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Emissions from surrounding strata in coalbeds: Guaduas formation (Colombia)

Emisiones de las rocas circundantes a los mantos de carbon: formación Guaduas (Colombia)

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Keywords:	**ABSTRACT**
Guaduas formation, emissions, methane desorption, surrounding strata, shales, GHG, CBM, Colombia.	During underground coal mining operations, greenhouse gas emissions are produced, mainly methane. These emissions originated not only from coal, but also from the subsidence of the surrounding rocks. Until now, emissions from surrounding rocks have been calculated from international tables, but it is proposed that they be calculated from gas measurements on coal-adjacent rocks in coalbed methane exploration in which drillings and canisters desorption systems were used in the provinces of Boyacá and Cundinamarca. The gas contents of the surrounding rocks, and thus the emissions, are less than those found in the coal at the same depth. The areas with the highest gas content values in the surrounding rocks are Samacá and Chinavita with contents between 40 and 50 feet3/ton. These values equate to one-third or a quarter of those obtained from the coalbeds close to such samples. The highest gas content did not correspond to the highest coal rank (Socotá) which would be explained by the intense folding and faulting in that area. The gas contents found in the shales (clays) of the Guaduas formation can also be used as a proxy indicator for older and deeper formations that could have good shale gas potential.

Palabras clave:	**RESUMEN**
formación Guaduas, emisiones, desorción de metano, rocas circundantes, lodolitas, GEI, CBM, Colombia.	Durante las operaciones de minería subterránea de carbón se producen emisiones de gases de efecto invernadero, principalmente metano. Esas emisiones no solamente proceden del carbon, sino también de la subsidencia de las rocas circundantes. Hasta ahora los cálculos de las emisiones de las rocas circundantes se han hecho a partir de tablas internacionales, pero se propone que se hagan a partir de las mediciones de gas en las rocas adyacentes al carbon en estudios con perforaciones de gas asociado al carbon en los departamentos de Boyacá y Cundinamarca en los que se utilizaron equipos de desorción cánisters. Los contenidos de gas de las rocas circundantes, y por ende las emisiones, son menores a las encontradas en el carbon a la misma profundidad. En las zonas con los valores más altos en contenido de gas en las rocas circundantes son Samacá y Chinavita donde se encontraron contenidos entre 40 y 50 pies3/tonelada. Esos valores equivalen a una tercera o cuarta parte de los que se obtuvo de los carbones cercanos a dichas muestras. Los contenidos de gas más altos no correspondieron con la zona de mayor rango de los carbones (Socotá) lo que se explicaría por el intenso plegamiento y fracturamiento de dicha zona. Los contenidos de gas encontrados en las arcillas (shales) de la formación Guaduas también se pueden utilizar como un indicador (proxy) para formaciones más antiguas y profundas que podrían tener un buen potencial de shale gas.

Introduction

During coal mining operations, there are greenhouse gas (GHG) emissions not only from the mining of the coal seams, but also from the subsidence of the surrounding strata. These GHGs are methane (CH_4), carbon dioxide (CO_2) and others, but mainly CH_4. The Intergovernmental Panel on Climate Change (IPCC) has considered that, during the extraction of coal seams, the rocks surrounding the coal seams also emit methane that affects an area 50 m below and 150 m above due to the subsidence produced by coal extraction [1]. The total amount of emissions from a coal seam is the emissions from the coal and the emissions from the surrounding strata above and below the coal layers. These emissions from the massif, where the coal is located, are generated by the fracture and sinking of the rocks above the coal, mainly the thin unmined mantle, carbon backs, claystones - mudstones (shales) and sandstones in general.

During the last few years Colombia has been calculating fugitive emissions from coal seams in mining areas (CBM-CMM) using international tables [2]. Fugitive emissions are known by this name because they are not formed by fuel burns, but rather by the escape of gases that are trapped in the rocks and minerals and are emitted into the atmosphere by anthropic action; this happens with the methane gas associated with coal that is emitted into the atmosphere slowly and almost imperceptibly; when the mineral is extracted through the process of exploration, exploitation, storage and transport of coal. Fugitive gas emissions associated with coal mining account for 5 percent of energy-related GHGs [3].

The carbon-associated gas (CBM) studied to date includes Cretaceous-Tertiary bituminous coals, which have been studied using desorption canisters, petrography, physical-chemical and isotope analyses to determine gas content, gas origin, and gas saturation of the coals [4], [5].

