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Estimation of reserves and prospective resources of Coalbed methane (CBM) in Peru

Estimación de reservas y recursos prospectivos de Coalbed Methane (CBM) en Perú

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Abstract

Methane and coal form together during carbonification, a process in which the biomass is converted by biological and geological forces into coal. Methane is adsorbed by the molecular structure of coal and is released by a simple desorption process when the water present in the fissures of the coal formation is dislodged. Although the development of these unconventional deposits of Coalbed Methane (CBM) has not been applied in Peru, there is a good prospect of CBM development in the Goyllarisquizga and Jatunhuasi formations.

Reserve estimation techniques include volumetric material balance, decrease curve analysis, simulation studies, and geophysical techniques. Entries for initially estimation of original gas in place (OGIP include geological parameters, specific parameters of carbon layer methane (CBM), and production history. Bituminous coal from the Goyllarisquizga and Jatunhuasi basins is very suitable for the exploration of CBM in terms of its depth of occurrence, the thickness of coal formation, coal reserve, and area extension. Consequently, the total gas that can be produced is 3 TSCF.

Keywords: Coalbed Methane; Unconventional resources; Langmuir adsorption isotherm.

Resumen

El metano y el carbón se forman juntos durante la carbonificación, un proceso en el que la biomasa es convertida por fuerzas biológicas y geológicas en carbón. El metano es adsorbido por la estructura molecular del carbón y se libera por un proceso simple de desorción cuando el agua presente en las fisuras de la formación de carbón es desalojada. Aunque el desarrollo de estos yacimientos no convencionales de Metano en Capas de Carbón (CBM) no comienza en Perú, existe una buena perspectiva de desarrollo de CBM en las formaciones de Goyllarisquizga y Jatunhuasi.

Las técnicas de estimación de la reserva incluyen el balance de material volumétrico, el análisis de la curva de disminución, los estudios de simulación y las técnicas geofísicas. Las entradas para la estimación inicialmente en su lugar (CIIP) incluyen parámetros geológicos, parámetros específicos del metano de la capa de carbón (CBM) y el historial de producción. El carbón bituminoso de las cuencas de Goyllarisquizga y Jatunhuasi es muy adecuado para la exploración de CBM en términos de su profundidad de ocurrencia, grosor de formación de carbón, reserva de carbón y extensión de área. En consecuencia, el gas total que puede llegar a producirse es de 3 TSCF.

Palabras clave: Metano en capas de carbón; Recursos no convencionales; Isoterma de Adsorción de Langmuir.

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1. Introduction

The purpose of this research is to provide technical information for CBM development projects in Peru. CBM has been successfully evaluated and developed in different parts of the world as in EEUU (Rocky Mountain, states of Colorado, Wyoming, and New Mexico), Canada (British Columbia), Australia (in Queensland and New South Wales) but currently is in early testing stages in Peru.

The exploitation of this relatively new source of energy has begun to develop at an industrial level less than two decades ago in North America (the USA and Canada) despite knowing the existence of Coal Gas since the beginning of mining, it was vented to the atmosphere because it was seen as an operational risk and not as an energy resource.

The studies conducted by Antonio Luyo Quiroz in his article called "Future Vision of the Peruvian Coal (Future vision of the Peruvian coal)" concludes that reserves of 1,087,200,000 metric tons of coal have been detected in its different varieties from anthracite, bituminous coal, and coal in Peru.

Also, it was seen that the main problem to exploit the mineral coal is the high transportation and hauling costs of the material.

The geological formations of these coal basins are Paleozoic, Mesozoic, and Cenozoic, which are not being exploited optimally, much less recovering the CBM.

The best prospects are Goyllarisquizga and Jatunhuasi basins because these basins have the characteristic of being bituminous coal deposits. These are those who present greater CBM content.

According to INGEMMET, the Jatunhuasi basin has a potential of 1 905 295 proved reserves and 60 457 255 of resources.

2. Geological classification of Coal

The classification of coal according to the USA-ASTM is lignite, sub-bituminous, bituminous, anthracite, and meta-anthracite. In Peru, anthracite and meta-anthracite coals predominate and, in a lesser proportion, bituminous coals and lignite. (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000, pág. 13).

3. Properties of Coal

Coal is defined as an organoclastic sedimentary rock constituted fundamentally by lithified plant stays, initially deposited in very humid or swampy environments. (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000).

This storage capacity gives the coal layers a unique initial behavior in terms of production, which is related to desorption, not to the drop-in pressure. Coal beds have a high methane storage capacity, just as the amount of gas accumulated in coal is easier to predict than in most conventional gas fields.

The amount of adsorbed methane can be significant, since the molecules are packaged, and the coal has a large area of the internal surface, more than $93x10^6$ m^2 ($1x10^9$ Ft^2) per ton (Hernández Ramos & Mejía González, 2014). As a result, coal can contain two or three times more gas than the volume of a conventional deposit.

3.1 Coal porosity

The size of the pores can range from fractures of the diaclases (also known as "cleats") to small intermolecular spaces. The pores of coal can be classified into three sizes: macropores (> 500 Å), mesopores (20 to 500 Å), and micropores (8 to 20 Å). The porous volume and the average pore size decrease with the range to low volatile bituminous. Porosity tends to decrease with the range in the level of bituminous low in volatility, then increases with the additional loss of volatile leaving porous spaces open. The macropores are found in larger spaces such as fissures and cracks between the coals or the spaces between the diaclases.

3.2 Permeability

The main mechanism of permeability in coal seams is the diaclases, also it can be fractured as conventional reservoirs. In deeper layers, overburden stress can crush the carbon structure and close the diaclases.

In such places, subsequent natural fracturing tends to be the main sustenance of permeability. The compression of the system of diaclases and natural fractures in the carbon layers is essential during all sides of the development of CBM deposits.

4. Coalbed methane

The coals according to the place of origin can be autochthonous (in situ) and allochthonous (transported). Products including water, methane, and carbon dioxide are generated during carbonizing or transforming (coal with lower carbon content and lower calorific value in combustion). With increasing coal range (maturation) from peat to anthracite, about 113 m^3 (5000 cubic feet) of methane is generated per ton, however, this volume exceeds the storage capacity of the coal. Methane shedding occurs during the process of burial which later, migrates and accumulates in the traditional sandy deposits that accompany the coal mantles.

The majority of the gas, however, there are lesser amounts of other gases such as ethane, propane, butane, pentane, hexane, heptane, and carbon dioxide.

