

PROSPECTING FOR COALBED METHANE: PRELIMINARY INVESTIGATION INTO THE POSSIBILITIES IN SPAIN

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SUMMARY

1. The fundamental objective of this study resides in investigating the potential suitability of Spanish coalfields to prospecting natural gas from coal in-situ (Coalbed Methane-CBM). The study was based not only on a literature survey and supplemented by on-site visits and investigations, but also on inhouse research activities.

Three selecting criteria have been defined:

- 1.1. **Existing resources:** a figure of 20MT of coal was established as the minimum in-situ tonnage worth considering. This limit is comprised of the sum of "very probable" and "probable" resources.
 - 1.2. **Coal rank:** in agreement with the generally accepted principle that the most significant amount of gas produced by coal corresponds to a coalification level of $R_r > 1.2\%$ (ca VM (daf) < 30%), only coalfields reporting such values were selected.
 - 1.3. **Geological and Structural** considerations such as:
 - 1.3.1. Identification of stratigraphic units, their sedimentary conditions including the presence of coal-bearing units with sufficient seams (frequency) with thickness that will potentially permit their in-situ exploration and exploitation for natural gas.
 - 1.3.2. Structural regime compatible with the retention of gas by the coal beds and adjacent host rocks.
2. On the basis of currently available information, and on applying the abovementioned criteria to Spanish

coalfields, the following ones have been identified as potentially the most suitable for coalbed methane prospecting (in decreasing order of importance):

- Ciñera-Matallana and Cerredo-Villablino, considered to have equivalent potential
- La Pernía-Barruelo
- Central Asturian Coalfield, South region
- El Bierzo

RESUMEN

1. El objetivo fundamental de este estudio, se examinar la posible conveniencia de investigar, en las cuencas carboníferas Españolas, el gas natural asociado al carbón *in situ* (Coalbed methane - CBM). Este estudio se basa, no sólo en el examen de las publicaciones ya existentes, sino también en investigaciones sobre el terreno, así como en ensayos de laboratorio. Para ello se han considerado tres criterios básicos:
 - 1.1. **Reservas existentes.** Se ha establecido un mínimo de 20 megatoneladas de reservas "muy probables" y "probables" de carbón *in situ*, para que sea rentable la explotación.
 - 1.2. **Rango del carbón.** De acuerdo con un principio, generalmente aceptado, de que la mayor cantidad de gas se produce por carbones con un grado de carbonificación de $R_r > 1.2\%$ (unas MV (base seca y libre de cenizas) < 30%), sólo han sido seleccionadas las cuencas carboníferas en las que el carbón reuna estas condiciones.
 - 1.3. **Consideraciones geológicas y estructurales,** tales como:
 - 1.3.1. Identificación de unidades estratigráficas cuyas condiciones sedimentarias

incluyan la presencia de capas de carbón, con un espesor tal, que potencialmente permitan su investigación *in situ* y la explotación de gas natural.

1.3.2. Régimen estructural que sea compatible con la retención del gas, por las capas de carbón y otras rocas adyacentes.

2. Basándose en la literatura existente sobre este tema, y de acuerdo con los criterios expuestos, en relación con las cuencas carboníferas españolas, se han seleccionado como las potencialmente más adecuadas, para prospección de metano asociado a las capas de carbón, las siguientes (en orden decreciente de importancia):

- Ciñera-Matallana y Cerredo-Villablino
- La Pernía-Barruelo
- Región Sur de la Cuenca Central Asturiana.
- El Bierzo

1. BRIEF HISTORICAL REVIEW

Horner and Milligan (1) presented an overview on potential prospecting of Coalbed Methane (CBM) in Spanish coalfields by broadly reviewing some general concepts. However these authors limit their statements only to guidelines. More recently Lemos de Sousa and Pinheiro (2) reviewed the subject in some detail and presented a preliminary account of CBM in Spain which details are herewith developed. On the other hand, Union Texas España Inc. jointly with HUNOSA held a licence for investigation into natural gas from coal in the Central Asturian Coalfield. In this venture some wells were drilled, but in the meantime the companies requested cessation of the licence.

2. GENERAL CRITERIA FOR SELECTING POTENTIAL AREAS [see also (3) and (4)]

Besides the all important aspects of existing resources, accessibility of coalfields and related geology and structure, it is also imperative to justify the rank criterion (*inter alia*) chosen as one of the selecting parameters to establish potentially suitable areas for prospecting natural gas from coal (i.e., excluding gas of inorganic origin). Consequently, a review of some of the most pertinent and generally recognized concepts follows, although somewhat limited in the current study due to constraints imposed by the available information on Spanish coals.

The process of gas generation is different from oil generation, although there is a relationship between the two, because oil cracking itself produces gas. Furthermore, it is also known (5, 6) that:

- “— a large fraction of the organic components produce gas;
- there is no main phase of gas generation; the rank range of generation is much wider and extends to practically all organic matter of various ranks”.