Colombia, as a signatory to the United Nations Framework Convention on Climate Change in 2015 (Paris Agreement), committed to measure and report periodically on its greenhouse gas (GHG) emissions. This is why the country has been measuring and reporting emissions in recent years at the sectoral and departmental levels; fugitive emissions from coal seams have also been calculated, measured and reported [2], [6].

Although some emission calculations have been made from the coal range using international tables [6], other calculations have used gas content gradients from CBM-CMM exploration wells [2]. Exploration wells in the eastern Andes have found that CBM-CMM values range from a few ft3/tonne near the surface to more than 200 ft3/tonne at depths greater than 500 m (Figure 1). In some cases, if gas content versus depth is plotted, a direct correlation or increase with depth is found that confirms the increase in CBM with burial, suggesting that when drilling at deeper levels, the gas content would be higher. However, although no direct measurements of CH_4 emissions from the surrounding strata have been reported in Colombia so far, in some of these exploration studies some measurements have been made in mudstones (shales) and sandstones near coal seams to understand the risk of explosions during mining, and these measurements can be used as a proxy to calculate the emissions from the surrounding rocks [7] - [11].

Therefore, the purpose of this study is to report, for the first time, the gas content in the strata surrounding the coal in the Guaduas formation in order to calculate the direct emissions from the strata above and below the coal [12] - [14]. The results of this study may be useful not only for the calculation of emissions, but also to calculate the risk of methane gas explosions in mining-related rock tunnels, and to know the shale gas potential of the Guaduas formation.

Materials and Methods

Although exploration studies for carbon-associated gas (CBM) have been conducted in many exploration wells in the Cundinamarca and Boyacá Altiplano, only a few mudstone and sandstone samples above and below the carbon have been tested for desorption. The sampled wells are located in the municipalities of Sutatausa, Cucunubá, Samacá, Ráquira, Socotá and Chinavita (Figure 1). In these wells, in addition to measuring the gas content, and making immediate analyses, the degree of maturity of the organic matter was also determined from vitrinite (Ro) reflectance tests (performed on a Leica DM4000P microscope, coupled with a Tidas MSP reflectometer from the UPTC). The immediate analyses included moisture, ash, volatile matter, fixed carbon, calorific value and sulphur content (using thermogravimetric analysis techniques on a TGA-Leco S-14DR analyser).

Although some mining fronts also took mudstone cores above and below the coal seams, the analysis focused on eight samples taken from seven well (Figure 1) (Table I).
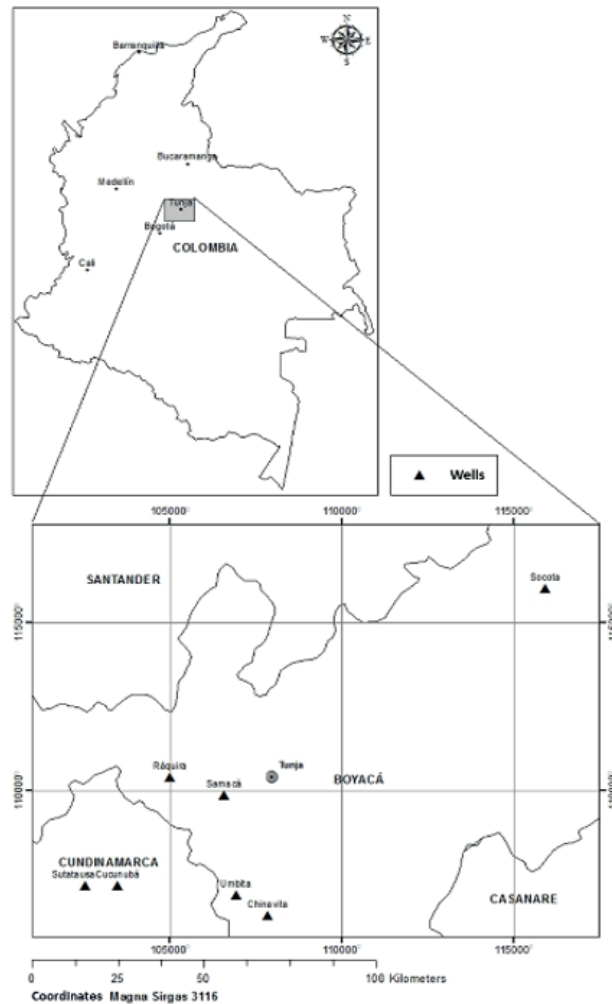

Figure 1. Location of municipalities where coal gas wells were drilled (CBM-CMM).

