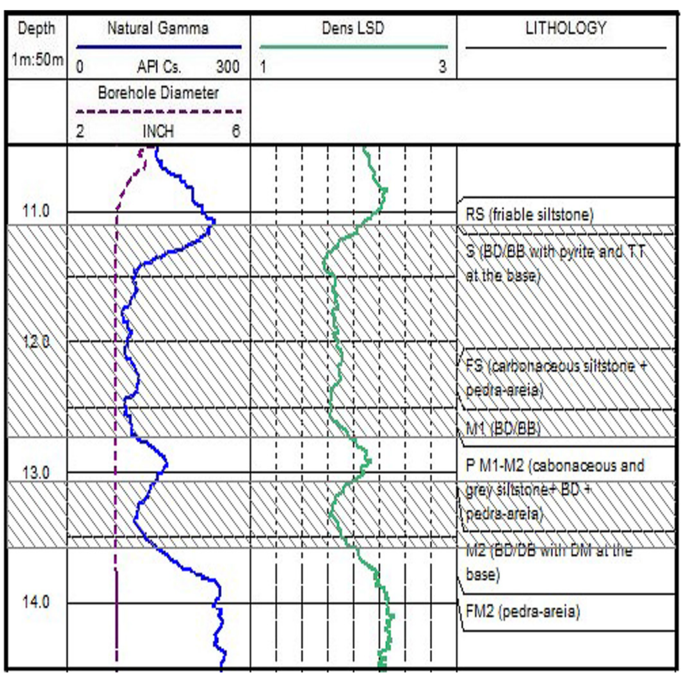

Figure 6 - Logging profile (natural gamma and gamma-gamma with lithological description) for a B3-03 drillhole.

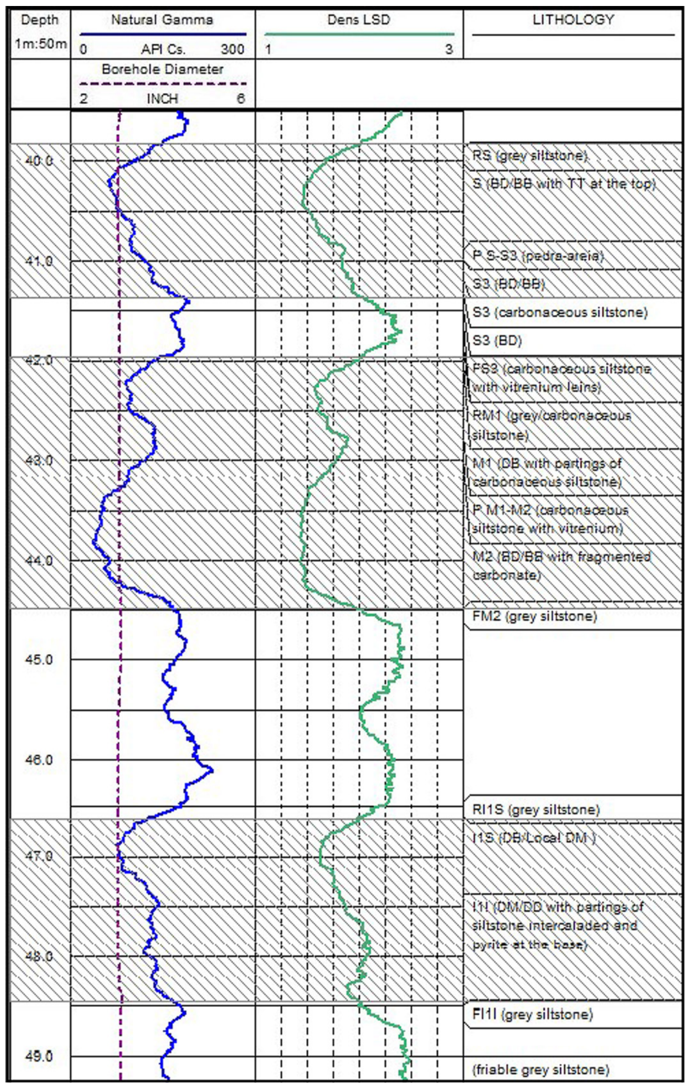

Figure 7 - Logging profile (natural gamma and gamma-gamma with lithological description) for a B3-12 drillhole.

