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Coal definition and classification revisited: an account of related problems

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Coal definition and classification revisited: an account of related problems

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Abstract

Coal is a sedimentary rock primarily composed of plant remains in various stages of alteration, along with mineral impurities. This rock is highly heterogeneous in terms of *petrographic composition*: besides mineral fraction, 28 other organic macerals, integrating 7 microlithotype groups and 4 lithotypes. Additionally, physical and chemical properties of organic components are highly dependent on geological maturation effects, i.e. the natural evolution in the sedimentary basin corresponding to the concept *rank* evolution, along the full coal range. Consequently, to define coal *quality* we must consider three parameters: *petrographic composition*, *rank* and *grade*, the latter referring to the level of mineral impurities.

Coal remains an important solid fuel, and as a commodity.

Mechanical properties of coal have been studied in the past mainly in relation to coal beneficiation or technological uses (e.g. size preparation, grindability, etc.). However, recently, the study of coal mechanical strength has been developed, leading to considering coal within *soft rocks* concept, with important mining applications.

In this framework, it became obviously important to revisit the main concepts of *coal definition* and *classification*. For this purpose, the authors address the main current problems in these two topics, proposing solutions for a more precise and comprehensive approach to the subject.

Two of the most internationally used standards for coal definition and classification, i.e. ISO11760 and ASTM D388 standards, are considered to address the existing problems. A practical exercise of the applicability of these standards was carried out with a set of selected coal samples.

Keywords

Coal, Coal definition, Coal classification, ISO classification, ASTM classification, Standard methods

1 Introduction: Coal as a sedimentary rock, as a solid fuel, a commodity, and as a soft rock

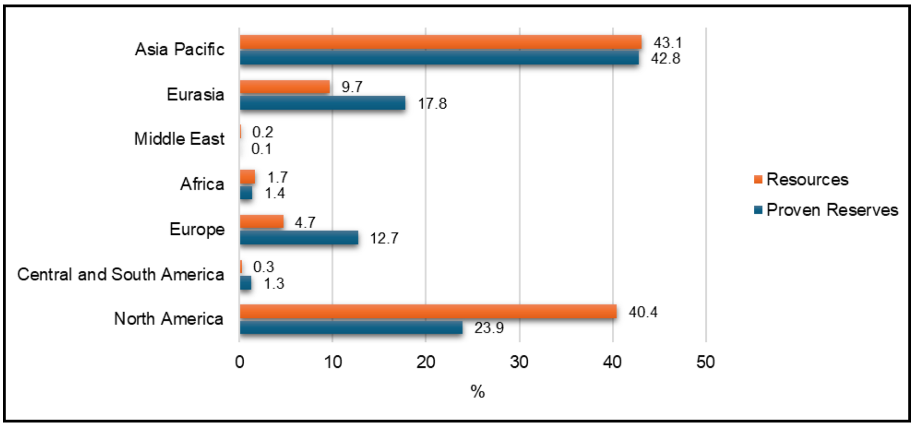
1.1 Coal as a sedimentary rock

The current concept of coal corresponds to a brown to black combustible sedimentary rock, mainly composed of fossilized plant remains, in different stages of alteration, together with varying amounts of mineral impurities.

Coal is a rather heterogeneous solid which, besides the mineral fraction, is composed of organic matter that includes 28 different individual constituents, i.e. the so-called macerals, classed in three groups, viz: huminite-vitrinite (12 macerals), liptinite (9 macerals) and inertinite (7 macerals), each one with different composition and behaviour, especially when in natural associations designated as microlithotypes/groups of microlithotypes (7 different groups), as well as, in 4 diverse lithotypes.

1.2 Coal as a solid fuel and a commodity

Regarding the current and future importance of coal we should consider the world proved reserves and resources of coal, by countries and regions, in 2023, indicated in Fig. 1: proved reserves 1 025×10^9 tonnes and resources 20 776×10^9 tonnes. In 2024, the estimated total coal production was 8.89×10^9 tonnes, of which approximately 7.78×10^9 are categorized as thermal coal, corresponding to 26 % of the total primary energy production.



Coal (billion tonnes)	Proven Reserves		Resources	
	Billion tonnes	%	Billion tonnes	%
North America	257	23.9	8 387	40.4
Central and South America	14	1.3	60	0.3
Europe	137	12.7	980	4.7
Africa	15	1.4	343	1.7
Middle East	1	0.1	41	0.2
Eurasia[1]	191	17.8	2 015	9.7
Asia Pacific[2]	460	42.8	8 950	43.1
World	**1 075**	**100**	**20 776**	**100**

[1]Caspian regional grouping and the Russian Federation (Russia).

[2]Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, The People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.

Fig. 1 Coal proven Reserves and Resources in 2023. Source: IEA 2024 (World Energy Outlook)

Technologies in which coal is most used today are combustion (thermal or steam coal) and coking (metallurgical or coking coals), as well as some others with a lower incidence, such as in gasification-liquefaction.

Given these statistics and the value of the reserves/production ratio, the durability of coal consumption in the BAU scenario is 115 years for all proven reserves.

In this context, it is therefore pertinent to ask: what role does coal play in the energy transition? The essentials on this subject are summarized in Rodrigues et al. (2022), and given the global energy scenario, coal will continue to be used for decades to come, contributing to the world's primary energy mix (Fig. 2). The rate of transition, from the use of fossil fuels to alternative sources, depends on several factors, amongst which are economic laws, including the impact on the price of coal, the impact of carbon taxing, advances in innovation and new technologies, and cohesive affordability in an economically and socially diverse world. Despite the efforts made during the past thirty years, global coal production (and of other fossil fuels has not seen any significant decline, continuing to contribute to the global energy mix – so much so, that it can be argued that energy addition remains predominant over energy transition as such.

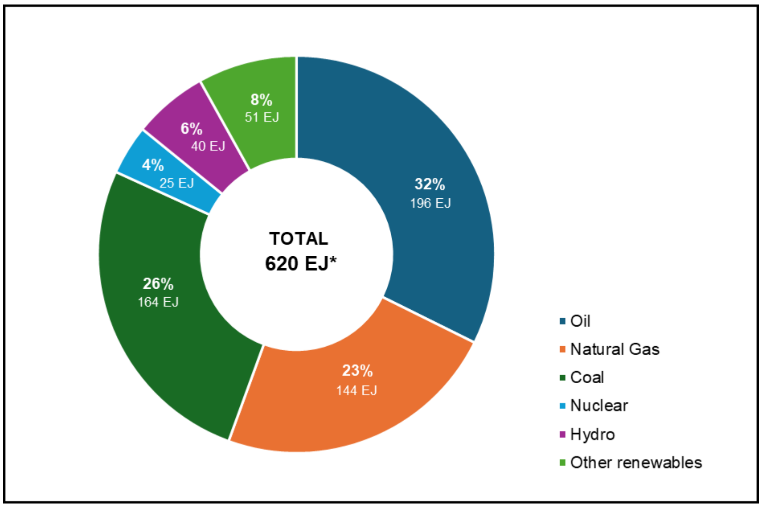


Fig. 2 Primary Energy Production in 2023**.** Source: Energy Institute 2024

In any case, coal, the mythical rock that made the industrial revolution of the 19th century possible, can still play an important role in energy transition. In fact, as mentioned earlier, additionally to the fact that it will not be possible to get along without fossil fuels for decades to come, particularly in electricity production, it is obvious that the use of coal will have to be done minimizing the production of greenhouse gases. In this regard, and in addition to the current widespread application of "clean coal" technologies, there is an extensive range of coals that can be used for gasification-liquefaction, while other ranges are sources of coalbed methane (CBM), i.e. natural gas considered the most acceptable fossil fuel in terms of environment (Flores 2014). It should also be emphasized that certain coal ranges are an ideal medium for the geological sequestration of CO_2 (Raza et al. 2019), and in such cases with the double advantage that the injection of CO_2 can be used for increased production of CBM. Technology exists to assist with coal use whilst mitigating emissions, but much depends, as always, on how the economy evolves globally and in each country.