After the methane was generated during the carbonization process, this is stored in the carbon as an adsorbed mono-molecular layer over the internal surfaces of the carbon matrix.

4.1 Natural Gas Storage in Coal

Once generated, methane is adsorbed or bound by the action of weak intermolecular attractive forces van der Waals forces to the organic materials that make up the coal.

Coal storage capacity is related to the pressure and adsorbed gas content, commonly described by the Langmuir adsorption isotherm measured from crushed coal samples. Also, each type of maceral stores, or adsorbs, different volumes of methane. On the other hand, coal can store more gas by increasing its range (from Sub-bituminous to Low volatile Bituminous).

During the transformation of the carbon that leads to its maturation, orthogonal fractures or diaclases are formed. Primary diaclases (frontal diaclases) in general are perpendicular to secondary diaclases (interposed diaclases). Front diaclases are often continuous and provide connectivity, while interposed diaclases are not continuous and often end at the front diaclases.

4.2 Natural Gas Adsorption

The factors that we must consider for the adsorption of gas in the coal mantles are the chemical composition of the coal, the pressure, the temperature, the humidity, and the ash content, the presence of other gases such as carbon dioxide and heavier hydrocarbons.

The adsorption process occurs between the gas phase and the solid phase resulting in two types of adsorption, physical and chemical. It is believed that physical adsorption is the most common mechanism in gas storage in coal mantles; in physical adsorption, the gas is absorbed as the result of intermolecular forces (Van der Waals forces), between the carbon molecules and the gas molecules.

4.3 Langmuir adsorption isotherm

Adsorption isotherms are the most used models for calculating the volume of adsorbed gas. The most used model for coal is Langmuir isothermal, which relates the ability of coal to store gas at a certain external pressure and is evaluated at a constant temperature (reservoir temperature), and is based on the following assumptions:

- All surfaces of the carbon matrix have adsorption characteristics.
- Adsorbed gas molecules occupy a single adsorption site.
- Molecular forces between gas particles are considered negligible
- Surface nuts do not overlap or interfere with adsorption.

The adsorption isotherm of Langmuir can be expressed as follows:

$$G_s = V_L[1 - (a + w_c)]\left[\frac{bp}{1 + bp}\right]$$

Where:
G_s = gas storage capacity, $\frac{scf}{ton}$

V_L = Langmuir volume, $\frac{scf}{ton}$
a = ash content, weight fraction
w_c = moisture content, weight fraction
b = Langmuir constant, psi^{-1}
p = pressure, psia

Or without considering corrections for ash and moisture content:

$$C_m = \left(\frac{V_L P}{P_L + P}\right)(0.031\ \rho_g)$$

C_m = gas concentration in the matrix

V_L = Langmuir volume, $\frac{scf}{ton}$
P = fractured system pressure, psia
P_L = Langmuir constant, psia
ρ_g = bulk density, g/cm^3

The adsorption of gas in coal as a single component is described efficiently for gas deposits associated with coal mantles by the Langmuir isotherm; However, coal adsorbs multicomponent gas mixtures, carbon dioxide, and nitrogen reduce the calorific value of the gas produced in mantles of coal as the final recovery of gas; Also, the heavier hydrocarbon gases adsorbed by coal affect the accuracy in the calculation of reserves (Ortega, 2008).

4.4 Transport mechanisms

The production of this gas contained in coal occurs in three stages or processes:

- Desorption of gas from the internal surface of the carbon matrix, flows from natural fractures, as shown in Figure 8.
- Gas diffusion through the coal matrix (Knudsen diffusion), and gas diffusion due to differences in concentration gradients (Fick's Law).
- Gas flow is released through natural fractures (Darcy flow), a response to pressure gradients.

5. World Statistics

5.1 Background and history

The Coalbed methane has been used or has begun to be produced on a small scale since the early 1900s when a person from a town in the Powder River basin in the US drilled a water well in a coalfield and began to heat the buildings with the gas produced.

Methane has traditionally been extracted from coal layers to reduce the danger of explosion and suffocation before using mining since the 19th century. It generally vented to the atmosphere and was not used for energy production. In the past, it was thought that the commercial extraction of deposits from CBM was economically impractical, and little or no consideration was given to this resource.

5.2 World reserves

The largest amount of CBM resources are in Russia, Canada, China, Australia, and the United States. However, much of the resource potential is still untapped. In 2006 it was estimated that of the total resources totaling 5,049 TSCF, only 35 TSCF was recovered from the reserves.

Table 1. Estimated reserves of CBM in the world

Country	Estimated CBM Reserves (TSCF)
Russia	200
China	100
United States	140
Australia / New Zealand	120
Canada	90

Source: Adapted from Department of Energy of the United States and BP Statistical Review, 2009.

6. Peruvian Coal Basins

The Paleozoic and Mesozoic carbons have reached a high degree of evolution ranging from bituminous to meta-anthracite, while in Cenozoic carbons the range goes from lignite to sub-bituminous. The basins of Oyón, Santa, and Alto Chicama are located in the northwestern facies of the Goyllarisquizga Group and the basins of Goyllarisquizga and Jatunhuasi in the eastern-southern facies.

The distribution of the range of Paleozoic and Mesozoic carbons shows a well-defined regional zonation in stripes parallel to the Andes. (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000, pág. 3).

The bituminous deposits are located towards the east being parallel to the earlier one, in her the basins of Goyllarisquizga, Jatunhuasi, and the east part of Oyón and Yura are located. The estimated total carbon resources reach 1,054 Mt, of which 78.3% (825.1 Mt) come from the Mesozoic basins, 21.4% (226 Mt) from the Cenozoic basins, and 0.3% (2.95 Mt) from the Paleozoic basins. 52.5% (553.5 Mt) of the total resources are of anthracite / meta-anthracite coal range, 10.9% (115.2 Mt) semi-anthracite, 8.9% (93.5 Mt) bituminous, 8.7% (66.5 Mt) sub-bituminous and 19.1% (201 Mt) lignites. Total proved reserves of coal are only 49.02 Mt.