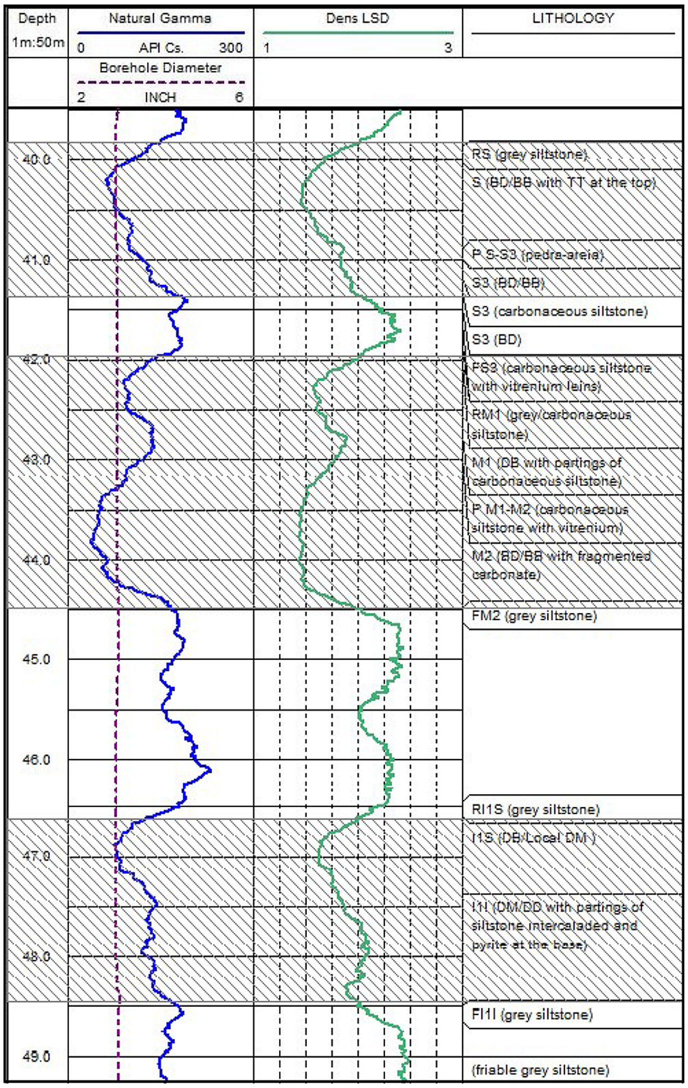

Figure 8 - Logging profile (natural gamma and gamma-gamma with lithological description) for a B3-13 drillhole.