The gas content in this study is based on direct methods that consist of measuring the amount of gas in a mudstone sample by slowly desorbing the gas from the cores obtained with drilling equipment. Currently, the measurement process comprises three different methodologies taking into account that the total gas content is the sum of three components:

TOTAL GAS CONTENT (ft3/ton)= lost gas+measured gas+residual gas   (1)

Lost gas

It is the gas that escapes in the time since the coal is extracted from its condition in situ and the time it is introduced and sealed inside a canister. For samples taken from mine faces, the gas that escapes during the time between the sample being taken from a mine face and the subsequent sealing within the canister. On the mine front, sampling is similar to the sampling of coal in a carcass. The gas leakage is determined from the extrapolation of the desorption test data during the first two hours of measurement using a linear regression (Figure 3 left). The amount of gas lost can be calculated by the USBM method expressed in cm3/g or in ft3/ton [4].

Measured gas

This is the amount of gas that a sample of coal or slurry releases in the desorption test with the canister, also known as desorbed gas. The coal samples are placed in sealed canisters or containers; the canister is then connected to a burette to measure the degassing of the coal by opening the valve that allows the gas to escape, which is measured by the displacement of water in a volumetric column in the burette at reservoir temperature and atmospheric pressure [4 and 15]. The difference in levels corresponds to the volume of desorption during that measurement (see Figure 2). The gas desorbed is reported in cubic meters per ton of coal (m^3 of gas/ton of coal), or also in cubic feet per ton of coal (ft^3 of gas/ton of coal) (Figure 3 Right).

residual gas

It is the amount of gas that remains absorbed into the carbon matrix after the desorption test has been completed, but is released and measured once the sample has been crushed. The measurement of residual gas is done by removing the coal sample from the canister and splitting it into quarters. One of these parts is taken and placed in a ball or roller mill, the coal is pulverized within 3 to 10 minutes; the container must be hermetically sealed and connected to a pressure gauge to measure the residual gas content.

The determination of the total gas desorbed will correspond to the sum of all the measured volumes (lost, measured and residual) in the three tests, all corrected to standard temperature and pressure (STP) [4].

Gas desorption equipment

The canister desorption system used to determine the gas content of mudstone samples consists of a cylinder-shaped airtight chamber made of metal or PVC. The container is sealed at one end (base) and a hermetic cap at the other end. The dimensions of the canisters are: length 30-37 cm and diameter 10-12 cm. At the top, there is a 5-15 psi gauge, and an additional hole with a tap to connect it to the burette of the gas measuring system (Figure 2). The volume of the containers should be about one litre. In addition to the containers, the measurement of the gas system is determined by the displacement of a column of

water consisting of a burette connected to the pipe with a system of hoses. The burette can be 250 ml or more. The assembly is carried out by connecting the two couplings at each end of the burette with the metal bracket so that the burette is completely vertical.

While one end of the burette is connected to the canister, the other end is connected with a flexible hose to a funnel. The burette is filled with coloured water for better observation of the gas movement as it leaves the cannister and pushes the water column (Figure 2).
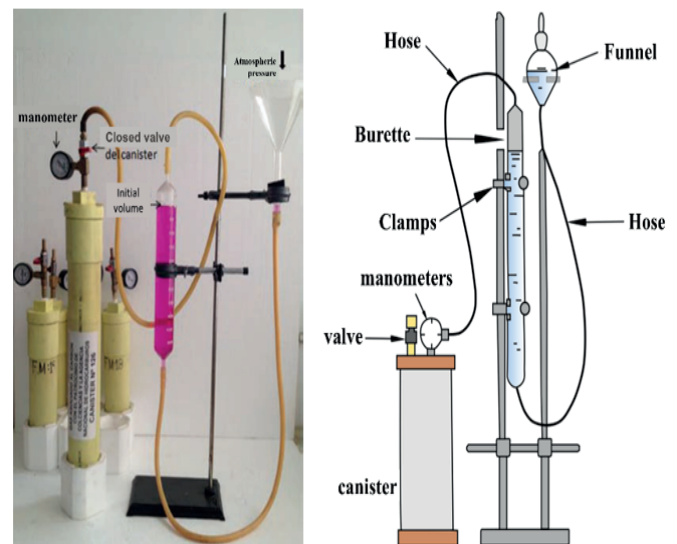

Figure 2. Desorption system with cannisters used to measure gas content.