Hence, there is a continuous generation of wet gas parallel to oil generation, and beyond the main phase of oil generation cracking of oil and kerogen becomes a predominant process. Therefore, more wet gas and subsequently dry gas is generated.

- “ — ‘biogenic’ gas which originates from the very first stages of organic matter alteration is dry gas and almost exclusively composed of methane;
- ‘catagenic’ gas is released by coalification during burial. It may be dry or be associated with higher homologues, or with condensates of low-gravity oils”.

The thermal stability of methane is such that a lower limit is not determined by high temperature as such, but by the depletion of hydrogen in the source material.

The case of wet gas and oil generation is particular to coals with hydrogen-rich components such as liptinite and some vitrinite. In fact, in terms of **catagenic** or **thermogenic** gas production, vitrinite steadily releases methane from Rr 0.6% to 3%, whilst liptinite have a mixed oil-gas production (oil, condensates and wet gas). The largest gas release occurs before the second coalification jump (ca. Rr = 1.2%), at which stage liptinite exsudes an important yield of volatiles. Furthermore, based on investigations performed in Europe, Robert (5) also refers to the fact that the greatest production of methane occurs between Rr 1.7% and 3% (where more than 50% of the total is released in this range), and consequently, accumulations of gas are expected to be regionally more linked to high coalification zones. Tissot and Welte (6) further state that during metagenesis some kerogen constituents are still able to generate methane. Rice and al. (7) state that, under natural conditions, estimations of methane generation during geochemical coalification probably yield in a range 150 to 200 cm³/g.

According to Rice (8) and Rice and al. (7), besides the catagenic gas mentioned, **biogenic** gas generation (by methanogenic microorganisms) occurring primarily at an early stage (biochemical coalification i.e., Rr < 0.5%, equivalent to peats and low rank coals) followed by a late stage (at any rank) several important conditions and requirements have to be taken into account in order to ensure that production of economically significant amounts of gas are generated over a period of tens of thousands of years of burial, namely: anoxic environment, low sulphate concentration, low temperature, abundant organic matter, and adequate space.

The abovementioned prerequisites for *in situ* biogenic gas generation jointly with the absence of this type of information for Spanish coals, have also led the authors to concentrate their efforts exclusively on the issue of potential suitability for thermogenic gas production. In addition, low rank coals may contain as much as 2.5cm³/g of gas, but higher rank coals are known to contain as much as 31cm³/g (7).

In terms of gas storage, it is worth mentioning that High Volatile Bituminous coals¹ that are hydrogen-rich have their storage capacity reduced due to the generation of high molecular weight hydrocarbons responsible for plugging the microporosity (i.e., reducing gas storage capacity). However, later in the coalification process (i.e., > Low Volatile Bituminous range²) the sorption capacity increases as a result of the thermal cracking of these heavier hydrocarbons.

Furthermore, at levels of rank from Medium Volatile Bituminous³ and higher, coals may have generated more methane than they can store, resulting in the possible expulsion of the gas into adjacent rocks (potentially acting as reservoirs).

Some other important factors which are said to affect gas storage are (7):

(i) Pressure and Temperature. Sorbed gas content increases with increasing pressure and decreases with increasing temperature. An expected result may be a higher gas content in high-rank coals than in low-rank coals because high pressures and temperatures are more commonly associated with higher rank coals. However, such factors as natural desorption resulting from uplift and erosion may cause low gas contents, thereby accounting for a wide variation in gas content within a given coal rank.

(ii) Mineral matter. Mineral matter is understood to be detrimental to sorption capacity of coal since it has no affinity to sorb gas. Consequently, coals with relatively high ash content will not contain as much gas as low ash coals of equal rank.

In terms of gas composition, the primary controls are rank, petrographic composition, depth/ temperature of the coal.

Finally, it is well known that a **well developed fracture (cleat) system** in a coal bed is required in order to make commercial gas production possible, since it provides flow pathways for gas. This is so because virtually all permeability in a coal occurs within the fracture system. Factors affecting the permeability of cleats are: cleat frequency, connectivity, and aperture width. These, in turn, are affected by: bed thickness, coal composition (organic and inorganic), rank, tectonic deformation and stress.

Besides meeting with the previously discussed prerequisites, Rice (8) refers to the fact that current coalbed gas production is achieved from relatively structurally undisturbed areas where a good cleat system is preserved. The same author states that, on the other hand, the economic production of gas from areas that are structurally complex

may be severely hindered even if the coal contains significant quantities of gas. Furthermore other factors can hinder the retention or the release of gas. A cleat system filled with secondary minerals will inhibit retention and release just as water (bed moisture), or circulating fluids and aquifers, inhibit desorption or block the pathway of gas to the well.

The authors are convinced that, in the absence of gas release data directly measured on the coal seams, such information as methane release required by safety procedures and norms of the Reglamento General de Normas Basicas de Seguridad Mineira and referred to in its chapter V, could have been an additional electing criterion.