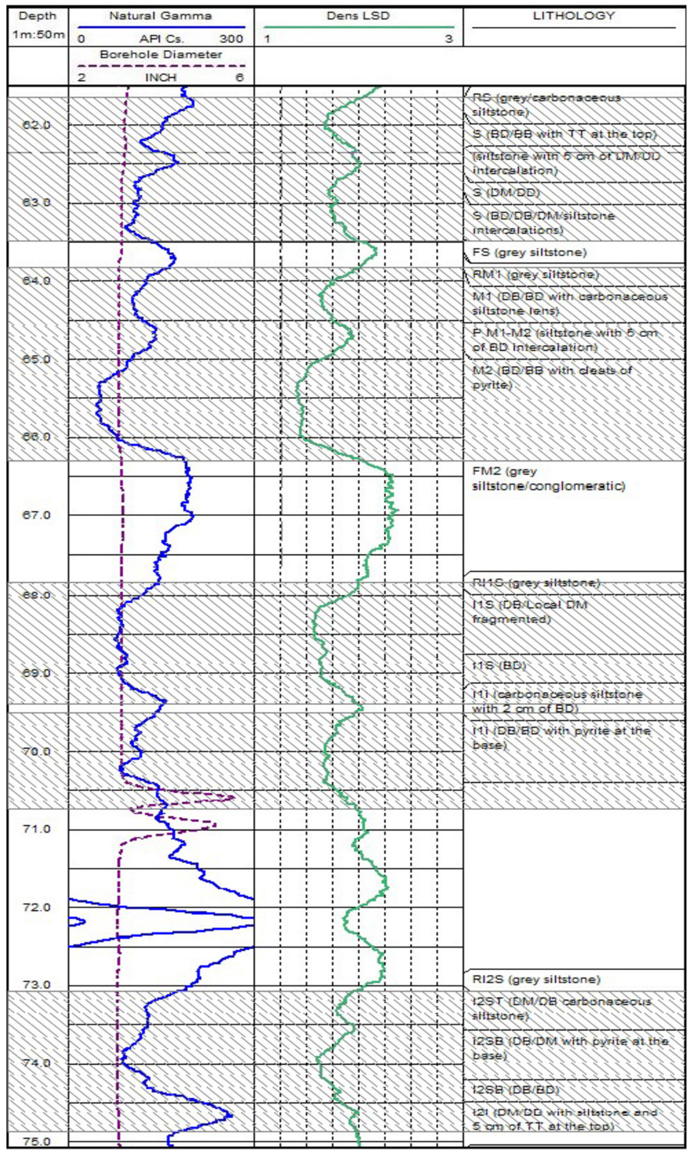

Figure 9 - Logging profile (natural gamma and gamma-gamma with lithological description) for a B3-18 drillhole.

Table 1 – Comparison between the geological description of the drillholes and the gamma-gamma data.

		GEOLOGICAL SURVEY				DENSITY LOG				Thickness	Density	Density
Borehole	Layer	From (m)	To (m)	Thickness (m)	Density (g/cm^3)	From (m)	To (m)	Thickness (m)	Density (g/cm^3)	Difference (m)	Difference (g/cm^3)	Difference %
B3-03	S+M1	11.10	12.64	1.54	1.79	11.10	12.74	1.64	1.84	0.10	0.05	2.79
B3-03	M2	13.08	13.78	0.70	1.92	13.07	13.60	0.53	1.87	-0.17	-0.05	-2.60
B3-12	S	38.95	39.95	1.00	1.78	38.99	39.93	0.94	1.73	-0.06	-0.05	-2.81
B3-12	M1	40.20	41.92	1.72	1.79	40.20	41.84	1.64	1.76	-0.08	-0.03	-1.68
B3-12	M2	42.42	43.12	0.70	1.76	42.58	43.21	0.63	1.80	-0.07	0.04	2.27
B3-12	I1	45.27	46.94	1.67	1.75	45.30	46.96	1.66	1.76	-0.01	0.01	0.57
B3-13	S+S3	40.02	41.48	1.46	1.64	39.83	41.38	1.55	1.70	0.09	0.06	3.66
B3-13	M1+M2	42.00	44.48	2.48	1.67	41.97	44.50	2.53	1.62	0.05	-0.05	-2.99
B3-13	I1S+ I1I	46.60	48.50	1.90	1.83	46.62	48.47	1.85	1.88	0.05	0.05	2.73
B3-18	S	61.87	63.47	1.60	1.87	61.65	63.50	1.85	1.83	0.25	-0.04	-2.14
B3-18	M1+M2	63.86	66.30	2.44	1.82	63.83	66.31	2.48	1.65	0.04	-0.17	-9.34
B3-18	I1S	67.91	69.20	1.29	1.66	67.83	69.40	1.57	1.72	0.28	0.06	3.61
B3-18	I1I	69.52	70.42	0.90	1.79	69.50	70.75	1.25	1.77	0.35	-0.02	-1.12
B3-18	I2ST+I2SB+I2I	73.05	75.10	2.05	1.84	73.08	74.89	1.81	1.81	-0.24	-0.03	-1.63
						Average of Differences				**0.03**	**-0.01**	**-0.62**

5. Discussions

The comparisons made in Table 1 involve the subtraction of both seam thicknesses and densities, through the values obtained via gamma-gamma (soft data) compared with the same strata values observed in the geological description (hard data). The average of differences show that the gamma-gamma method is quite effective in measuring the thickness of the strata, since the average of differences is 0.03 m which is satisfactory for the purpose of this investigation. For the densities data, the average of differences is -0.01 g/cm^3. To ensure data accuracy, the average differences must be close to zero, showing that the estimates are unbiased, which happens in this situation with respect to density and thickness.