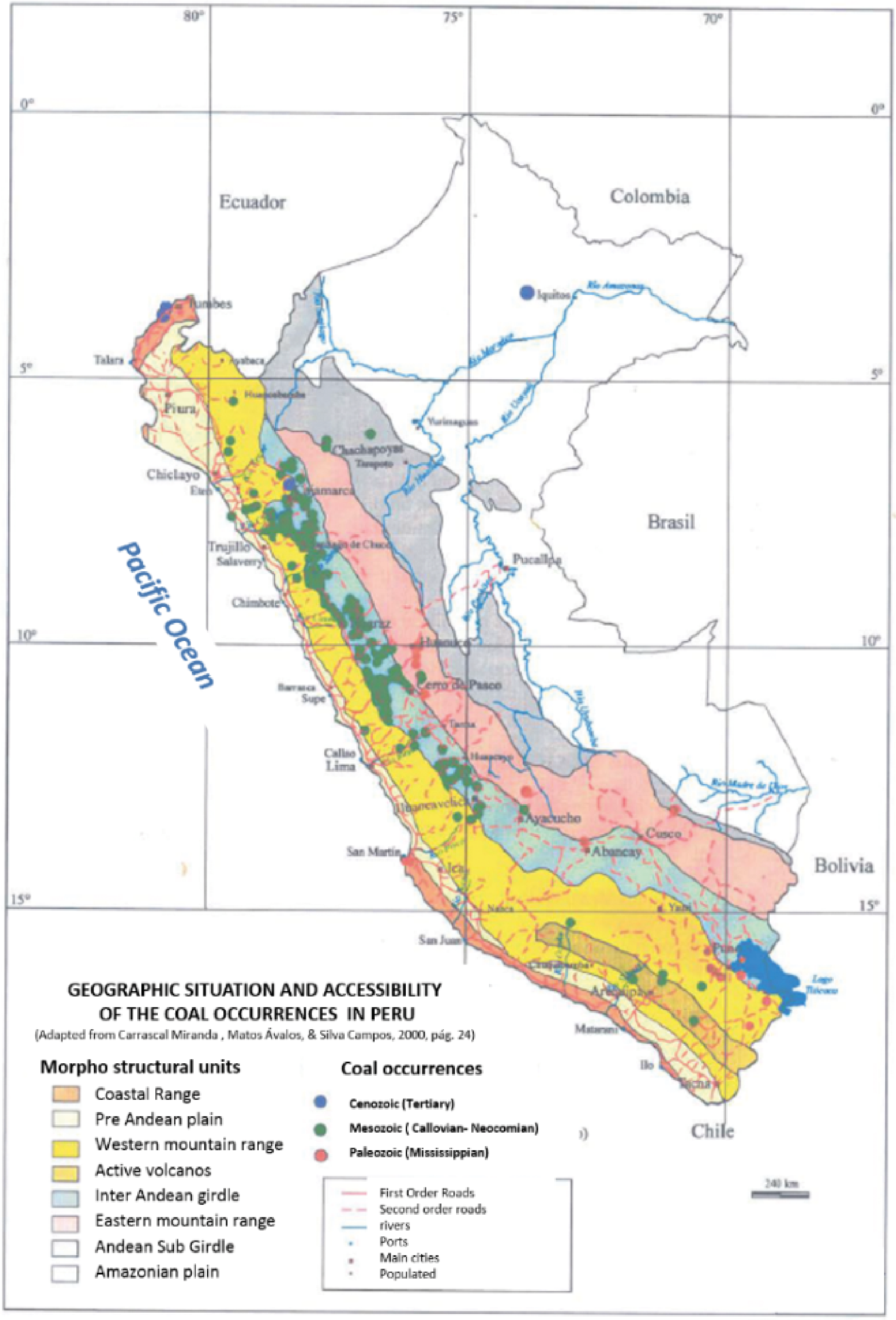

Figure 1. Geographic situation and accessibility of the Coal Occurrences in Peru
Source: Adapted from (Carbón en el Perú, 2000)

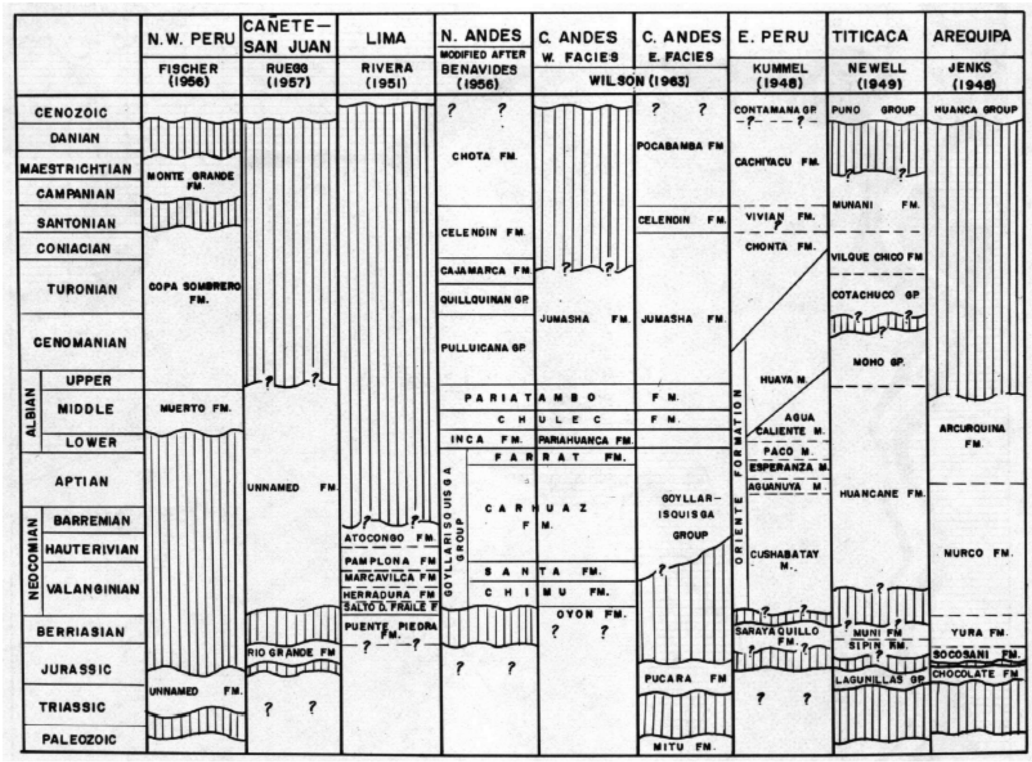

Figure 2. Correlation table for the Peruvian stratigraphic column (after Wilson, 1963).
Source: (Petersen C. R., 1978;1979)

6.1 Goyllarisquizga basin

The sedimentary series in this basin is based on the Excelsior, Mitu, and Pucara groups, on which the Goyllarisquizga Group (Lower Cretaceous) rests, continuing with the Machay Group (Albian), and unconformity overlapping the Pocobamba Formation (red layers). The basin has suffered various tectonic phases of the Andean orogeny, resulting in substantial fracturing and deformation, presenting synclines and Andean orientation anticlines. The structure that controls the location of the coal layers is an asymmetric syncline with NW-SE bearing whose axis inclines to the SE (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000).