In the absence of specific analytical information such as methane release data, desorption and sorption isotherm tests, even detailed ash content of run-of-mine coal⁴ reflectance data from all coalfields or collieries, etc., the authors have opted on the following criteria for selecting coalfields suitable for natural gas prospecting, and present the available information collected to date in this regard:

- Existing resources
- Coal rank, based on Volatile Matter content, dry, ash-free basis (VM daf %), and in some cases complemented by the all important Mean Random Vitrinite Reflectance (Rr%)
- Geological and structural conditions.

3. AREAS WITH POTENTIAL FOR PROSPECTING NATURAL GAS FROM COAL IN SPAIN

3.1. Introduction

The occurrence of coal in Spain has been identified in basins of different ages, from Palaeozoic and Mesozoic to Cenozoic. However, the Mesozoic and Cenozoic coals are of low rank, leaving the hard coals (bituminous coals and anthracites) of the Palaeozoic (Carboniferous and Permian systems) to be the ones of any interest and importance to the present investigation.

There are numerous publications on the geology of both Systems, not only concerning Spain but also the Iberian Peninsula. It is beyond the objectives of this paper to list all literature concerning the geology of Spanish Carboniferous and Permian. However on describing particular coalfields those references considered most relevant will be cited.

The publication entitled *Actualización del Inventario de Recursos Nacionales de Carbón* (9)⁵ presents a panoramic

¹ ASTM term equivalent to ca.VM_{dmmf} > 30%; Rr < 1.2%.

² ASTM term equivalent to ca.VM_{dmmf} < 22%; Rr > 1.5%.

³ ASTM term equivalent to ca.VM_{dmmf} > 22%; Rr < 1.5%.

⁴ The only reference to ash content of spanish run-of-mine coals is provided by *Actualización del Inventario de Recursos Nacionales de Carbón* (9) that refers to range 30% to 45%. Otherwise, ash content data are only reported for beneficiated coal.

⁵ For ease of reference in the text this publication will simply be referred to as "Inventario 1985" (9).

perspective of active and inactive Spanish coalfields and of other locations where evidence of coal is reported. Detailed palaeontological studies of the major coalfields has permitted age dating as summarized in Wagner (10, Fig. 1).

By taking into consideration only the Carboniferous and Permian coalfields the three main criteria described above are now applied to the relevant areas.

3.2. First criterion - Available resources

According to "Inventario 1985" (9), the recorded resources of hard coals in Spain are shown in Table 1. In our opinion, the analysis of this table provides the first insight into the first selection criterion with regards to potential areas for prospecting natural gas from coal *in situ*.

Based on this criterion, only coalfields with "very probable" and "probable" estimated and classified tonnages above 20MT will be considered as potentially suitable. In fact, values below this pre-established minimum are consi-

dered unattractive for the objective in question⁶. Coalfields that report accepted tonnages are presented in Table 2, and we draw attention to the following:

With the exception of coalfields geographically located to the **South** (Puertollano, in the Central Iberian Zone, and Guadiato/Peñarroya-Belmez-Espiel at the boundary between the Central Iberian and Ossa Morena zones) all others are located in the **North** in the so-called Cantabrian Mountains. In the latter case, the majority of the coalfields are in the Cantabrian Zone, with some in the Asturian-Lionese Zone. Coalfields located in the Cantabrian Mountains are shown in some detail in Figure 1.

3.3. Second criterion - Coal rank

3.3.1. Introduction

Considering the number of coalfields and/or other evidence of the presence of coal, published references to rank of Spanish coals are extremely scarce:

	Coalfields		Tonnage (x 10 ³ t)				
			Total	Very probable	Probable	Possible	Hypothetical
North (Cantabrian Mountains)	Asturias	Central Asturian (C.A.C.)	914.601	165.735	146.108	133.423	469.335
		Northern extension of C A C	183.406	17.904	18.226	19.700	127.576
		Quirós	31.643	5.889	5.360	5.103	15.291
		Teverga	46.595	6.307	8.544	8.881	22.863
		Ventana	2.341	797	529	320	695
		Tineo	18.114	3.558	2.040	1.659	10.857
		Carballo	8.551	2.506	928	1.910	3.206
		Rengos	40.640	7.267	6.842	5.565	20.966
	Cangas	339	123	108	99	8	
	Villablino	Tormaleo	12.218	3.274	2.585	2.667	3.682
		Cerredo	137.826	13.886	11.329	14.683	97.928
		Villablino	309.001	35.091	25.557	22.744	225.609
	Bierzo	El Bierzo	583.685	68.645	53.122	56.917	405.000
	North of Léon	La Magdalena	72.440	11.026	10.625	8.419	42.300
		Ciñera-Matallana	228.007	52.120	21.761	16.434	137.692
		Sabero	55.742	8.782	14.875	11.858	20.227
		San Emiliano	18.761	1.387	1.628	1.789	13.957
		Parajes-Lillo	4.422	2.085	1.841	331	165
		Caseco-Carande	3.681	747	492	218	2.224
Guardo Barruelo	Valderrueda-Guardo	532.786	15.336	15.917	16.747	484.786	
	La Pernía-Barruelo	106.451	13.514	13.540	14.327	65.070	
South	South Westen	Puertollano	101.304	23.895	3.647	23.762	—
		Guadiato	59.662	21.281	11.944	10.603	15.897
		Marianicas	5.111	730	1.117	1.106	2.158

Table 1. Resources of Spanish Hard coals [after "Inventario 1985" (9)].