1.3 Coal as a soft rock: mechanical properties of coal

The classic treatises on coal science (e.g. Stach et al. 1982, van Krevelen 1993, Taylor et al. 1998) include chapters on the mechanical properties of coal, essentially relating to *elastic deformation,* distinguishing between the concepts of *hardness* (a physical property of matter which can only be determined in homogeneous substances) and *mechanical strength* (a physical property of matter that can also be measured on non-homogeneous or heterogeneous bodies). Consequently, as far as coal is concerned, hardness can only be measured on individual constituents, in macerals, namely in the terms

of microhardness (Vickers or Knoop). In contrast, strength can be measured both in microlithotypes and lithotypes and, of course, in coal when considered as a whole, i.e. as a rock.
Lastly, the behaviour of this rock to mechanical degradation in coal processing has traditionally been associated with the studies of the mechanical properties of coal, such as in coal beneficiation, including mechanical breakage and the preparation of sized coal required for use in combustion (including pulverized fuel) and coking (standard size consist for coke oven charges) technologies. Consequently, standardized tests have been developed to determine the fracturing, breakage and grinding ability of coals, such as the Hardgrove grindability test (ISO 5074 and ASTM D409 standards), the Shatter test (ASTM D440 standard) and the Tumbler test (ASTM D441 standard).

Note: There are also authors that include in the context of mechanical properties of coal, the behaviour known as *plastic deformation*, related to the behaviour of coal when heated, as in the case of coke making. These refer to the tests relating to swelling in crucible, dilatometric and plastometric behaviour, which are not considered in the scope of this article.

More recently, mainly in the last five years, many papers and books were published dealing with mechanical properties of coal, framing this fossil fuel as a soft rock with important implications to mining. As an example, we will quote some of these articles, which makes obvious that there is a need to define and classify this sedimentary rock with increasing rigor, and not just on the basis of descriptive terms, which is the essential aim of the current paper (Gonzatti et al. 2020; Le et al. 2020; Peng et al. 2021; Huang et al. 2023a; Huang et al. 2023b; Liu et al. 2023; Zang et al.2023).

3. Coal definition and classification, and related problems

3.1 First problem: The definition of coal, coal composition and the modern concept of "coal quality"

ISO standard 11760 provides a comprehensive and precise, internationally accepted, definition of coal as follows: "Carbonaceous sedimentary rock largely derived from plant remains with an associated mineral content corresponding to an ash yield less than, or equal to, 50 % by mass (dry basis)".
Being a carbonaceous (organic) rock, coal cannot contain more mineral matter (corresponding, in practical terms, to the "ash yield") than organic matter. Consequently, any rock containing coal material but with an ash content (“dry” basis) greater than 50 % by mass, must be classified as coally shale, and not as coal.
Furthermore, as coal is constituted by very heterogeneous organic and inorganic constituents, its physical and chemical properties can vary widely, and consequently the wide range of applications of this commodity in various technologies.

In order to characterize any coal, one should consider the following three main characteristics/attributes, which should always be taken jointly, viz: *rank* (corresponding to its geological maturity in the sedimentary basin), *petrographic composition* (corresponding to the components, either organic or inorganic, identifiable/recognized under the microscope), and *grade* (i.e., the amount of mineral impurities, corresponding to the mineral matter present). Indeed, these three characteristics are the ones that, jointly, can synthesize the modern concept of "coal quality". In the current state of knowledge, it is not correct to state that a coal is of "good" or "bad" quality, because it depends on the technology in which we envisage to use that coal. In other words: a certain quality of coal could be good to be utilized in one technology (for example combustion) and be bad, or even impossible, to be used in another one (for example coke making).

3.2 Second problem: How to classify coal

3.2.1 Historical

Being a rock, coal needs to be classified as all other rocks under the general rules of Systematics, i.e. first establishing similar groups (Taxonomy), and secondly giving names to the groups (Nomenclature).

Since the first tentative classification by V. Regnault in 1837 and L. Grüner in 1874, the main issues of coal classification and its historical developments have been the object of several papers, book chapters and congress communications (e.g. Francis 1961; Carpenter 1998; van Krevelen 1993; Lemos de Sousa and Pinheiro1994; Lemos de Sousa et al. 1995). Consequently, we only would like to remind that of the three attributes that make nowadays possible to qualify and classify a coal, rank is the one that is the most distinctive macroscopically and, therefore, has been the only one initially used as a criterion for classification. Additionally, when quantifying rank, it can only be done by measuring a chemical property, a physical-chemical test or any other physical property - which is called a "rank parameter" - that is sensitive to the geological evolution of the coal in the sedimentary basin in which it was formed, and in which it occurs. However, there is no single parameter with sufficient sensitivity to allow repeatability of measurements over the entire rank range, making it necessary to use different parameters to cover all coals, from lignite to anthracite.

Historically, since the pioneering work of various scientists, the first rank parameters selected were only chemical, evolving later to the use of other properties. This gave rise to important systems such as the Seyler chart which, however, failed to be successfully applied to most coals (Francis 1961; Lemos de Sousa et al. 1992). In fact, it was much later concluded that it was impossible to classify a coal only by rank, unless correction formulas were used, which we now know were related to maceral composition and grade. This is what was achieved for the first time with the so-called Parr formulas, which gave rise to a classification that would evolve into the current ASTM D388 standard classification (see section 3.2.4).

Only later did the initial individual contributions evolve into standardized systems, drawn up by groups of specialists within the framework of international (International Organization for Standardization - ISO, United Nations Economic Commission for Europe - UN-ECE, and International Committee for Coal and Organic Petrology – ICCP - Lemos de Sousa et al. 1998) or national standardization bodies, at the same time as the modern petrographic study of coal became increasingly important and even decisive, following the pioneering work of Marie Stopes, Clarence Seyler, Erich Stach, André Duparque, etc.

Presently there are two types of coal classification systems, both standardized: systems based on international standards and those corresponding to national standards.

Note: In the past and for a long time, it was considered that there were scientific/genetic classifications (for coal as a rock, namely *in situ, in the* seam) and technical/commercial classifications (for coal as a commodity, after beneficiation, i.e. crushed, washed, sized, and/or in blends), the latter often expressed by numerical codes, and known as Codifications. This is now an outdated concept.

The trend today is to consider both international and national standards to be valid for all coals, whether *in situ, in the* seam or as an industrial product/commodity. Such is the case for the coal classification standards that we will deal with in this paper:

(i) International standards: The UN-ECE *International Classification of In-Sean Coals* for the so-called "general classification", and the ISO 11760 standard Classification of Coals.

(ii) National/regional standard: The ASTM D388 standard on Coal Classification.

Notes:

1. The UN-ECE *International Classification of In-Sean Coals* (Lemos de Sousa and Pinheiro 1998; UN 1998) was the result of a long collective work of synthesis that took as its starting point an official proposal from the French government, based on the pioneering work carried out at the Centre d'Études et Recherches des Charbonnages de France (CERCHAR) by Boris Alpern who, for the first time, drew up a proposal for classifying coal based on the three characteristics/attributes that are now recognized as indispensable for defining the "quality" of a coal: rank, viz.: petrographic composition and grade (Alpern et al. 1988; Alpern et al. 1989; Alpern and Lemos de Sousa 1991; Alpern and Lemos de Sousa 2002).

2. The reason why the ASTM D388 standard on Coal Classification is the only national system considered in the present paper is that, usually, national standards are conceived on the basis of, and adapted to, the coals occurring in the domestic context, independently of the real importance of the country in the international framework, as is the case for example of Australian (AS 1982; AS 1983; AS 1987) and Chinese (Chen Peng 2000) systems.

3. As all coal classification systems are based in measurable analytical standardized parameters, it is important to remember that, for any parameter value, it must consider the reproducibility limits of the respective standard test method.