The Goyllarisquizga Group (Neocomian), in the area of this mine, is about 500 m thick and consists of 6 members consisting of: a lower series with coal (varied lithology and in the lenticular form), Murucata sandstones, a superior series with charcoal (volcanic at the base and clays), the Bolognesi layers (red and volcanic layers), the Chonta sandstone and calcareous sandstone (Page, 1960). The carrier series containing coal are in the lower part of the Goyllarisquizga Group. Being integrated by the members' Series inferior and Superior series constituted as well by sandstones and layers of coal. These series are separated by the Murucata Member formed by sandstones and quartz conglomerates (Broggi, 1927).

6.1.1 Characteristics

The presence of pyrite and calcareous concretions associated with the coals indicate that this basin was deposited in deltaic environments (Wilson, 1963), generating the coals in the vicinity of the sea, under humid conditions, the basin being probably of paralytic character.

Petrographic data and some chemical analyses say that the coals in the Goyllarisquizga basin have reached the rank of sub-bituminous / bituminous coals. At the regional level, this basin correlates with the Jatunhuasi basin, being the least evolved within the Mesozoic basins, forming the bituminous carbon strip.

In general, the layers are lenticular and have thicknesses of up to 3 m, presenting, in the central part, purest coals gradually passing into carbonaceous shales. Principal and Parallel layers are the most continuous and extensive layers, separated by a layer of clayey slate whose thickness varies from a few centimeters to a few meters. (Carrascal Miranda, Matos Ávalos, & Silva Campos, pág. 63).

6.1.2 Reserves

The Goyllarisquizga deposit in 1985 had 242 198 tons of coal reserves, with 51.6% of ashes and 28.3% of volatile materials (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000). The total estimated resources for the Goyllarisquizga basin reach 7.97 Mt and 1 542 Mt of proven reserves of coals of sub-bituminous to semi-anthracite ranges.

6.2 Jatunhuasi basin

In this basin, the Goyllarisquizga Group (Neocomian) is constituted by white and yellowish quartz sandstones presenting cross lamination interspersing dark shales and layers of coal. The basin has suffered various tectonic phases of the Andean orogeny being failed and deformed.

The main structure is the Jatunhuasi syncline, on whose flanks NE and SO the carrier series with layers of coal is located, the same that is in the upper part of the Goyllarisquizga Group. The layers have the greatest thicknesses in Celica, Negro Bueno, Cosmos, lnsolina-Esperanza, Cachi Sur-Cachi Norte, Llacsa, and Chaucha.

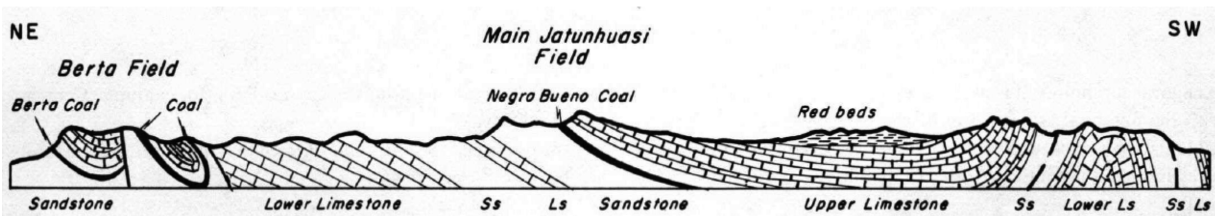

Figure 3. Diagrammatic cross-section through Jatunhuasi district viewed toward the southeast. No Scale. Length of section 10 to 12 km (After McLaughlin, 1922). Ls=Limestone; Ss=sandstone.
Source: (Petersen C. R., 1978;1979)

6.2.1 Characteristics

Petrographic and chemical parameters indicate that the coals in the Jatunhuasi basin have reached the range of high volatile bituminous coals (oil generation phase of the catagenesis stay: Calancho, Wealth, Melenique, Celica, Black Well, Cosmos, lnsolina, Esperanza, Cachi, Llacsa), bituminous low volatile (Chaucha) and semi-anthracite / anthracite (Estancia).

At the basin level, it is observed that the less evolved coals are located towards the NE of the basin, and the most evolved are distributed towards the west sector. This distribution could be related to the location of intrusive bodies that would have thermally influenced the evolution of the coals.

6.2.2 Reserves

The total estimated resources for this basin reach 62 457 Mt and 1 905 Mt of proven reserves of bituminous coals from high volatility to bituminous low volatility (Carrascal Miranda, Matos Ávalos, & Silva Campos, 2000).

Concerning the other basins, there is very timely information, so in the Cajamarca basin, it is estimated 54.87 Mt of total resources and proven reserves of the order of 20 000 t of sub-carbon bituminous to anthracitic.

7. Methodology

For the estimation of gas reserves, the basins that have bituminous coal have been selected, because they are Coals that have the highest content of adsorbed gas according to the bibliography (Ortega, 2008).

It is necessary to raise a series of considerations because the information available in the bibliography is insufficient to carry out a more accurate study. However, the methodology presented in this chapter will serve as a basis for future estimates of reserves in the Peruvian basins. For this case, data from the Warrior basin properties, located in the United States, have been used.

The Warrior Basin is located on the border between the states of Alabama and Mississippi. The coals are found in the Pottsville Formation of Pennsylvania. The Posville formation has around 35 billion tons of coal and a methane gas production of 20 TPC. The coals of the Warrior basin are classified as bituminous high in volatile remarkably similar in physicochemical characteristics of the Jatunhuasi and Goyllarisquizga basins.

Goyllarisquizga and Jatunhuasi basins are used in this study due to the characteristics of the area, access routes, surface geography. For the Oyón basin, the estimation of reserves has not been carried out due to the superficial geography of difficult access.