⁶ Even using 30 MT as the minimum probable tonnage estimate required, the coalfields selected remain the same.

North (Cantabrian Mountains)	<ul style="list-style-type: none"> • Central Asturian Coalfield and extensions • Cerredo-Villablino • El Bierzo • La Magdalena • Ciñera-Matallana • Sabero • Valderrueda-Guardo • La Pernía-Barruelo
South	<ul style="list-style-type: none"> • Puertollano • Guadiato/Peñarroya-Belmez-Espiel

Table 2. List of coalfields reporting cumulative “very probable” and “probable” resources above 20 Mt.



Figure 1. Schematic geological map of the Cantabrian Mountains showing the location of the most important coalfields: 1-Teverga-San Emiliano; 2-Quirós; 3-Santiforme-Naranco; 4-La Camocha, 5-Central Asturian; 6-Coballes; 7-Sueve-Libardon; 8-Sebarga; 9-Cabrales; 10-La Pernía-Barruelo; 11-Guardo-Valderrueda; 12-Sabero; 13-Ciñera-Matallana; 14-La Magdalena; 15-El Bierzo; 16-Villablino; 17-Carballo; 18-Rengos; 19-Cangas-Tineo; 20-Arno (adapted from 13).

(i) North (Cantabrian Mountains)

For this area only three papers on the subject are known: Mendes Cecilia (11), Calvo Perez (12), and Colmenero and Prado (13). The first of the three references is a doctorate thesis on the Ciñera-Matallana Coalfield, and uses vitrinite reflectance as the rank parameter. The second and third works cited refer only to Volatile Matter content (VM %). In fact, the latter work was considered a rather useful report for the investigation.

(ii) South**a) Puertollano Coalfield**

The geology of this coalfield is well established (14, 15, 16). Also, several petrologic studies (rank and maceral composition) and some chemical analyses were carried out in the past (17, 18).

b) Guadiato/Peñarroya-Belmez-Espiel

A recent doctorate thesis (19) presents a geological synthesis for this coalfield and provides important data and information concerning coal petrography and petrology (maceral, microlithotype and facies analyses, and rank on the basis of vitrinite reflectance).

3.3.2. Selecting by rank

In the logic of the facts and generally accepted concepts expressed in 2 above, coalfields reporting VM (daf) >30% (equivalent to about Rr < 1.2%) have been excluded from the list of potentially economically suitable for prospecting of natural gas. The remaining coalfields are the following:

(i) North (Cantabrian Mountains)

Figure 2 illustrates the areas corresponding to rank isolines on the basis of VM% (daf). The application of this selecting criterion leads to the ultimate choice of potentially suitable coalfields listed in Table 3 (selected from those previously recorded in Table 2).

(ii) South**a) Puertollano Coalfield**

The coals from this Coalfield are reasonably well known, i.e., those of Seams II and III report mean random vitrinite reflectance values of 0.63% and 0.57% to 0.64% respectively (18). According to the rank criterion, these coals are therefore not considered, at this point in time, to be of interest for natural gas prospecting. In addition, this coalfield is rather shallow, explored by opencast mining, and almost tectonically undisturbed, reaching little over 400m in depth in the central part of the coalfield.

b) Guadiato/Peñarroya-Belmez-Espiel

This coalfield comprises essentially two sectors (Western and Central-Eastern). Refer to 3.3 for coalfield details. Rank is well established on the basis of vitrinite reflectance (19). In the Western Sector, the variation in reflectance is between

1.24% and 2.70%, whilst in the Central-Eastern Sector it varies between 0.57% and 0.93%. The correlation between mean random vitrinite reflectance and VM% (daf) rejects the Central-Eastern Sector in terms of potential for natural gas prospecting.

3.4. Third criterion - Geological and structural conditions of the different coalfields**3.4.1. Introduction**

The criterion of geological and structural conditions of the different coalfields obviously involves several aspects of which the following are particularly highlighted with respect to the main objective pursued:

(i) stratigraphic units and respective depositional conditions, thus implying the presence of sufficient number of coal seams of recognized importance within each coal-bearing unit (frequency), and consequently ensuring enhanced possibilities of extracting natural gas;

(ii) structural regime compatible with retention of natural gas by the coal itself.

On applying these geological criteria to the coalfields approved up to this stage (refer to Table 3), the following ones are considered to be potentially interesting for the prospecting of natural gas:

3.4.2. North (Cantabrian Mountains)**3.4.2.1. El Bierzo**

The study *Revisión y Síntesis Geológico-Minera de la Cuenca Carbonífera de "El Bierzo" (León)* (20, Figs 6-11, Planos 1-10) permitted to establish five distinct areas that correspond approximately to equivalent number of geological/structural blocks, namely: Fabero, Langre, Noceda, Almagarinos, and Torre (del Bierzo).