3.2.2 The so-called General Classification

Independently of the classification system used, coals can be systematized, as a first approach, on the basis of the so-called *general classification* whose criteria were established by consensus within the framework of the UN-ECE's *International Classification of In-seam Coals*. Within this framework, coals are classified in two stages, based on rank parameters. In the absence of a known single parameter reliable enough to cover the full range of rank, the boundary limits for the main divisions and subdivisions are based on Vitrinite mean Random Reflectance per cent ($\bar{R}r$ %) and Gross Calorific Value "moist ash free" basis in MJ/kg (GCV maf MJ/kg) (Figs. 3a and 3b).

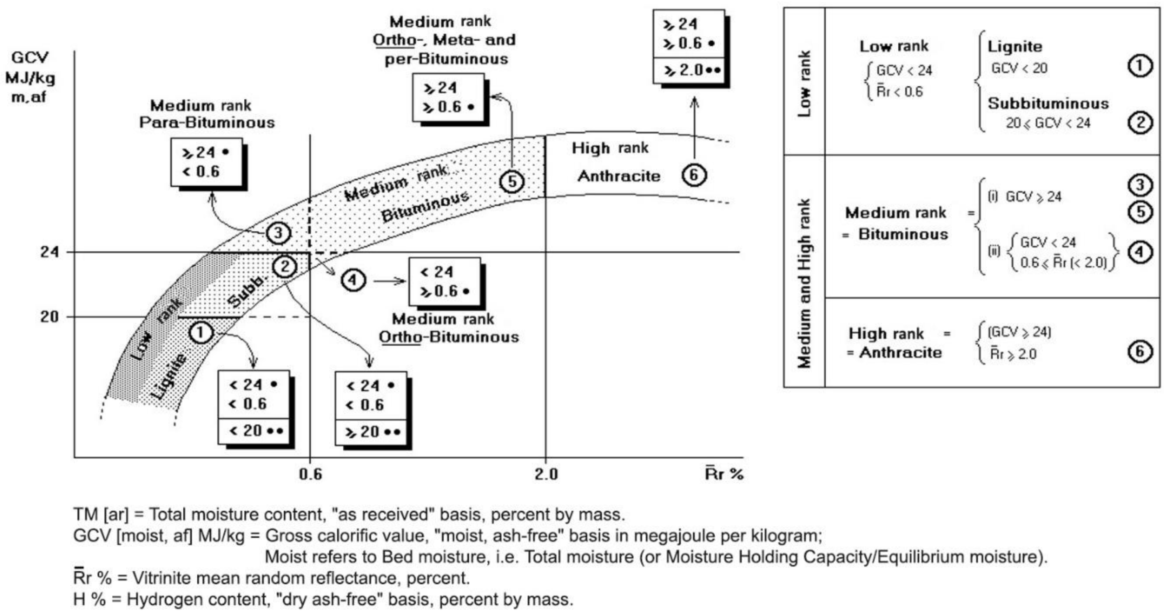


Fig. 3a General classification of coals according to United Nations Economic Commission for Europe (UN-ECE): the coal band and its main divisions and subdivisions based on rank parameters

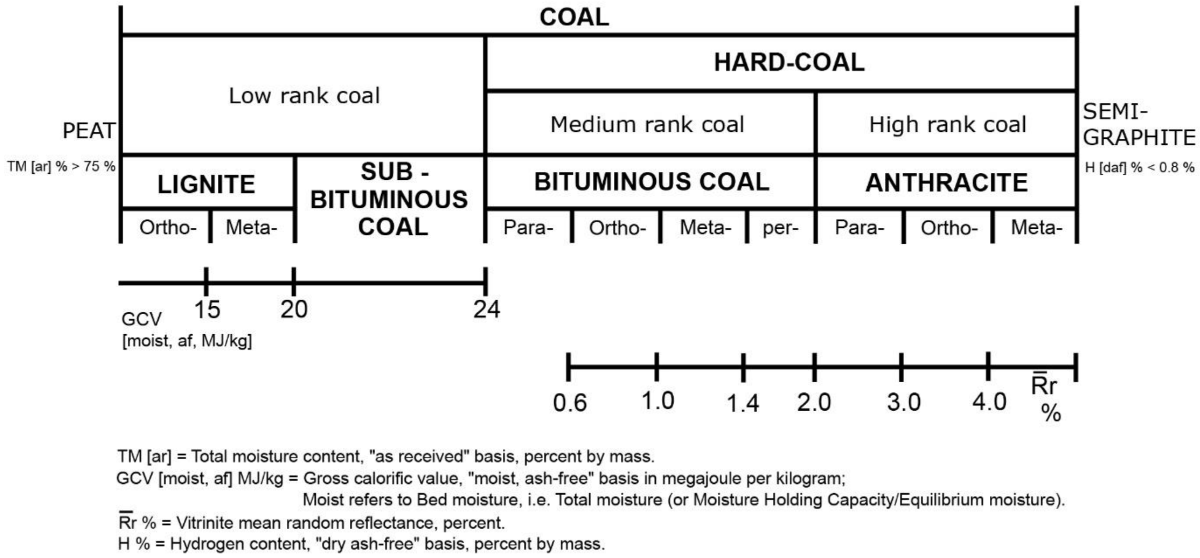


Fig. 3b A simplified chart of the general classification of coals according to United Nations Economic Commission for Europe (UN-ECE): Main divisions and subdivisions based on rank parameters

Analytical methods for these two parameters shall conform with the pertinent ISO standards (Table 1).

Table 1 List of ISO standards related with coal definition and classification

Subject	Standard		
Total moisture (Bed moisture)	ISO 589:2008 - Hard coal: Determination of total moisture ISO 5068-1:2007 - Brown coals and lignites - Determination of moisture content. Part 1 - Indirect gravimetric method for total moisture		
Moisture Holding Capacity = Equilibrium moisture	ISO 1018:2023 - Coal: Determination of moisture-holding capacity		
Proximate analysis			ISO 17246:2024 - Coal and coke: Proximate analysis
Moisture in the analysis sample	ISO 11722:2013 - Solid mineral fuels - Hard coal: Determination of moisture in the general analysis test sample by drying in nitrogen ISO 5068-2:2007 - Brown coals and Lignites - Determination of moisture content. Part 2 - Indirect gravimetric method for moisture in the analysis sample		
Ash content	ISO 1171:2024 - Coal and coke: Determination of ash		
Volatile matter content			
Fixed carbon			
Ultimate analysis			ISO 17247:2020 - Coal and coke: Ultimate analysis
Carbon content Hydrogen content	ISO 609:1996 - Solid mineral fuels: Determination of carbon and hydrogen - High temperature combustion method	ISO 29541:2025 - Coal and coke: Determination of total carbon, hydrogen and nitrogen - Instrumental method	
Nitrogen content			
Oxygen content	(by difference)		
Gross Calorific Value	ISO 1928:2020 - Coal and coke: Determination of gross calorific value		
Calculations on different bases	ISO 1170:2020 - Coal and coke: Calculation of analyses to different bases		
Petrography (ICCP[1] System 1994)			
Vocabulary	ISO 7404-1: 2016 - Methods for the petrographic analysis of coals. Part 1: Vocabulary		
Sample preparation	ISO 7404-2: 2009 - Methods for the petrographic analysis of coals. Part 2: Methods of preparing coal samples		
Reflectance	ISO 7404-5: 2009 - Methods for the petrographic analysis of coals. Part 5: Method of determining microscopically the reflectance of vitrinite		
Maceral group	ISO 7404-3: 2009 - Methods for the petrographic analysis of coals. Part 3: Method of determining maceral group composition		
Hardgrove index	ISO 5074:2015 - Hard coal - Determination of Hardgrove grindability index		
Classification	ISO 11760:2018 - Classification of coals		
Sampling of coal in seam	ISO 14180:2023 - Coal - Guidance on the sampling of coal seams		

[1]ICCP – International Committee for Coal and Organic Petrology.