Considering all the strata observed in Table 1, approximately 93% of the situations showed that the absolute difference between the laboratory density and the density obtained by logging is less than 5%. Analogously, considering the data in Table 1, approximately 71% of the situations showed that the absolute difference between the thickness of rock samples and the thickness obtained by logging is less than 0.2 m. Also, the average density difference between survey logs and density logs is -0.62%.

Other observations can be made regarding area B3. According to the soft and hard data analyzed and the threshold established, the B3-13 and B3-18 boreholes show the most economical situations. The B3-13 borehole has a total coal thickness of 5.84 m (hard data) and 5.93 m (soft data). Furthermore, B3-13 has the coal package S+S3 with the lowest average density among all the boreholes investigated, which is 1.64 g/cm^3 (hard data) and 1.70 g/cm^3 (soft data). The drillhole B3-18 presents a total coal thickness of 8.28 m (hard data) and 8.96 (soft data), which is the thickest coal total package among all the boreholes analyzed. However, the average density for this drillhole is higher when compared with B3-13, as can be observed in Table 1.

In drillhole B3-03 (Fig. 6 and Tab. 1), the S+M1 seam can be seen as the most valuable package because it has a thickness of 1.54 m according to the geological survey or 1.64 m according to the density log and density values below the threshold. In this situation, the density difference for the S+M1 seam is 2.79%.

In B3-12 (Fig. 7 and Tab. 1) layers M1, M2 and I1, form another economically valuable carbonaceous package, showing thicker layers with lower densities, which are easily visible in the logs, but the waste material between those layers makes the density difference increase as observed in Table1. In terms of density difference, the I1 seam is more reliable in comparison with all the drillholes analyzed because it presents the lowest density difference among all observed data, which is about 0.57%. This can be attributed to the fact that I1 is a thick layer and there is almost no amount of waste material inside it. Also, the top and bottom limits of this layer were captured with more accuracy by the long-spaced sensor and are easily identifiable.

In the case of drillhole B3-13 (Fig. 8 and Tab. 1), the configuration of some strata of coal contained in the main package of greater economic interest (beds S, M and I), separated by thinner layers of waste, did not allow the individualization of the beds. As can be seen in Figure 7, adjacent layers such as S and S3 are separated by a thin layer of waste material (parting S – S3 approximately 0.10 m thick), which is not clearly seen in the logging. A similar situation is observed in the same logging with the layers M1 and M2 (they are separated by carbonaceous siltstone), and in I1S and I1I (Fig. 8). The same feature happens in B3-18 (Fig. 9) when the layers of waste material are so thin between M1 and M2 and between I2ST and I2SB, that coal seams cannot be individualized. However, in B3-18 (Fig. 9 and Tab. 1) due to a considerable increase in density due to a layer of waste material, it is possible to separate the package S from M1+M2.

6. Conclusions

Based on the analyses, it is concluded that borehole geophysical density logging is effective in distinguishing the coal seams from the sedimentary waste rocks which are present in the study area (Area B3) in the southern part of Brazil. A threshold of 2.0 g/cm^3 was established for the gamma-gamma log analysis results for identifying the coal seams with possible potential of exploration. As can be seen in Table1, the comparison between the core sample data and the values obtained from the density log show some discrepancies. However, the density information from the gamma-gamma method may serve as supporting data for mineral research in places where drilling is not feasible or for low sample recovery scenarios; situations that happened in some drillholes, as mentioned in Webber (2008). Thus, soft data (from geophysical logs, for example) values can be important for exploration research, when combined with hard data (core samples), in order to apply evaluation techniques to quantify economically exploitable reserves.

Furthermore, it was observed that the method is more effective in identifying homogeneous coal seams with a thickness equal or greater than 0.4 m (expected vertical resolution for long-spaced sensor), which attend the thickness standards used in the coal industry. However, one of the next steps of this research, aims to show the results between the comparation provided by the LSD and HDR sensors, which have different vertical resolution. Also, a larger study should be carried out, in order to analyze more drillholes in order to obtain more reliable results and the estimation of other coal quality parameters, as high-ash content and water presence.

Refereces

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