The stratigraphy and structure of each one of the blocks is well known (refer to detailed stratigraphic columns in the quoted reference). To date, however, it has not been possible to establish correlations among them. In our opinion, each area may possibly correspond to an evolutionary depocentre within a sedimentary basin, and the suggestion in the reference to have the correlation of coal seams, identified in each block, done by geochemical parameters seems to be inappropriate. In fact, such attempts in other well-studied basins have failed. The correlation between the different areas/blocks should be carried out following a detailed study based on modern stratigraphy/sedimentology, and simultaneously on coal petrology. In the latter case an additional result would be the definition of the coalification trends.

Each of the five blocks is characterized by well defined stratigraphy, that in the Carboniferous includes various members, most of which contain coal-bearing units with various

Rank (see Figure 2)	Coalfields (see Figures 1 and 2)	No (see Figure 1)
Anthracites (VM daf 4-10%) and Peranthracites (VM < 4%)	El Bierzo	15
Low Volatile BC (VM daf 10-18%)	La Pernía-Barruelo Ciñera-Matallana Cerrede-Villablino	10 13 16
Coking coal (VM daf 18-30%)	Sabero La Magdalena	12 14
MIXED (VM daf 4-10%; 10-18%; 18-30%)	Central Asturian Coalfield and extensions Valderrueda-Guardo	5 1

Table 3. Coalfields in the North (Cantabrian Mountains) reporting cumulative “very probable” and “probable” resources above 20 Mt, and with VM (daf) < 30%

seams and/or coal veins. The frequency in seams and/or veins is high, and thickness varies between 0.40m and 1.30m.

In a mining perspective⁷ four zones are established:

- Western (“Fabero”) - corresponding to Fabero and Langre blocks
- Central (“Noceda”) - approximately equivalent to the block with the same name
- Eastern (“Valdesamario”) - an extension to the east of the Central zone (“Noceda”)
- Southern (“Torre”) - corresponding to the Torre (del Bierzo) block.

Mining interest of Almagarinos block is very limited due to scarcity of coal seams.

A detailed study of both geological profiles and stratigraphic columns for the different areas of the coalfield permit to certify the frequency of coal seams and the depths at which they occur. Further background to the coalfield is summarized in Table 4.

In conclusion, this coalfield, previously selected on the basis of resources (see 3.2) and rank (see 3.3), also manifests favourable geological/structural characteristics that would make it suitable for natural gas prospecting, especially in the Western (“Fabero”) and South (“Torre”) mining zones. Both zones contain the thickest seams, highest coal seam frequency, and highest resources (Table 4). Applying the same criteria, the interest in the Eastern zone (“Valdesamario”) is only a relative one, whilst none is given to the Central zone (“Noceda”). The major obstacle concerning the coalfield is an administrative one, resulting from the high number of concession areas distributed through a number of small areas.

3.4.2.2. La Pernía - Barruelo

This coalfield actually comprises two distinct sedimentary basins: La Pernía and Barruelo (21, Figs 1-2; 22, Figs 56 and 61-63). Only the latter is considered to be of any interest, since La Pernía only registers insignificant coal veins in terms of frequency and thickness.

Mining Zone	Resources (Mt)		Seam thickness (m) (min-max)	No. of main explored seams	Gross production (ton) [1983]	No. of concessioned companies	No. of producers
	Very probable	Probable					
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Western (“Fabero”)	20	17	0.50-1.30	7	1 349 366	10	15
Central (“Noceda”)	9	2	0.40-0.90	4	477 131	12	15
Eastern (“Valdesamario”)	17	15	0.40-0.90	10	395 199	19	23
Southern (“Torre”)	17	14	0.50-1.00	4	877 162	25	27

Table 4. El Bierzo Coalfield - some basic information

⁷ Most collieries are underground, with some opencast.

The set of elements in the quoted references permit to verify that the Barruelo Coalfield stratigraphically and structurally contains coal seams or units that can reach up to 4m in thickness, although irregularly from place to place as normally occurs in areas that are tectonically strongly affected. Also, the extension, frequency and depth of the seams further provide interesting evidence for the prospecting of natural gas.

In conclusion, the information given by Wagner and Winkler Prins (21, Fig.2) and Wagner and al. (22, Figs 56 and 63) as well as the resource evaluation (3.2) and rank (3.3) are considered sufficient to warrant potentially interesting attributes to Barruelo Coalfield in terms of natural gas prospecting. The additional favourable factor is related to the Barruelo Anticline which extends eastwards below the Mesozoic, thus further increasing the real prospects and potential suitability of the coalfield.