The general classification by rank comprises two steps, as follows:

The first step aims to distinguish between Low-Rank coals and Higher-Rank coals (Hard coals) by the following way:

Low rank coals are coals with GCV (maf) < 24 MJ/kg **and** $\overline{\mathrm{R}}\mathrm{r} < 0.6$ %;

Higher rank coals (or *Hard coals*) i.e., all *Medium rank and High Rank coals* (Hard Coals), are coals with:

GCV (maf) $\geq$ 24 MJ/kg or GCV (maf) < 24 MJ/kg, provided that $\overline{\mathrm{R}}\mathrm{r} \geq 0.6$ %.

Notes:

1. The moist value used to recalculate the Gross Calorific Value to a "moist, ash free" basis (maf) is the Bed Moisture, i.e., the natural moisture content of the coal in situ, in the seam, determined by Total Moisture or the equivalent Moisture - Holding Capacity/Equilibrium Moisture (Lemos de Sousa et al. 1997; Flores et al. 1998; Flores et al. 1999).

2. The UN-ECE concept for Low Rank Coal does not correspond to the classic concept of Brown-coal, a term very often used as synonym of lignite, reason why the former designation is not used in the modern coal classifications.

The second step to classify a coal by rank involves a refinement of the first one, in order to plot it in the rank main divisions and subdivisions, i.e., in low rank coals being lignite and subbituminous coals subdivisions, and in higher rank coals or hard-coals, the bituminous coal and the anthracite subdivisions.

To avoid misinterpretations, it was decided that:

If $\overline{\mathrm{R}}\mathrm{r} \geq 0.6$ %, coals must be classified according to Vitrinite mean Random Reflectance per cent;

If $\overline{\mathrm{R}}\mathrm{r} < 0.6$ %, coals must be classified according to Gross Calorific Value (maf) in MJ/kg.

In such cases where $\overline{\mathrm{R}}\mathrm{r} < 0.6$ % and GCV (maf) < 24 MJ/kg, i.e. in Low-Rank coals, and remembering that, in this range, the detailed classification is based on the Gross Calorific Value. This parameter must be, also, recalculated to a "moist, ash free" basis (maf).

In the general classification, coal as a whole is framed by a lower rank limit corresponding to peat (nowadays not considered coal, but only the raw material that gives rise to coal, included in "renewable energies concept") and an upper rank limit corresponding to semi-graphite, the precursor of graphite, i.e., the end of the coalification scale, within the following fixed limits:

(i) *Lower limit* (Ortho-Lignite or Low-Rank C coal/Peat boundary): less than 75 % moisture content ("as received" basis), moisture being Bed Moisture, i.e. Total Moisture or the equivalent Moisture-Holding Capacity/Equilibrium Moisture.

(ii) *Upper limit* (Meta-Anthracite or High-Rank A coal/Semi-Graphite boundary): less than 0.8 % Hydrogen content in "dry, ash free" basis (daf).

Between the indicated limits, the following main divisions are delineated (Figs 3a and 3b):

Lignite, Subbituminous, Bituminous and *Anthracite* or, alternatively, *Low rank, Medium rank* and *High rank* divisions.

3.2.3 The ISO 11760 standard Coal Classification

In 1991, ISO developed a new Working Group (WG 18) to prepare an ISO Standard on coal classification. The basic working document for this purpose was the previous issue of the *International Classification In-seam Coals* of UN-ECE. After several meetings, the final issue was first published in 2005 as ISO 11760 standard with a current second edition published in 2018 (Fig. 4).

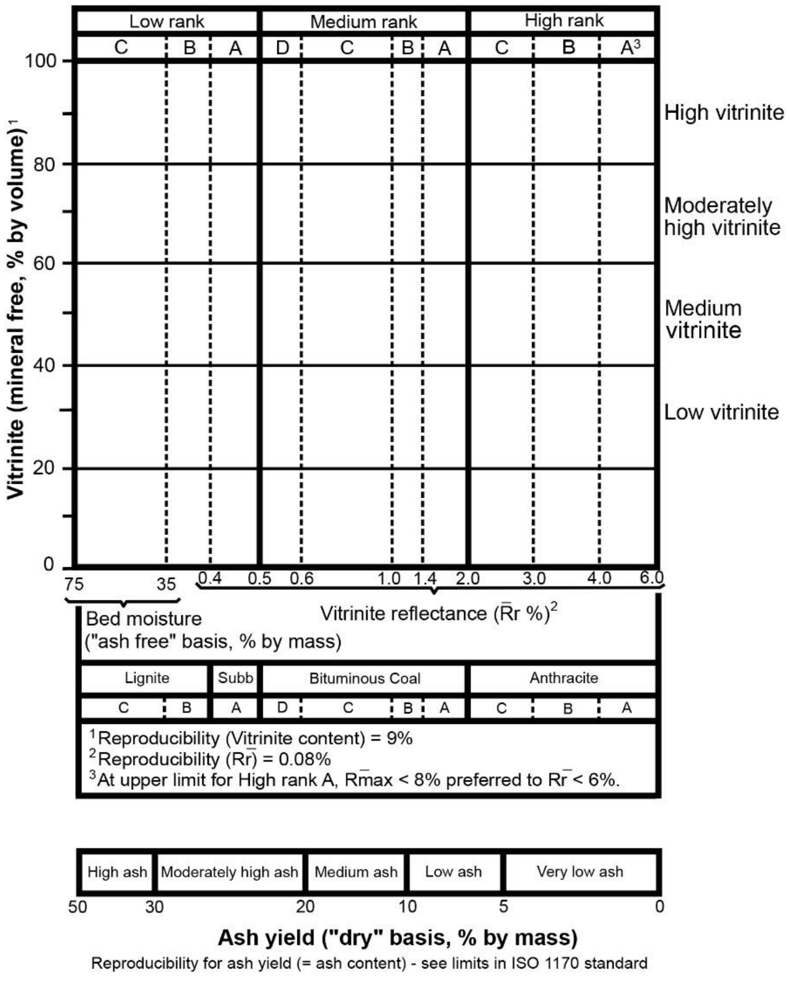


Fig.4 ISO 11760 standard Coal Classification

As an international standard, ISO 11760 is applicable to all coals, either for scientific or commercial and industrial purposes. In fact, this classification system conforms with the above referred concept of coal quality based on the three main characteristics/attributes that, jointly, can qualify a coal, all of them defined through quantitative parameters determined by ISO standards (Table 1), as follows:

- *Rank* (geological maturity) - Depending on the rank level, quantified by either Bed moisture, Total moisture, or the equivalent Moisture-Holding Capacity/Equilibrium moisture, on "ash free" basis (af), percent by mass or Vitrinite mean random reflectance, percent (as per ISO 7404-5).

Three primary rank categories are considered: Low rank, Medium rank and High rank. In order to provide a greater classification resolution, the three main rank categories are subdivided in sub-categories marked with A, B, C and D.

- *Petrographic composition* (components, either organic or inorganic, identifiable recognized under the microscope) - Quantified by maceral group composition – as per ISO 7404-3.

Four categories are considered under this parameter: Low vitrinite, Medium vitrinite, Moderately high vitrinite and High vitrinite (boundary limits are shown in Fig. 4).

Note: For High rank A or the equivalent Anthracite A upper limit of $\overline{R}r$ = 6% it is recommended to alternatively use the mean maximum reflectance $\overline{R}r$ = 8%. For detailed correlation between the $\overline{R}r$ and $\overline{R}max$, see Marques et al. (2009) and Rodrigues et al. (2013).

- *Grade* (degree of mineral impurities) - Quantified, in practical terms, by the parameter ash yield, corresponding to ash yield, "dry" basis, percent by mass - ISO 1171.

Five categories are considered for this parameter: Very low ash, Low ash, Medium ash, Moderately high ash, and High ash (boundary limits are shown in Fig. 4).

Note: Samples for petrographic analyses should be prepared and microscopically examined as prescribed by ISO 7404-2 standard.