In addition to recording the centimeters of gas desorbed at each measurement, the time of each measurement, temperature, pressure, and date are also recorded in the desorption format. This procedure is repeated for each sample analyzed during the drilling of the well.

Results and Discussion

Table I shows the results of the 8 samples for gas in surrounding strata taken from 7 CBM wells drilled in 6 municipalities in the Cundiboyacan highlands in the Guaduas formation (Figure 1). Each sample has gas content and depth, the lost, measured and residual gases of the sample are reported separately and as a total sum. The total gas is presented in ft^3/ton and m^3/ton (cm^3/g). The last column shows the average reflectance of the vitrinite (Ro).

Table I: Results of measurement of lost, measured, residual and total gas, and of reflectance of the vitrinite (Ro) for 8 samples of lodolites (shales) in the formation of guaduas.

ID Sample	Municipality	Well	Depth (m)	Lost gas (ft³/ton)	Measured gas (ft³/ton)	Gas residual (ft³/ton)	Gas Total (ft³/ton)	Gas total (m³/ton)	Vitrinite reflectance (R$_o$)
C8-98	Sutatausa	Sutatausa 1	398	0	9,96	-	9,96	0,28	0,68
C3-183	Cucunuba	Cucunuba 3	231	0	3,64	10,67	14,31	0,40	0,73
PS2-29	Samacá	Samacá 2	321	23,94	16,19	-	40,13	1,13	0,85
PR1-38	Ráquira	Ráquira 1	140	0,48	24,65	-	25,31	0,71	0,75
PSOC1-5	Socotá	Socotá 1	306	0,34	1,18	14,40	16,22	0,46	1,32
PSOC2-6	Socotá	Socotá 2	509	0,00	0,08	21,79	21,87	0,62	1,36
PCHI1-12	Chinavita	Chinavita 1	475	1,36	34,30	14,58	50,24	1,42	-
PHUM1-14	Chinavita	Chinavita 1	513	9,17	21,19	13,25	43,61	1,24	-

Below are the calculations of lost, measured and residual gas for one of the eight samples analyzed (Chinavita well 1, sample PCH1-12).

Sample PCHI1-12 (Pozo chinavita 1)

Initially the gas lost was measured, then the gas measured and finally the residual gas. For each gas measurement, the following were measured and recorded: date, temperature, pressure and gas content, because these are necessary for the standardized gas content (SCF) of the desorbed gas in ft3/ton and m3/ton [10].

Figure 3 (left) represents the lost gas procedure using the first day's measurements. The calculation of the lost gas is done using a linear regression to calculate the amount of gas that was lost from the time the drill bit touched the coal seam to the time the tank was sealed. The intersection of the regression line with the Y-axis corresponded to 1,365 ft3/ton. Figure 3 (right) presents the results of the gas measured over a three month period. The behavior of the cumulative measured gas curve shows good desorption at first to gradually decrease to zero. The accumulated measured gas value is 34.30 ft3/ton. The residual gas calculation was 14.58 ft3/ton. After adding lost, measured and residual gas, the total gas for that sample is 50.24 ft3/ton (Table I).
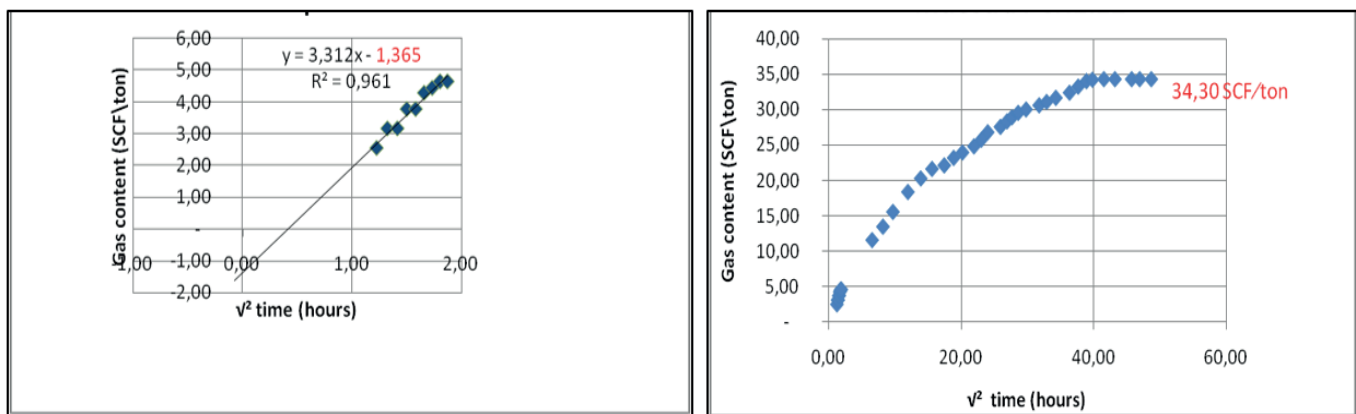