Table 2. CBM potential in Peruvian Coal basins

Basins	Exploitable Coal In place (MT)[1]	Total Carbon in place (MT)[2]
Goyllarisquizga	1.54	7.97
Jatunhuasi	1.91	60.46

[1]Mineable coal is coal no deeper than 300 meters.
[2]Assume mineable coal is one-third of the total coal in place.
Source: Adapted from INGEOMINAS Colombia, 2004

7.1 Content calculation of gas in situ of CBM basins

To rely on the estimate, or when there is insufficient data to start the material balance calculations, a volumetric method is applied, which is used for this particular case. For the development of this method, the following parameters were taken into account:

- Carbon porosity.
- Water saturation.
- Reservoir pressure
- Reservoir temperature.
- The specific gravity of gas (methane).
- The thickness of the mantle.
- Langmuir volume.
- Langmuir pressure.
- Carbon density.
- The molecular mass of gas (methane).
- Area of the selected zone
- Volumetric gas formation factor.
- Compressibility factor.
- Adsorption density.

For a total in situ gas storage, it is found that the amount of gas adsorbed is determined through an adsorption isotherm equilibrium experiment, from which data are obtained: Langmuir pressure and volume of adsorbed gas. These data have been taken from tests carried out in the San Juan and Warrior basins (Murcia Paéz & Sana Sanchez, 2012).

From the analyzes, corrections, and calculations used by (Murcia Paéz & Sana Sanchez, pág. 139) to determine the equations that are needed to calculate the gas storage capacity in situ, this is the sum of free gas and the adsorbed gas.

$$G_a = V_{langmuir} * \frac{P}{P + P_{langmuir}}$$

$$G_f = \frac{32.0368}{B_g} * \frac{\phi(1 - S_w)}{\delta_{coal}} - \frac{1.318 * 10^{-6} M}{\delta_{adsorbed}} * G_a$$

$$Gas_{in-situ} = Gf_{free\ gas} + Ga_{adsorbed}$$

Where:

B_g=Volumetric gas formation factor, $\frac{cf}{scf}$

G_a=Ability to store adsorbed gas, $\frac{scf}{ton}$

G_f=Free gas, $\frac{scf}{ton}$

V_l=Langmuir volume, $\frac{scf}{ton}$

M=Molecular weight, $\frac{lbm}{lbmole}$

P =Pressure,psia

P_L =Langmuir pressure,psia

δ_b =Carbon density, $\frac{g}{cc}$

δ_s =Density of the adsorbed phase, $\frac{g}{cc}$

$\emptyset$=Porosity

7.1.1 Calculation of the volumetric gas formation factor (Bg)

This represents the division of the reservoir gas volume by the gas volume at standard conditions.

$$B_g = 0.02829 * \frac{ZT}{P} \frac{ft^3}{PCS}$$

$Z = Gas\ compressibility\ factor$
$T = Reservoir\ temperature, °R$
$P = Reservoir\ pressure, psia$

7.1.2 Calculation of the gas compressibility factor (Z)

It is defined as the deviation of a real gas from an ideal gas. It is obtained from the Standing and Katz graph, in which we must locate the data of the pseudo-reduced temperature and pressure (at reservoir temperature and pressure), employing the following equations:

$$P_{pr} = \frac{P}{P_{pc}}$$

$$T_{pr} = \frac{T}{T_{pc}}$$

To determine the pseudo-reduced temperature and pressure, we must graph the values according to the specific gravity of the gas.

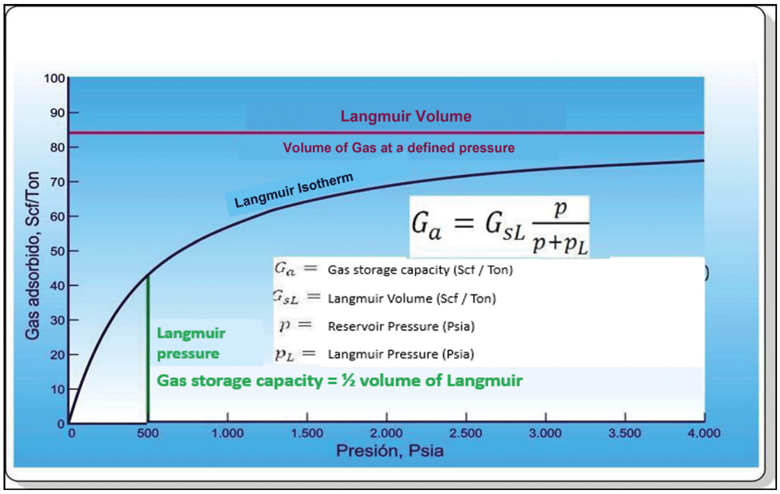

Figure 4. Langmuir adsorption isotherm

Source: LANGMUIR, I.; the Constitution and Fundamental Properties of Solids and Liquids, Journal of the American Chemical Society. Vol 38, 1996, p.p. 221-295.

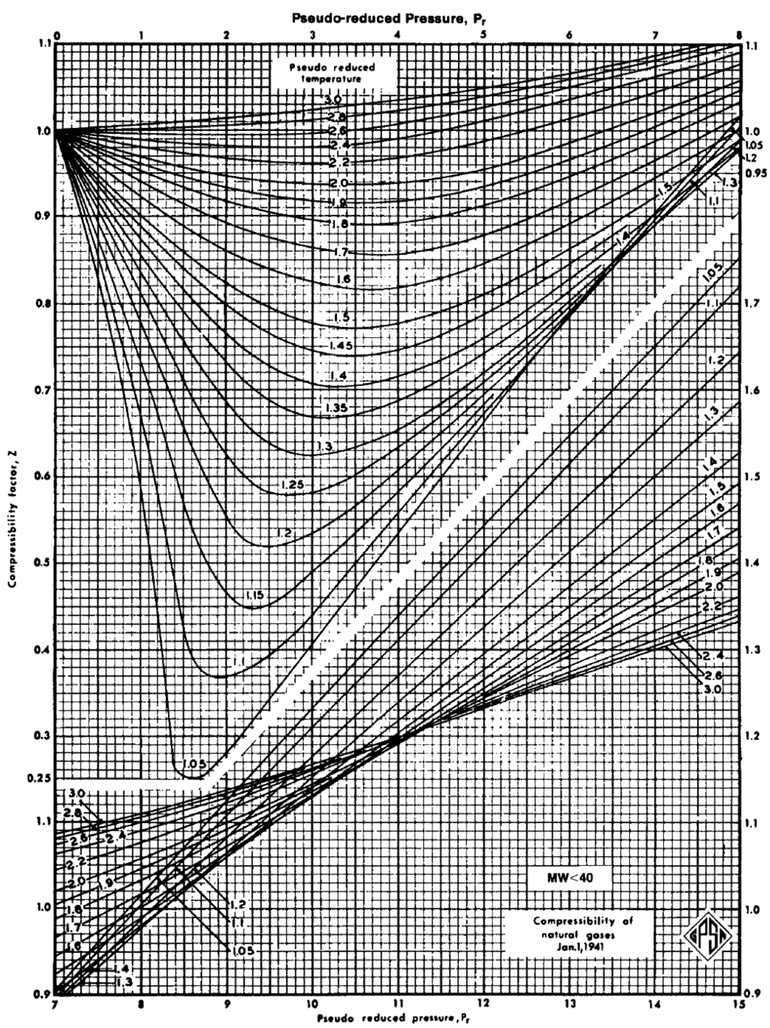

Figure 5. Compressibility factor for natural gases.