3.2.4 The ASTM D388 standard Coal Classification

3.2.4.1. Introduction

Despite being a national/regional standard, this system originated from Parr's scientific classification of 1928, that was first published, as an experimental standard of the ASTM system, in 1934 (Lemos de Sousa et al. 1995). Apart from the USA and Canada, this classification is widely known and used outside the North American continent and is, in practice and as stated above, a classification system used internationally. In fact, if you follow all the rules on which it is based, without oversimplification, practice has shown that it is possible to apply the system to most coals of the world, even though the only classification criterion is rank (Lemos de Sousa and Pinheiro 1999; Vasconcelos 1999).

This fact is acknowledged in the standard itself, which assumes that the standard is valid for coals in which vitrinite is the main component, thus excluding coals with dominant inertinite or liptinite from the system. We should recall that both the petrographic composition and the grade can significantly influence the values of several rank parameters, such as volatile matter and carbon, but not vitrinite reflectance.

3.2.4.2 Objective and field of application

The essential of the ASTM classification is summarized in Table 2.

Table 2 ASTM D388 standard Coal Classification by rank

Class/Group	Fixed Carbon Limits (dmmf, %)		Volatile Matter Limits (dmmf, %)		Gross Calorific Value Limits (mmmf)				Agglomerating Character
					Btu/lb		MJ/kg[1]		
	Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	Equal or Greater Than	Less Than	
Anthracitic									
Meta-anthracite	98	…	…	2	…	…	…	…	
Anthracite	92	98	2	8	…	…	…	…	nonagglomerating
Semianthracite[2]	86	92	8	14	…	…	…	…	
Bituminous									
Low volatile bituminous coal	78	86	14	22	…	…	…	…	
Medium volatile bituminous coal	69	78	22	31	…	…	…	…	
High volatile A bituminous coal	…	69	31	…	14 000[3]	…	32.557	…	commonly agglomerating[4]
High volatile B bituminous coal	…	…	…	…	13 000[3]	14 000	30.232	32.557	
High volatile C bituminous coal	…	…	…	…	11 500	13 000	26.743	30.232	
					10 500	11 500	24.418	26.743	agglomerating
Subbituminous									
Subbituminous A coal	…	…	…	…	10 500	11 500	24.418	26.743	
Subbituminous B coal	…	…	…	…	9 500	10 500	22.09	24.418	
Subbituminous C coal	…	…	…	…	8 300	9 500	19.30	22.09	nonagglomerating
Lignitic									
Lignite A	…	…	…	…	6 300	8 300	14.65	19.30	
Lignite B	…	…	…	…	…	6 300	…	14.65	

dmmf - "dry, mineral matter free" basis.
mmmf - "moist, mineral matter free", Moist refers to Bed moisture, i.e., Total moisture (or Moisture Holding Capacity/Equilibrium moisture).

[1]Megajoules per kilogram. To convert British thermal units per pound to megajoules per kilogram, multiply by 0.0023255.
[2]If agglomerating, classify in low volatile group of the bituminous class.
[3]Coals having 69 % or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of gross calorific value.
[4]It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and that there are notable exceptions in the high volatile C bituminous group.

All analytical methods and applicable procedures shall conform with ASTM standards (Table 3).

Table 3 List of ASTM standards related with coal definition and classification

Subject	Standard
Total moisture (Bed moisture)	ASTM D3302/D3302M-22 - Standard Method for Total Moisture in Coal
Moisture Holding Capacity = Equilibrium moisture	ASTM D1412/D1412M-20 - Standard Method for Equilibrium Moisture of Coal at 96 to 97 Percent Relative Humidity and 30°C
Proximate analysis Moisture in the analysis sample Ash content Volatile matter content Fixed carbon	ASTM D7582-24 - Standard Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis[1]
Ultimate analysis Carbon content Hydrogen content Nitrogen content	ASTM D5373-21 - Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke
Oxygen content	(by difference)
Total sulfur content	ASTM D4239-18 - Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion
Ash composition analysis	ASTM D4326-21 - Standard Test Method for Major and Minor Elements in Coal Ash by X-Ray Fluorescence
Gross Calorific Value	ASTM D5865/D5865-19 - Standard Test Method for Gross Calorific Value of Coal and Coke[2]
Sample preparation for analysis	ASTM D2013/D2013M-24 - Standard Practice for Preparing Coal Samples for Analysis
Calculations on different bases	ASTM D3180-15(2023) - Standard Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases
Coal Grindability Test	ASTM D409/D409M-16 - Standard Test Method for Grindability of Coal by the Hardgrove-Machine Method
Coal Shatter Test	ASTM D440-07(2019) - Standard Method of Drop Shatter Test for Coal
Coal Tumbler Test	ASTM D441-07(2019) - Standard Test Method of Tumbler Test for Coal
Terminology	ASTM D121-24 – Standard Terminology of Coal and Coke
Classification	ASTM (by rank) - ASTM D388-23 - Standard Classification of Coals by Rank
Sampling of Coal in Seam	ASTM D4596-22 - Standard Practice for Collection of Channel Samples of Coal in a Mine
Sampling of Coal from Borehole Cores	ASTM D5192/D5192M-22 - Standard Practice for Collection of Coal Sample from Core

[1]In the ASTM system there is an alternative method for the determination of Moisture in the analysis sample.

[2]In the ASTM system there are various alternative methods for the determination of Gross Calorific Value.

The system was designed to classify, by rank, coals sampled either in situ, in the seam (geological characterization), or lots for industrial use (characterization of individual coals, even after beneficiation, or as coal blends).

Notes:

1. When applying the ASTM D338 standard to the above referred cases, we must also use different sampling standard procedures. Within the ASTM system and considering the aim of the present paper, the sampling standards listed in Table 2 only refer to the geological concept of coal, viz.: in the mine, i.e. in situ, in seam (ASTM 4596 standard) or in borehole cores (ASTM 5192 standard). Finally, it should be remembered that in all cases, samples intended for any laboratory analysis or determination must first be prepared in accordance with the relevant standards of the ASTM system.

2. When applying the ASTM D388 standard to classify a sample within the concept of coal as a commodity, and therefore obtained by a different and specific sampling standard procedure (for example sampling in stockpiles, barges, railway wagons and conveyor belts), the analytical results must contain the mention "apparent grade", followed by all the information deemed necessary to unequivocally identify the sample and the sampling method.

This system applies to coal of all degrees of coalification. It is based on the following main rank parameters: *Fixed Carbon content*, "dry, mineral matter free" basis, per cent, by mass (FC %, dmmf) and *Gross Calorific Value*, "moist, mineral matter free" basis, in Btu/lb or the equivalent in MJ/kg (GCV Btu/lb, mmmf or GCV MJ/kg, mmmf).

Notes:

1. In the above definitions, "moist" refers to Bed moisture, i.e. the natural moisture content of the coal in situ, in the seam, determined by Total moisture or the equivalent Moisture Holding capacity/Equilibrium moisture.

2. Although the Volatile Matter content, calculated on a "dry, mineral matter free" basis, is not a classification parameter, it is usual to include this parameter as an indication, only.

3.2.4.3 Classification

The following rules are used to classify a coal in this system:

(i) Samples with GCV (mmmf) ≥ 14,000 Btu/1b (32.6 MJ/kg) or with FC (dmmf) ≥ 69 % are classified according to their Fixed Carbon content.

(ii) Samples with GCV (mmmf) < 14,000 Btu/1b (32.6 MJ/kg) are classified in accordance with this same property, provided they have FC (dmmf) < 69 %.

(iii) The *agglomerating character* is an additional parameter that serves to clarify the classification of coals that are in the transition between the class of bituminous coals and the classes of anthracitic coals and subbituminous coals.

Note: The agglomerating character is determined from the residue obtained after testing for volatile matter content. Coal is considered to agglomerate if the residue shows swelling and cellular structure or is, at least, capable of supporting a mass of 500 g without pulverizing.