Figure 3. Left, linear regression to calculate the value of the gas lost. Right, desorbed gas curve representing the sum of all measured gas measurements over a 3 month period. Sample PCh 1-12 from Chinavita Well 1.

This research is a pioneer in calculating emissions from rocks surrounding coal, and aims to demonstrate that gas contents in rocks close to coal in CBM exploration serve as a basis for calculating emissions from rock mass subsidence as a result of coal extraction (Figure 4).
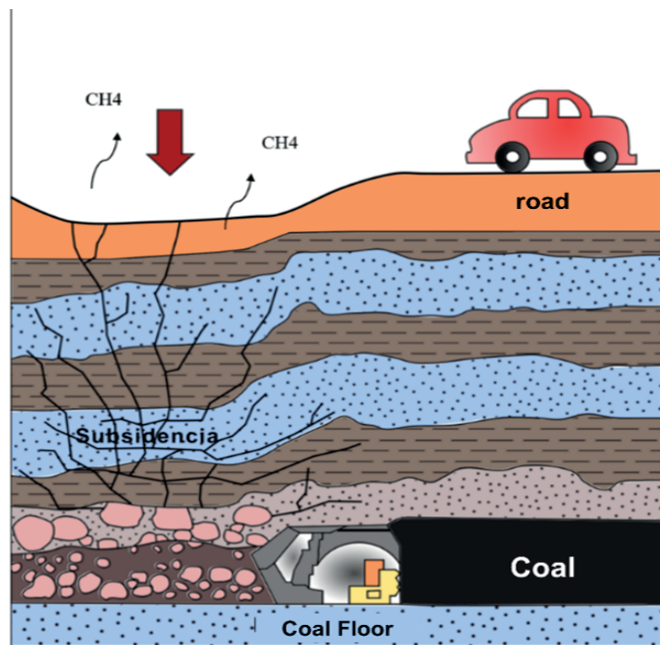

Figure 4. Methane emissions from the surrounding rock into the coal from subsidence caused by mining.

Of the eight samples analyzed from surrounding rocks (Table I), the Samaca 2 and Chinavita 1 wells produced the highest gas content of 40.13 and 50.24 ft³/ton respectively, this despite the fact that residual gas was not measured in the Samaca 2 well samples. Lower gas contents (9.96 and 14.31 ft³/ton) were observed in the Sutatausa 1 and Cucunuba 3 wells. The total gas, with approximately 50% residual gas, provides the highest percentage that may indicate low permeability (Table I). Therefore, if the residual gas in the Samaca and Raquira wells were calculated, the total content could be around 50 ft3/ton. That gas content would be close to the gas content found in some of the North American shales such as the New Albany [16]. The main gas contents were expected in the Socota wells because they were coking coal with vitrinite reflectance greater than 1%, but this was not the case because the total content did not exceed 22 ft³/ton. For coking coal, the vitrinite reflectance is above 1% (1.32-1.36%) [4], [9].

The samples presented in Table I are not the only ones analyzed because samples were also taken in front of the mine, but they were not included in this investigation because they were not cores. For each well, 2 or 3 mudstone samples were processed at different depths. The information has been consolidated in Table II, by average gas content, by municipality and by depth. In the Sutatausa well, with samples taken at depths ranging from 100 to 400 m, the average gas content was about 9.96 ft³/ton; in Cucunubá, between 200 and 300 m deep, the gas values were 14.31 to 14.33 ft³/ton; in Ráquira between 100 and 150 m deep, the gas values were between 10.79 and 15.13 ft³/ton; in Samacá at a depth of about 100 m, the values reached 19.41 ft3/ton; in Socotá at depths between 300 and 500 m, the gas content was between 5.4 and 39.14 ft³/ton; and in Chinavita at depths between 400 and 500 m, the values were between 50.24 and 43.61 ft³/ton (Table II).