Source: Standing, M. B., and Katz, D. L., Density of Natural Gases, trans. AIME 142 (1992).

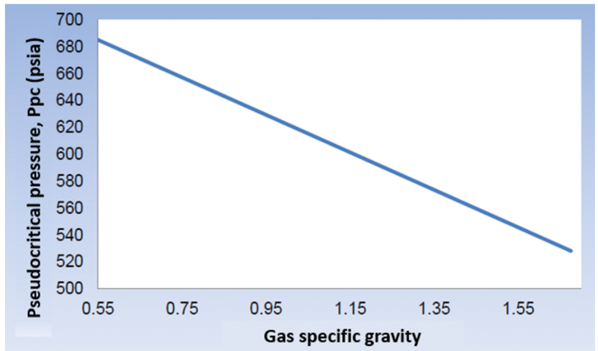

Figure 6. Pseudocritical Properties of Natural Gases, Pseudo critical Pressure.
Source: The properties of petroleum fluids-McCain Williams second edition page 119.

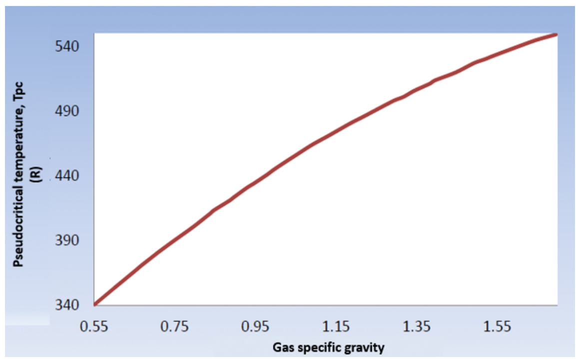

Figure 7. Pseudocritical Properties of Natural Gases, Pseudo critical Temperature
Source: The properties of petroleum fluids-McCain Williams second edition page 119.

7.1.3 Calculation of adsorption density ($\delta_{adsorbed}$)

The estimated average adsorption density of methane is 0.372 g/cm^3 at 176 °F, 0.368 g/cm^3 at 212 °F, and 0.355 g/cm^3 at 266 °F.

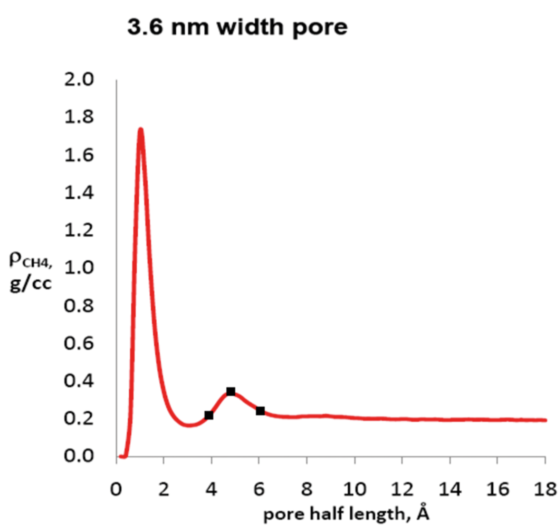

Figure 8. The density of the absorbed methane phase.
Source: LANGMUIR, I.; The Constitution and Fundamental Properties of Solids and Liquids, Journal of the American Chemical Society. Vol 38. 1996.

7.1.4 Calculation of adsorbed gas

It is related to the Langmuir volume.

$$G_a = V_{langmuir} * \frac{P}{P + P_{langmuir}}$$

7.1.5 Calculation of Free gas

It is the one found in the fractures of the carbon matrix.

$$G_f = \frac{32.0368}{B_g} * \frac{\phi(1 - S_w)}{\delta_{coal}} - \frac{1.318*10^{-6}M}{\delta_{adsorbed}} * G_a$$

7.2 Content calculation of gas in place of CBM basins

Because geophysical logs cannot detect gas content in coals, as in sandstone or carbonate reservoirs, methane content can be determined by an adsorption isotherm or by controlled desorption of recovered cores, which is an expensive and time-consuming task (Murcia Paéz & Sana Sanchez, 2012).

$$G_i = 1.36 * A * h * \delta_{coal} * Gas_{in-situ}$$

Where:

$G_i = Initial\ gas\ in\ place, Mscf$
$A = Reservoir\ area, acres$
$h = Net\ thickness\ of\ carbon, ft$
$\delta_{coal} = Carbon\ density, g/cm^3$
$Gas_{in\text{-}situ} = Gas\ in\ situ\ content, csf/ton$

8. Results y discussion

8.1 Basin characterization

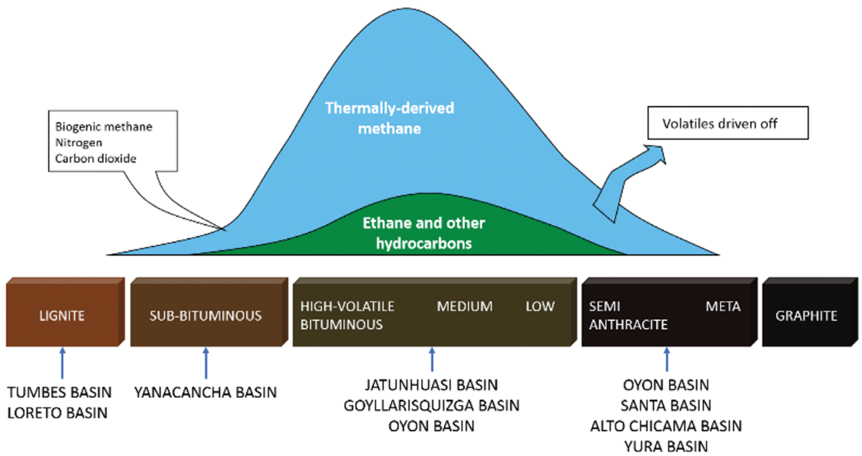

Figure 9. Gas Content in Basins according to the Coals.