3.3 Third problem: The need to conform with the mandatory rules of the various classifications: some examples

3.3.1 Introduction

Although the statement may seem redundant, when classifying coal, it is crucial to strictly comply with all the mandatory rules set out in the standard being used. In fact, there are frequent cases where abusive simplifications are discretionally introduced leading to results that, may sometimes be completely wrong.

To decide whether a given sample fits into a given classification system, or into this or that division or subdivision of the same system, the reproducibility limits accepted for each of the analytical standards for the various parameters used in any classification must be considered.

Finally, special care must be taken when applying the standardized sampling rules for each case, particularly regarding *in situ*, in the seam or in borehole cores.

3.3.2 Samples

To exemplify the application of the definition of coal and the classification rules considered in diverse standards listed, we selected a set of ten samples of Paraná Basin, Brazil (Corrêa da Silva 1989; Corrêa da Silva 1993) that were studied based on chemical analysis, physical-chemical tests and petrographic analysis. The samples from the Barro Branco and Bonito coalbeds were collected in collieries in the state of Santa Catarina (Almeida 2019). The samples from the Upper and Lower Candiota, and the Lower Leão Seams, were collected in the state of Rio Grande do Sul and are in our archives.

The list of samples and analytical results are shown in Tables 4, 5 and 6.

Table 4 Results of Total moisture and Proximate analysis (ASTM)

Coalbed/ Layer	Sample	Total moisture (%, by mass)	Moisture in the analysis sample (% by mass)	Proximate analysis (db, % by mass)		
				Ash	Volatile matter	Fixed carbon
Barro Branco	CR1	7.33	1.42	40.93	23.37	35.70
	CR 3	2.36	0.68	41.67	21.59	36.74
	CR 4	3.93	0.74	31.04	27.78	41.18
	CR 6	5.63	1.53	22.66	29.59	47.75
Bonito	CR 2	2.25	1.10	44.57	21.73	33.70
	CR 5	2.81	1.12	54.34	17.05	28.61
	CR 7	2.88	1.05	50.11	17.43	32.46
Upper Candiota		16.7	7.8	38.72	25.16	36.12
Lower Candiota		15.9	5.2	52.64	19.62	27.74
Lower Leão		12.6	9.6	29.87	30.31	39.82

db - "dry" basis

Table 5 Results of Ultimate and Ash analyses, and Gross Calorific Value determination (ASTM)

Coalbed/ Layer	Sample	Ultimate analysis (db, % by mass)					$S0_3$ in ash (db, % by mass)	Gross Calorific Value (aa, Btu/lb)
		C	H	N	O	St		
Barro Branco	CR1	48.09	3.73	1.05	1.59	4.61	0.275	8221
	CR 3	47.84	3.42	1.17	<0.10	5.80	3.261	8087
	CR 4	51.24	3.78	1.30	<0.10	12.53	0.341	9135
	CR 6	62.90	4.56	1.55	0.23	8.10	0.287	10735
Bonito	CR 2	41.82	3.07	1.16	<0.10	9.28	3.105	7195
	CR 5	37.84	2.83	0.84	<0.10	4.06	1.842	6226
	CR 7	42.90	3.03	0.91	<0.10	3.57	1.647	7018
Upper Candiota		48.67	2.97	0.60	8.38	0.66	2.48	7691
Lower Candiota		35.53	2.33	0.73	7.92	0.85	0.60	5808
Lower Leão		53.44	3.32	0.95	7.46	4.97	3.09	8616

db - "dry" basis; aa - "as analysed" basis = ad - "as determined" basis

Table 6 Results of petrographic analyses: Vitrinite reflectance and Maceral groups analysis (ISO)

Coalbed/ Layer	Sample	$\bar{R}r \pm \sigma$ (%)	Maceral groups analysis (mf, % by volume)		
			Vitrinite	Liptinite	Inertinite
Barro Branco	CR1	0.66±0.08	62	17	21
	CR 3	0.87±0.08	60	12	28
	CR 4	0.66±0.04	74	13	13
	CR 6	0.64±0.06	83	10	7
Bonito	CR 2	0.70±0.05	45	28	27
	CR 5	0.68±0.07	47	23	30
	CR 7	0.70±0.06	39	29	32
Upper Candiota		0.46±0.03	39	17	44
Lower Candiota		0.45±0.04	38	7	56
Lower Leão		0.43±0.03	51	16	33

mf - mineral free

3.3.3 Classification of the samples studied

The analytical results in Tables 4, 5 and 6 lead to the following conclusions:

(i) *Coal definition*: Sample CR5 must be excluded from any classification because it does not meet the definition of coal, since its ash yield (54.34 %) exceeds the 50 % limit, even taking into account the reproducibility of the analytical method, i.e. 3.0 % of the average value of duplicate analyses. Consequently, sample CR5 should be classified as coally shale and not as coal. In contrast, samples CR7 and Lower Candiota can be considered as coal, since the ash yield values of 50.11 ± 3.00 and 52.64 ± 3.00, respectively, fall within the reproducibility limits of the analytical method.

(ii) *ISO 11760 standard Coal Classification*: Except for sample CR5, which, as seen, was excluded from any classification, all other samples can be classified within the framework of ISO 11760 standard (Table 7).

Table 7 Classification of the samples according to ISO 11760 standard

Coalbed/ Layer	Sample	Vitrinite reflectance ($\bar{R}$r %)	Vitrinite content (mf, % by volume)	Ash yield (db, % by mass)	Classification		
					Rank	Petrographic composition	Ash yield
Barro Branco	CR1	0.70	62	42	Bituminous C	Moderately high vitrinite	High ash
	CR 3	0,90	59	43	Bituminous C	Medium vitrinite	High ash
	CR 4	0.70	74	32	Bituminous C	Moderately high vitrinite	High ash
	CR 6	0.60	83	23	Bituminous C	High vitrinite	Moderately high ash
Bonito	CR 2	0.70	45	46	Bituminous C	Medium vitrinite	High ash
	CR 7	0.70	39	51	Bituminous C	Low vitrinite	High ash
Upper Candiota		0.50	39	39	Subbituminous	Low vitrinite	High ash
Lower Candiota		0.50	38	53	Subbituminous	Low vitrinite	High ash
Lower Leão		0.40	51	30	Subbituminous	Medium vitrinite	Moderately high ash

mf - mineral free; db - "dry" basis

(iii) *ASTM D388 Coal Classification*: In addition to sample CR5, which was excluded because it did not meet the general definition of coal, sample Lower Candiota cannot be included in the ASTM classification because the inertinite content (56 %) far exceeds that of vitrinite (38 %). However, samples CR7 and Upper Candiota can be included in this system since the vitrinite contents, in both cases 39 %, are within the reproducibility limits allowed by the standard for petrographic analysis of maceral groups when compared to the inertinite contents of 32 % and 44 % respectively (Table 8). Consequently, with the exception of samples CR5 and Lower Candiota, all the other samples were in position to be classified under the ASTM D388 standard.

As a final and very important note on the application of this standard, we would like to emphasize that it uses values calculated on "mineral matter free" basis, and not on "ash free" basis. In fact, the frequent use of the "ash free" basis, for reasons of pure abusive and discretionary simplification, leads to erroneous classifications, as demonstrated in Table 8, when comparing two cases, in which the correct classifications are the ones whose calculations have been carried out in strict compliance with the agreed rules in the standard itself, i.e. carrying out all the calculations relating to the classification parameters on a "mineral matter free" basis. In the examples given, the wrong use of “ash free” instead of “mineral matter free” results in underestimating the rank category of most coals.