3.4.2.3. Ciñera-Matallana

This is a rather well known coalfield (11; 23, Figs 9-10, 15, 18, 20-21, 23-24, 26, 34-35 and 37-38). The following are the formations and stratigraphic levels: Matallana Formation (roof); Bienvenidas Formation; San José Formation; Roguera Formation; Cascajo Formation; Pastora Formation; Tabliza Horizont; San Francisco Formation (floor). Mean random vitrinite reflectance iso-contours were produced by Mendes Cecília (11, Fig.17) (see also 13, Fig.8). The available information permit to suggest that only Pastora and San José formations are worth considering, since they contain sufficiently thick coal seams (always variable, as expected in such a tectonically affected basin, but as in the case of Pastora Formation where as many as 30 seams with thickness variation from 0.50m to at least 15.0m, although including sterile partings), extension, frequency and sufficient depth to generate and retain natural gas in economically interesting quantities. Note is made of the presence of dykes of volcanic rocks locally affecting several seams.

The information provide above, and in 3.2 and 3.3 permit to conclude that Ciñera-Matallana Coalfield manifests real potentiality in terms of natural gas prospecting.

3.4.2.4. Cerredo - Villablino

The designation Villablino or Cerredo-Villablino Coalfield refers to a group of four *zones*, more or less continuous from west to east, namely: Tormaleo, Cerredo, Monasterio de Hermo, and Villablino. (24, Planos 1-2 and 9-10).

Due to scarce resources and suitability, Tormaleo and Monasterio de Hermo are rejected. However, Cerredo and Villablino zones possess seams in sufficient number, frequency, depth and thickness to warrant attention and detailed study of the geological profiles and maps.

a) Cerredo (24, Planos 1-2).

The following coal-bearing units are identified:

- Inesperada (roof) - 7 seams with thickness ranging from 0.35m to 2.00m
- Rosario - 3 seams with thickness ranging from 0.80m to 2.00m
- Paulina - 6 seams with thickness ranging from 0.40m to 1.80m
- Calderón (floor) - 13 seams with thickness of about 1m.

b) Villablino (24, Planos 9-10).

Coal seams in this zone are referred to according to mining areas. Although it has not been possible to correlate with precision the various seams, the otherwise reasonable records for each area provide a concrete picture about the importance of this zone (Table 5). Attention is drawn to the presence of igneous intrusions that locally affect some seams to the extent of converting, on contact, the coal into natural coke.

Nevertheless, the information gathered shows that seam frequency, thickness and depth at which they occur may be compatible with the generation and conservation of natural gas, probably also in significant quantities.

According to resource and rank criteria (3.2 and 3.3) and to the information presented above, the Cerredo-Villablino Coalfield is considered to have real potential in terms of natural gas prospecting.

3.4.2.5. Sabero

In the Sabero Coalfield the following formations and horizons are identified (25, Text-Figs 2,3 and 21): Perla beds (roof); Herrera beds; Unica beds; Quemadas Formation; Sucesiva Formation; Gonzalo Formation; Raposa Formation; and Alejico Formation (floor).

The only producing coal-bearing units, are: Herrera (at least 8 seams with varying thickness between 1.50m and 7.00m) and Unica (11 seams with thickness between 0.50m and 2.00m). The depths at which the seams occur, and the extremely variable thickness of seams resulting from typical thin-skinned tectonic regimes will very probably be detrimental to the conservation of any natural gas that may have been generated.

Although resources and rank criteria were met by this coalfield, the shallow depths at which the seams occur, and the typical tectonic influence it manifests are major factors against recommending this coalfield for prospecting of natural gas.

3.4.2.6. La Magdalena

This coalfield is poorly known in terms of geological/structural (26) and resource evaluation (very probable and pro-

Mining area	Seams	
	Number	Thickness (m) min-max
Paulina	2	0.60-1.80
María-Bolsada	6	0.70-2.30
Calderón-Villablino	15	0.50-2.15
Lumajo		
a) Llamas	11	0.65-2.20
b) Brañas	15	0.60-1.90
Carrasconte	26	0.50-2.00

Table 5. Cerredo-Villablino Coalfield; Villablino Zone. Some coal seam characteristics in the different mining areas.

bable resources). An important sedimentological study by Heward (27) is available, yet, little information is drawn for the objectives in this investigation. Nevertheless, according to the mentioned author, the density of coal seams and their respective thickness are considered irregular.

The known resource figures, coal seam frequency, thickness and depth of the different seams are not sufficient to favourably consider this coalfield in terms of natural gas prospecting.

3.4.2.7. Central Asturian Coalfield and extensions

The significant resources and reserves attributed to this coalfield have justified continuous investigations, resulting over the years in rather important publications. However, most of them are outside the scope of information required to meet current objectives, and the following references are considered to be the only suitable ones: Caride de Liñan and García-Loygorri (28); Feys and al. (29); García-Loygorri (30, 31); Wagner and Alvarez-Vásquez (32); Aller and Gallastegui (33).

In this coalfield, two significant and well studied areas are contemplated (32, Fig.1): Aller-Nalón area to the East (refer to 29, Fig.2; 30; 31, Fig.9) and Riosa-Olloniegro area to the West (refer to 28). Both areas are separated from each other by an important tectonic disturbance, resulting in both exhibiting distinctly different stratigraphy that have been correlated on the basis of palaeontology (32, Fig.4), after a first attempt by Feys and al. (29).