Table II. Average gas content in the rocks surrounding the coal vs. depth of the guaduas formation.

Prof. (m)	Total gas content (ft³/ton) in the pits:					
	Sutatausa	Cucunuba	Ráquira	Samacá	Socotá	Chinavita
100			10,79	19,41		
150			15,13			
200		14,31				
300		14,33				
400	9,96					50,24
500					5,40	43,61
700					39,14	

The highest contents were found in Chinavita at depths exceeding 400 m; therefore, depth appears to be a key factor in gas content because, on average, gas content increases with depth. For example, in the Socota 2 well at about 500 m depth, the content reached 21.87 ft³/ton, and in the Chinavita 1 well at 475 m depth the gas content reached 50.24 ft³/ton, in both cases the majority of the gas is measured gas (Table I).

As mentioned above, samples were also collected from mine faces. These contents were relatively low and did not exceed 15 ft³/ton. The gas content in shale samples taken at depths of 500 m ranged from 10 to 50 ft³/ton (Table I), which is lower than that found in the coal seams of the same wells that have reached 300 ft³/ton [7]. In many of the samples from Cucunuba, Socotá and Chinavita, a large percentage of the total gas corresponds to residual

gas, which could be indicating low permeability (Table I).

With the methodology described above, the emission measurements are assumed to be equivalent to the calculation of gas reserves in the rocks surrounding the coal; and this calculation is made by multiplying the volume of the rock by the density of the rock, and by the gas content of the desorption test or total gas (Table I) [2]. The volume of gas is multiplied by the density of the methane to convert the emissions to tonnes, which is how greenhouse gases are reported [1].

No isotope or desorption isotope tests were performed for these samples. For now, it is only possible to associate the gas content with the vitrinite reflectance. The vitrinite reflectance (Ro), which indicates the maturation of organic matter and the thermal transformation of the kerogen, was found in all samples. In most samples, Ro below 1% indicates that there is not enough thermal maturation to produce thermogenic gas; the only exception is in Socotá, where the reflectance of the vitrinite is approximately 1.3% which places it in the range of condensate formation. The highest gas content was found in Chinavita (Table I), but Ro was low, around 0.68%; this could be explained by the possible influence of gas of biogenic origin [16].

The percentage of methane in these samples is unknown, but chromatography in CBM samples of the same formation indicates that the percentages of methane are close to 85%. Similarly, saturation percentages are not known because the adsorption isotherm test has not been performed, but in CBM samples associated with shales (mudstones), saturation percentages of around 30% were found [4]. The gas content in coal-producing formations is not only important from an energy point of view as an unconventional hydrocarbon potential, but also for emission reporting and mine explosion prevention. From an environmental point of view, desorption tests are important for calculating and reporting greenhouse gases required as part of the 2015 climate change agreement in Paris according to IPCC standards [3]. From the mining point of view, in tunnels and other mining works, it is necessary to know the gas content of the rocks above and below the coal layers for safety reasons.

If the results are analyzed from the perspective of shale

gas, the findings in the Guaduas formation confirm the hypothesis that this formation could be a proxy for older and deeper formations. In the main Cretaceous shales of Colombia such as La Luna, Macanal, Paja, Chipaque, Olini, etc., where the TOC contents are approximately 2%, indicating a good quality of kerogen. As these shales are deeper than the Guaduas formation, Ro values are approximately 1.5%, and from these values it would be expected that the gas content would be 50 ft^3/ton or higher [17].

Conclusions

Gas contents in rocks close to coal can serve as an indicator for calculating emissions from rock mass subsidence, which occur as a result of underground coal mining. Gas contents in rocks surrounding coal seams can also be used to calculate the risk of methane gas explosions in surrounding rocks during coal mining.

The gas contents of the surrounding rocks, and therefore the emissions, are lower than those found in coal at the same depth. The areas with the highest values of gas content in the surrounding rocks are Samacá and Chinavita, with contents between 40 and 50 ft3/ton. These values correspond to a third or a quarter of those obtained from the coals near these samples. The highest gas contents did not correspond to the highest range zone of the coals (Socotá), which would be explained by the intense folding and fracturing of that zone.

The gas contents found in the shales of the Guaduas formation can also be used as an indicator (proxy) for older and deeper formations that could have a good gas shale potential such as La Luna, Macanal, Paja, Chipaque, Olini, etc.

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