Table 8 Classification of the samples according to ASTM D388 standard coal classification by rank - Comparative results using "mineral matter free" basis versus "ash free" basis

Coalbed/ Layer	Sample	"Mineral matter free" basis					"Ash free" basis				
		Fixed carbon (dmmf, % by mass)	Volatile matter (dmmf, % by mass)	Gross calorific value (mmmf)		Classification	Fixed carbon (daf, % by mass,)	Volatile matter (daf, % by mass,)	Gross calorific value (maf)		Classification
				Btu/lb	MJ/kg				Btu/lb	MJ/kg	
Barro Branco	CR1	66	34	13232	30.77	High volatile B bituminous coal	60	40	12450	28.96	High volatile C bituminous coal
	CR 3	68	32	14136	33.26	High volatile A bituminous coal	63	37	13404	31.18	High volatile B bituminous coal
	CR 4	66	34	13447	31.78	High volatile B bituminous coal	60	40	12598	29.31	High volatile C bituminous coal
	CR 6	65	35	13614	31.66	High volatile B bituminous coal	62	38	13087	30.44	High volatile B bituminous coal
Bonito	CR 2	67	33	13532	32.29	High volatile B bituminous coal	61	39	12601	29.30	High volatile C bituminous coal
	CR 7	71	29	14494	34.22	Medium volatile bituminous coal	65	35	13419	31.20	High volatile B bituminous coal
Lower Leão		59	41	11542	26.84	High volatile C bituminous coal	57	43	11272	26.22	Subbituminous A coal

dmmf - "dry, mineral matter free" basis; mmmf - "moist, mineral matter free" basis; Moist refers to Bed moisture, i.e. Total moisture (or Moisture Holding Capacity / Equilibrium moisture)
daf - "dry, ash free" basis; maf - "moist, ash free" basis

4. Final remarks

A rock essentially composed by fossil sedimentary organic matter, coal is part of a wider group of natural organic rocks and products (which includes oil and natural gas, both conventional and unconventional), i.e. caustobioliths, which, given the genetic and the geological evolution of these materials, falls within the subdomain of Geology called Organic Petrology and Geochemistry.
It is precisely because of the geological evolution unit of organic sedimentary matter in a sedimentary basin, that coal can now be considered the standard rock for Organic Petrology and Geochemistry. This is the reason why the universal diagrams that quantitatively integrate all caustobioliths (van Krevelen Diagram - Fig. 5, and Karweil Diagram - Fig. 6) are built considering similar basic parameters used to classify coals. This is an additional reason to recognize a coal seam within the category of “unconventional reservoir” in the framework of the modern concept of "Petroleum System".

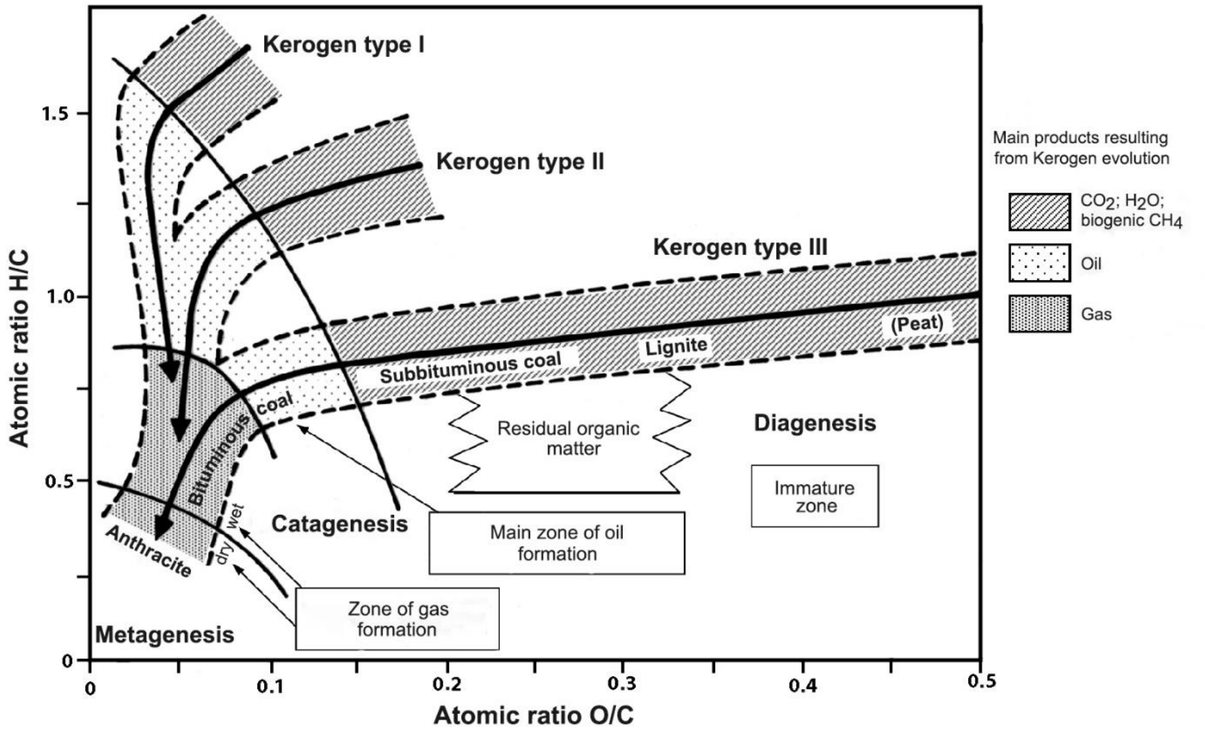


Fig. 5 van Krevelen diagram showing the different steps of coal and kerogen types, rank evolution, and the resulting products

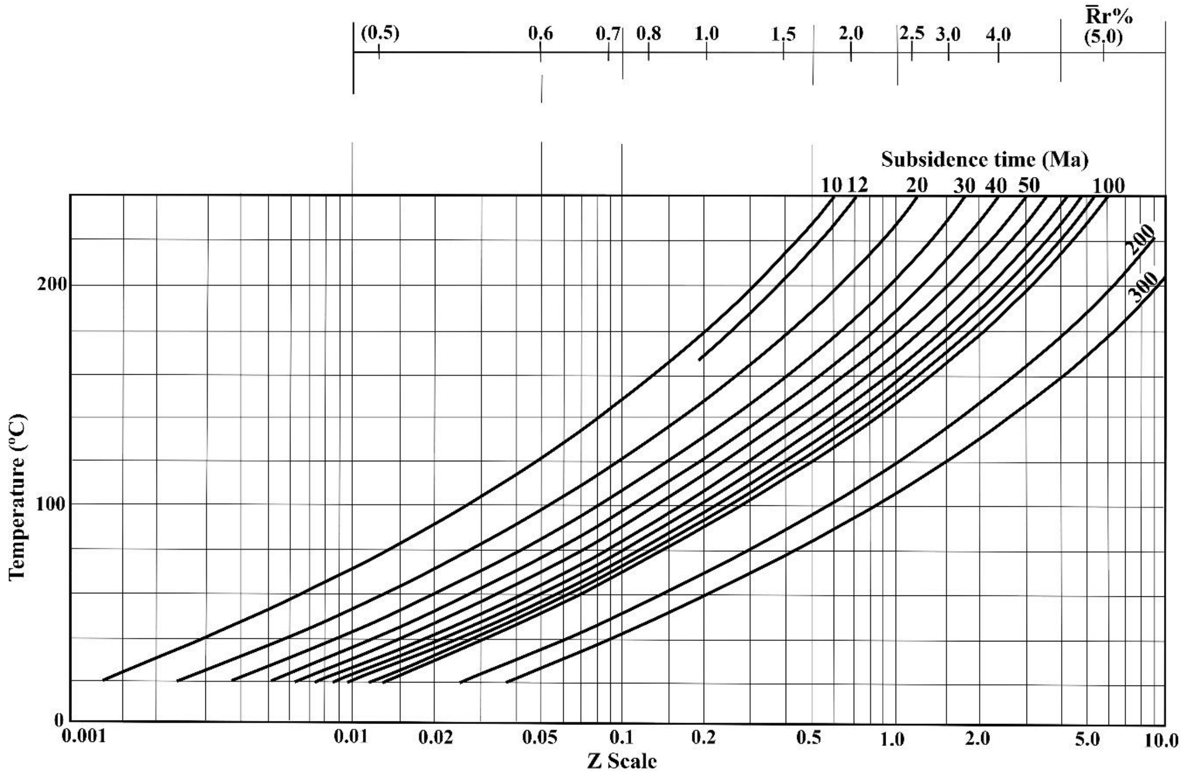


Fig. 6 Karweil diagram showing relationships among temperature, subsidence time and rank of coals. Rank scale: Vitrinite mean random reflectance percent ($\overline{R}r$ %) scale; according to Teichmüller (1971)

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Author contribution

M.J. Lemos de Sousa and Henrique Pinheiro designed the research and provided the redaction of the manuscript. C.F. Rodrigues, P.F. Moreira and José R. Lemes de Almeida provided sampling, sample preparation and coordinated the laboratory analyses and tests. C.F. Rodrigues and P.F. Moreira provided all calculations needed to classify the samples.