Furthermore, both mentioned areas, located in the northern part of the Coalfield, contain the main mining sectors, and are also placed outside the scope of imposed rank criterion (VM (daf) > 30%)⁸. However, the close spatial relation between zones with coals having VM (daf) of 30 to 35% and coals with VM (daf) < 30% could account, in some way, for a possible increase in in-situ generation and accumulation of gas, and eventual migration to the selected areas.

The area considered relevant to the present study is situated further South, extending into areas of sheets 53

(Mieres) and mainly 79 (Pola de Lena) of the 1/50.000 geological map of Spain, and corresponding to coals with VM (daf) < 30% (Figure 2). Unfortunately this part of the Coalfield is insufficiently studied, leading to information input only from accompanying map explanatory notes. This permitted to verify that practically all coal-bearing units well studied in the north part of the coalfield are also present in the mapped Mieres region. Further South, in the Pola de Lena map, the lower seam frequency becomes evident although within a similar stratigraphic sequence.

Although the frequency of seams reduces progressively from North to South as a result of the progressive increase in marine series, the information about the number of seams (several dozens) that are in some cases poorly correlated (implying the need for more detailed study should prospecting be required), their thickness (reaching several metres), the frequency of the seams within the coal-bearing units, and the depth at which some of them occur in Mieres and Pola de Lena areas, could support interesting possibilities for generation and storage of natural gas in reasonable amounts.

On the other hand, the rather complex structure of the South region (33) implies careful ponderation as to the prospecting potential of the area.

In conclusion, although the region in the Central Asturian Coalfield considered to be of interest (i.e., South region, coals with VM (daf) < 30%) is the least well known and contains lower seam frequency, the very important resources and the structure of the coalfield in the area permit to suggest that the region could be potentially suitable and important for prospecting natural gas. However, complementary investigations at start are strongly recommended.

3.4.2.8. Valderrueda - Guardo

This coalfield extends, West to East, from Valderrueda to Guardo, and with some continuity further eastwards until Cervera de Pisuerga (34, 35).

⁸ There is an important extension of the coalfield further to the north through the area of Lieres.

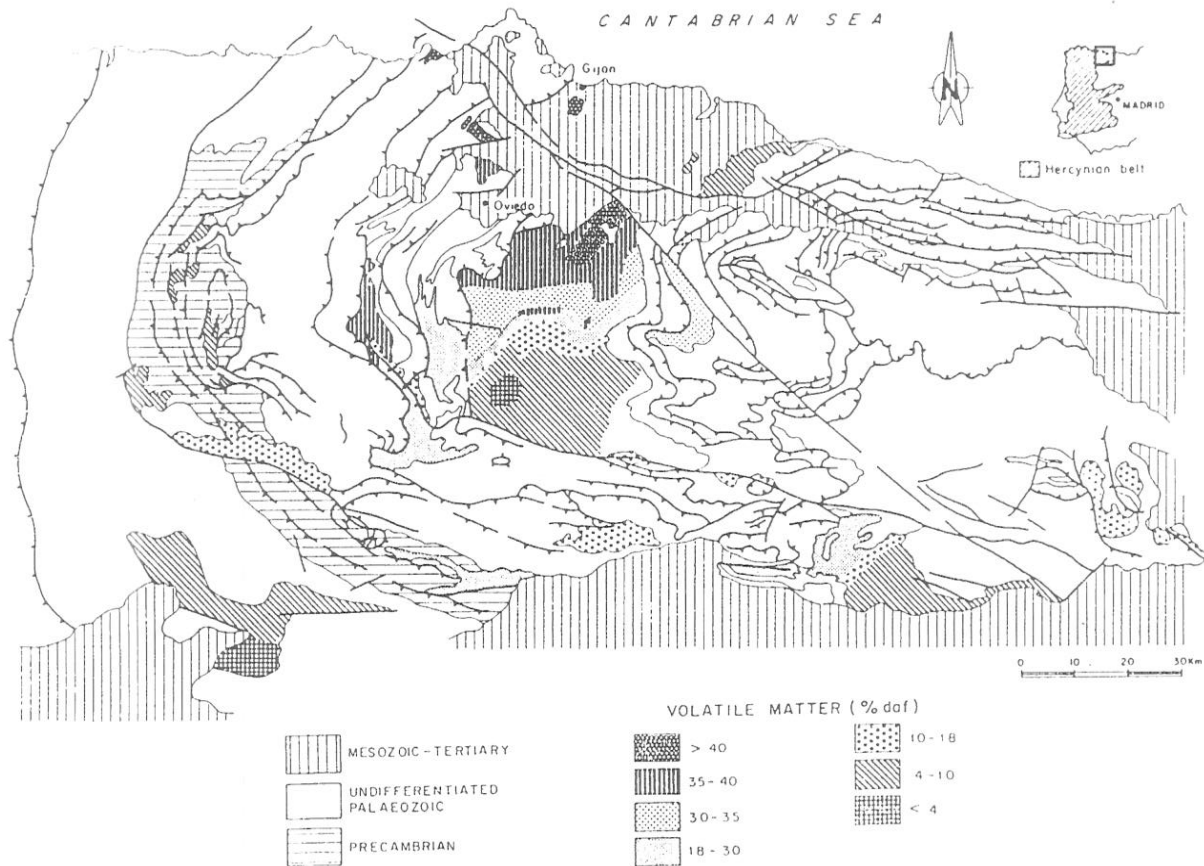


Figure 2. Regional variation in coal rank in the coalfields of the Cantabrian Mountains (adapted from 13).