Table 3. Components and characteristics of coal from the Goyllarisquizga and Jatunhuasi basins

	Goyllarisquizga			Jatunhuasi		
Components	**Raw (%)**	**Washed (%)**	**Coked (%)**	**Raw (%)**	**Washed (%)**	**Coked (%)**
Volatile matter	23.4	30.4	4.0	27.6	34.3	1.4
Fixed carbon	22.6	43.1	54.1	30.1	39.0	59.8
Ash	54.0	26.5	41.9	42.3	26.7	38.8
Sulfur	12.1	3.3	2.4	5.1	2.7	2.2

9. Content Estimation of Gas in Place of Jatunhuasi basin

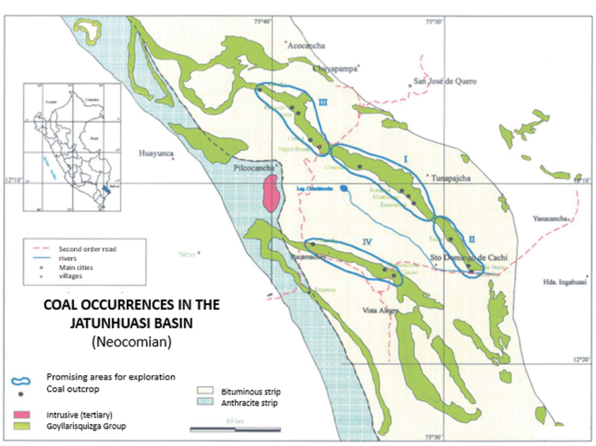

Figure 10. Coal occurrences in the Jatunhuasi Basin
Source: Adapted from (Carbón en el Perú, 2000)

9.1 Warrior Analog Basin (USA)

$Ø = 0.5$
$S_W = 0.7$
$P = 1664\ psia$

$T = 120\ °F \rightarrow 580\ °R$
$V_{Langmuir} = 1118\ scf/ton$
$P_{Langmuir} = 606\ psia$

9.2 Calculation parameters obtained from the Jatunhuasi Area

$GE_{Methane} = 0.55$, specific gravity
$H_{thickness} = 4\ ft$
$\delta_{Coal} = 1.3\ ton/m^3 \rightarrow 0.0368\ ton/ft^3$
$M_{Methane} = 20\ lb/lb\text{-}mol$
$A_{Area} = 110\ km2 \rightarrow 1.184 * 10^9\ ft^2$

9.3 Calculation of the volumetric factor of gas formation

$$B_g = 0.02829 * \frac{ZT}{P},\ \mathrm{ft^3/PCS}$$

$P_{PC} = 667$ psia
$T_{TC} = 343.37$ °R
P_{pr} = Pseudoreduced Pressure
T_{tr} = Pseudoreduced Temperature

$$P_{pr} = \frac{P}{P_{pc}} = \frac{1664}{667} = 2.49$$

$$T_{tr} = \frac{T}{T_{Tc}} = \frac{580}{334.37} = 1689$$

$$B_g = 0.02829 * \frac{0.87\ (580\ °R)}{1664\ psia}$$

$$B_g = 0.008578\ \frac{ft^3}{PCS}$$

9.4 Compressibility factor for natural gases

Of graphics: Z = 0.87

9.5 Calculation of adsorption density

$\delta_{adsorption} = 0.378\ \mathrm{gr/cm^3} \rightarrow 0.0107\ \mathrm{ton/ft^3}$

9.6 Adsorbed gas calculation

$$G_a = V_{langmuir} * \frac{P}{P + P_{Langmuir}} = 1118\ \frac{scf}{ton} *$$

$$\frac{1664\ psia}{1664\ psia + 606\ psia} = 819.5\ \frac{scf}{ton}$$

9.7 Calculation of Free Gas

$$G_f = \frac{32.0368}{B_g} * \frac{\phi(1 - S_W)}{\delta_{coal}} - \frac{1.318*10^{-6}M}{\delta_{adsorbed}} * G_a$$

$$G_f = \frac{32.0368}{0.008578} * \frac{0.5(1-0.7)}{0.0368\ \frac{ton}{ft^3}} - \frac{1.318*10^{-6}(20)}{0.0107\ \frac{ton}{ft^2}} * 819.5\ \frac{scf}{ton}$$

$$G_f = 15221.20\ \frac{scf}{ton}$$

9.8 On-site gas Calculation

$$Gas_{in\ situ} = G_{free} + Ga$$

$$Gas_{in\ situ} = 15221.20\ \frac{scf}{ton} + 819.5\ \frac{scf}{ton}$$

$$Gas_{in\ situ} = 16040.70\ \frac{scf}{ton}$$

9.9 In-Place Gas Calculation

$$G_I = 1.36 * A * h * \delta_{coal} * Gas_{in-situ}$$

$$G_I = 1.36 * 1.184 * 10^9 * 4 * 0.0368 + 16040.70$$

$$G_I = 2.67 * 10^{12}\ \mathrm{cf}$$

$$G_I = 2.67\ TCF$$

10. Content Estimation of Gas in Place of Goyllarisquizga basin

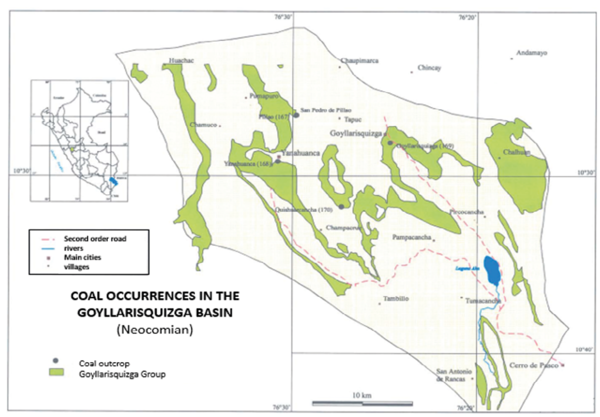

Figure 11. Coal occurrences in the Goyllarisquizga Basin
Source: Adapted from (Carbón en el Perú, 2000)

10.1 Warrior Analog Basin (USA)

Ø = 0.5
$S_W = 0.7$
P = 1664 psia
T = 120 °F → 580 °R
$V_{Langmuir} = 1118$ scf/ton
$P_{Langmuir} = 606$ psia

10.2 Calculation parameters obtained from the Goyllarisquizga Area

$GE_{Methane}$ = 0.55, specific gravity
$H_{thickness}$ = 4 ft
δ_{Coal} = 1.3 ton/m^3 → 0.0368 ton /ft^3
$M_{methane}$ = 20 lb/ lb-mol
A_{Area} = 110 km2 → 1.184 *10^9 ft^2

10.3 Calculation of the volumetric factor of gas formation

$B_g = 0.02829 * \frac{ZT}{P}$, ft³/PCS

P_{PC} = 667 psia

T_{TC} = 343.37 °R

P_{pr} = Pseudoreduced Pressure

T_{tr} = Pseudoreduced Temperature

$$P_{pr} = \frac{P}{P_{pc}} = \frac{1664}{667} = 2.49$$

$$T_{tr} = \frac{T}{T_{Tc}} = \frac{580}{334.37} = 1689$$

$$B_g = 0.02829 * \frac{0.87\ (580\ °R)}{1664\ psia}$$

$$B_g = 0.008578\ \frac{ft^3}{PCS}$$

10.4 Compressibility factor for natural gases

Of graphics: Z = 0.87

10.5 Calculation of adsorption density

$\delta_{adsorption}$= 0.378 gr/cm^3 → 0.0107 ton/ft^3

10.6 Adsorbed gas calculation

$$G_a = V_{langmuir} * \frac{P}{P + P_{Langmuir}} = 1118\ \frac{scf}{ton} *$$

$$\frac{1664\ psia}{1664\ psia + 606\ psia} = 819.5\ \frac{scf}{ton}$$

10.7 Calculation of Free Gas

$$G_f = \frac{32.0368}{B_g} * \frac{\phi(1 - S_w)}{\delta_{coal}} - \frac{1.318*10^{-6} M}{\delta_{adsorbed}} * G_a$$

$$G_f = \frac{32.0368}{0.008578} * \frac{0.5(1-0.7)}{0.0368\frac{ton}{ft^3}} - \frac{1.318*10^{-6}(20)}{0.0107\frac{ton}{ft^2}} * 819.5\ \frac{scf}{ton}$$

$$G_f = 15221.20\ \frac{scf}{ton}$$

10.8 On-site gas Calculation

$$Gas_{in\ situ} = G_{free} + Ga$$

$$Gas_{in\ situ} = 15221.20\ \frac{scf}{ton} + 819.5\ \frac{scf}{ton}$$

$$Gas_{in\ situ} = 16040.70\ \frac{scf}{ton}$$

10.9 In-Place Gas Calculation

$$G_I = 1.36 * A * h * \delta_{coal} * Gas_{in-situ}$$

$$G_I = 1.36 * 6.997 * 10^8 * 4 * 0.0368 + 16040.70$$

$$G_I = 1.826 * 10^{12}\ \text{cf}$$

$$G_I = 1.83\ TCF$$

11. Conclusions

- From the characterization of CBM deposits in the Goyllarisquizga and Jatunhuasi basin, it is possible to determine that these present the ideal conditions for the generation, accumulation, and production of gas associated with coal basins, considering the results obtained from the gas in place on these areas. A gas-in-place content is estimated to be between 2.67 TCF for the Jatunhuasi basin and 1.83 TCF for the Goyllarisquizga basin.
- This paper proposes a preliminary study for the characterization and estimation of CBM reserves, for future exploration and exploitation investigations of this resource, to supply the energy needs in Peru. To complement this study, we suggest taking coal samples to analyze the real adsorption capacity and adjust the values obtained in this estimation.
- Analyzing the information required for the

development of the methodology, it was possible to differ that Peru being a country with great potential for coal areas, requires a detailed study of the physical and chemical properties of coal, to carry out an accurate study of the reserves present in Peru, to avoid the use of analogies from other basins outside Peru.

- The estimate that we make is of high uncertainty, which makes it possible to consider that the recovery of CBM in the country would not be very attractive from an economic point of view (without the issuance of green certificates).
- Taking into account that the percentage of methane released into the atmosphere is considerably higher than that recovered by CBM production, it is necessary to take advantage of the commitments made by the Peruvian government to reduce polluting emissions, the best way to achieve this commitment is the economic incentive translated into pollutant gas emission certificates or green certificates for investments in projects of this nature.
- From an environmental point of view, draining the gas would reduce greenhouse gas (methane) emissions, generate clean energy with the volumes of methane produced, and could generate income from carbon offsets.

12. Recommendations

- When trying to perform a search of the recoverable resources of CBM in Peru, it was difficult to find any geological study and analysis of hydrocarbons to coal basins in Peru.
- It is recommended to carry out tests of gas content and storage capacity on certain carbon samples, ashes, humidity, and sulfur, to specify the specification of coal methane reserves.
- It is recommended to conduct a study regarding the water produced in CBM deposits, its treatment for agricultural, livestock, and/or human consumption.
- Accuracy of alternatives for combustion and/or consumption of coal methane in the deposits studied to avoid ventilation to the atmosphere, with methane being a gas of much greater toxicity than CO_2.

Nomenclature

G_i : *Initial gas in place,Mscf*

A : *Reservoir area,acres*

h : *Net thickness of carbon,ft*

δ_{coal} : *Carbon density,* g/cm^3

$Gas_{in-situ}$: *Gas in situ content ,csf/ton*

B_g : *Volumetric gas formation factor,* $\frac{cf}{scf}$

G_a : *Ability to store adsorbed gas,* $\frac{scf}{ton}$

G_f: *Free gas,* $\frac{scf}{ton}$

V_l : *Langmuir volume,* $\frac{scf}{ton}$

M : *Molecular weight,* $\frac{lbm}{lbmole}$

P : *Pressure,psia*

P_L : *Langmuir pressure,psia*

δ_b:*Carbon density,* $\frac{g}{cc}$

δ_s : *Density of the adsorbed phase,* $\frac{g}{cc}$

$\emptyset$: Porosity

Z : *Gas compressibility factor*

T : *Reservoir temperature,°R*

P : *Reservoir pressure,psia*

TSCF : Trillion standard cubic feet

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