The Carboniferous is comprised of 21 sedimentary formations, with alternating marine and terrestrial (containing coal seams) sediments. Although the stratigraphy is well known, including correlations (35, Figs 8a-8b), cartography and structure (35, Figs 2a-2b and 4), the available geological profiles are only schematic (35, Figs 3 and 6) and do not provide sufficient information as to the total number of seams. There is also no general record of coal seams, their thickness or frequency of occurrence.

Based upon mine shaft exploration data, the coalfield (at least in the currently explored areas) is placed at too shallow a depth to consider it interesting for the generation and preservation of natural gas.

This coalfield was selected on the basis of resources (refer to 3.2) and rank (see 3.3) and is reasonably well studied from a stratigraphic point of view. However, the lack of mining information and apparent low depth of the productive units known to date lead to the rejection of the Valderrueda-Guardo Coalfield in terms of natural gas prospecting.

3.4.3. South (Guadiato/Peñarroya-Belmez-Espiel Coalfield)

This coalfield is situated in the contact between the Ossa Morena and Central Iberian zones. As previously mentioned,

and from the point of view of spatial distribution of coal, there are two main Sectors: Western Sector (anthracite zone) and Central-Eastern Sector (bituminous coal zone) (19, Fig.5; Wagner pers. comm.).

Furthermore, it is known that in terms of sedimentation, the coalfield evolved in four depocentres (I, II, III, IV) (19, Fig.7). In depocentre I no coal seams were formed. The "anthracite zone" in the Western Sector was formed during the II depocentre. In the case of the bituminous coal zone of the Central-Eastern Sector, coals formed in the III and IV depocentres.

Bearing in mind the relevance of coal rank, and what was previously stated (refer to 3.3.2), the logical conclusion would be to consider the Western Sector in terms of natural gas potential, i.e., the anthracite zone. However, this sector as known to date, does not seem to provide sufficient interest to this effect, mainly for the following reasons: only two coal-bearing units are highlighted (Paquete San Rafael in the area of mine shaft Cervantes, and Paquete Cervantes in the area of mine shaft San José) that are rather irregular but can reach several metres in thickness. Seam Cervantes sometimes occurs strongly affected by volcanic rocks leading to the conversion of coal into natural coke. In addition, the entire tectonic structure is represented by tectonic lenses resulting in the coal being irregularly distributed (19, Fig.2). Finally,

the entire Sector is rather superficial and hence difficult to ensure retention of any produced natural gas.

On the basis of currently available information, the Guadiato/Peñarroya-Belmez-Espiel Coalfield appears to be of limited interest for prospecting natural gas. Nevertheless, it is worth stating that this opinion may change in the future, and once more information is known about the Western Sector (anthracite zone) below the Lower Namurian. In effect, it seems logic that coal seams may exist with required rank and depths that would make prospecting for natural gas a viable possibility. Unanswered questions would then be related to the number and frequency of coal seams.

4. CONCLUSIONS

On the basis of currently available literature and the information gathered on Spanish coalfields, three criteria were chosen for their appraisal to the prospecting of natural gas from coal in-situ (coalbed methane):

- Existing resources
- Coal rank
- Geological/structural conditions

This review identifies the following coalfields as potentially the most suitable (in order of decreasing importance):

- Ciñera-Matallana and Cerredo-Villablino, considered to be of equivalent potential
- La Pernía-Barruelo
- Central Asturian Coalfield, South region
- El Bierzo

For prospecting of natural gas it is recommended that the abovementioned coalfields (in the order given) be subjected to detailed studies through a carefully planned exploration programme, followed by a feasibility study that would ensure or reject commercial production of coalbed methane.

Preliminary prospecting should include the following studies in coals (2): (i) total moisture and moisture-holding capacity analyses; (ii) density; (iii) proximate and ultimate analyses, (iv) petrographic analyses (reflectance, macerals, microlithotypes, carbominerites and minerite), (v) palaeofacies of coal sedimentation, (vi) mineral matter content by low temperature ashing, (vii) chemical and mineralogical analyses of the mineral matter, (viii) detailed study of cleat system, (ix) determination of the Q_1 (lost), Q_2 (desorbed) and Q_3 (residual) gas contents, (x) methane adsorption isotherms, (xi) molar composition of the produced gas, (xii) isotopic composition of the produced gas.

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