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Declarations

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Data availability: All data generated or analysed during this study are included in this published article**.**

Code Availability: Not applicable.

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Table 1

Click here to access/download;Table;Table 1.docx

Subject	Standard		
Total moisture (Bed moisture)	ISO 589:2008 - Hard coal: Determination of total moisture ISO 5068-1:2007 - Brown coals and lignites - Determination of moisture content. Part 1 - Indirect gravimetric method for total moisture		
Moisture Holding Capacity = Equilibrium moisture	ISO 1018:2023 - Coal: Determination of moisture-holding capacity		
Proximate analysis			ISO 17246:2024 - Coal and coke: Proximate analysis
Moisture in the analysis sample	ISO 11722:2013 - Solid mineral fuels - Hard coal: Determination of moisture in the general analysis test sample by drying in nitrogen ISO 5068-2:2007 - Brown coals and Lignites - Determination of moisture content. Part 2 - Indirect gravimetric method for moisture in the analysis sample		
Ash content	ISO 1171:2024 - Coal and coke: Determination of ash		
Volatile matter content			
Fixed carbon			
Ultimate analysis		ISO 29541:2025 - Coal and coke: Determination of total carbon, hydrogen and nitrogen - Instrumental method	ISO 17247:2020 - Coal and coke: Ultimate analysis
Carbon content	ISO 609:1996 - Solid mineral fuels: Determination of carbon and hydrogen - High temperature combustion method		
Hydrogen content			
Nitrogen content			
Oxygen content	(by difference)		
Gross Calorific Value	ISO 1928:2020 - Coal and coke: Determination of gross calorific value		
Calculations on different bases	ISO 1170:2020 - Coal and coke: Calculation of analyses to different bases		
Petrography (ICCP[1] System 1994)			
Vocabulary	ISO 7404-1: 2016 - Methods for the petrographic analysis of coals. Part 1: Vocabulary		
Sample preparation	ISO 7404-2: 2009 - Methods for the petrographic analysis of coals. Part 2: Methods of preparing coal samples		
Reflectance	ISO 7404-5: 2009 - Methods for the petrographic analysis of coals. Part 5: Method of determining microscopically the reflectance of vitrinite		
Maceral group	ISO 7404-3: 2009 - Methods for the petrographic analysis of coals. Part 3: Method of determining maceral group composition		
Hardgrove index	ISO 5074:2015 - Hard coal - Determination of Hardgrove grindability index		
Classification	ISO 11760:2018 - Classification of coals		
Sampling of coal in seam	ISO 14180:2023 - Coal - Guidance on the sampling of coal seams		

[1]ICCP – International Committee for Coal and Organic Petrology.

Class/Group	Fixed Carbon Limits (dmmf, %)		Volatile Matter Limits (dmmf, %)		Gross Calorific Value Limits (mmmf)				Agglomerating Character
					Btu/lb		MJ/kg[1]		
	Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less Than	Equal or Greater Than	Less Than	
Anthracitic									
Meta-anthracite	98	…	…	2	…	…	…	…	
Anthracite	92	98	2	8	…	…	…	…	nonagglomerating
Semianthracite[2]	86	92	8	14	…	…	…	…	
Bituminous									
Low volatile bituminous coal	78	86	14	22	…	…	…	…	
Medium volatile bituminous coal	69	78	22	31	…	…	…	…	
High volatile A bituminous coal	…	69	31	…	14 000[3]	…	32.557	…	commonly agglomerating[4]
High volatile B bituminous coal	…	…	…	…	13 000[3]	14 000	30.232	32.557	
High volatile C bituminous coal	…	…	…	…	11 500	13 000	26.743	30.232	
					10 500	11 500	24.418	26.743	agglomerating
Subbituminous									
Subbituminous A coal	…	…	…	…	10 500	11 500	24.418	26.743	
Subbituminous B coal	…	…	…	…	9 500	10 500	22.09	24.418	
Subbituminous C coal	…	…	…	…	8 300	9 500	19.30	22.09	nonagglomerating
Lignitic									
Lignite A	…	…	…	…	6 300	8 300	14.65	19.30	
Lignite B	…	…	…	…	…	6 300	…	14.65	

dmmf – "dry, mineral matter free" basis.
mmmf – "moist, mineral matter free", Moist refers to Bed moisture, i.e., Total moisture (or Moisture Holding Capacity/Equilibrium moisture).

[1]Megajoules per kilogram. To convert British thermal units per pound to megajoules per kilogram, multiply by 0.0023255.
[2]If agglomerating, classify in low volatile group of the bituminous class.
[3]Coals having 69 % or more fixed carbon on the dry, mineral-matter-free basis shall be classified according to fixed carbon, regardless of gross calorific value.
[4]It is recognized that there may be nonagglomerating varieties in these groups of the bituminous class, and that there are notable exceptions in the high volatile C bituminous group.

Table 3 Click here to access/download;Table;Table 3.docx

Subject	Standard
Total moisture (Bed moisture)	ASTM D3302/D3302M-22 - Standard Method for Total Moisture in Coal
Moisture Holding Capacity = Equilibrium moisture	ASTM D1412/D1412M-20 - Standard Method for Equilibrium Moisture of Coal at 96 to 97 Percent Relative Humidity and 30°C
Proximate analysis Moisture in the analysis sample Ash content Volatile matter content Fixed carbon	ASTM D7582-24 - Standard Methods for Proximate Analysis of Coal and Coke by Macro Thermogravimetric Analysis[1]
Ultimate analysis Carbon content Hydrogen content Nitrogen content	ASTM D5373-21 - Standard Test Methods for Determination of Carbon, Hydrogen and Nitrogen in Analysis Samples of Coal and Carbon in Analysis Samples of Coal and Coke
Oxygen content	(by difference)
Total sulfur content	ASTM D4239-18 - Standard Test Method for Sulfur in the Analysis Sample of Coal and Coke Using High-Temperature Tube Furnace Combustion
Ash composition analysis	ASTM D4326-21 - Standard Test Method for Major and Minor Elements in Coal Ash by X-Ray Fluorescence
Gross Calorific Value	ASTM D5865/D5865-19 - Standard Test Method for Gross Calorific Value of Coal and Coke[2]
Sample preparation for analysis	ASTM D2013/D2013M-24 - Standard Practice for Preparing Coal Samples for Analysis
Calculations on different bases	ASTM D3180-15(2023) - Standard Practice for Calculating Coal and Coke Analyses from As-Determined to Different Bases
Coal Grindability Test	ASTM D409/D409M-16 - Standard Test Method for Grindability of Coal by the Hardgrove-Machine Method
Coal Shatter Test	ASTM D440-07(2019) - Standard Method of Drop Shatter Test for Coal
Coal Tumbler Test	ASTM D441-07(2019) - Standard Test Method of Tumbler Test for Coal
Terminology	ASTM D121-24 – Standard Terminology of Coal and Coke
Classification	ASTM (by rank) - ASTM D388-23 - Standard Classification of Coals by Rank
Sampling of Coal in Seam	ASTM D4596-22 - Standard Practice for Collection of Channel Samples of Coal in a Mine
Sampling of Coal from Borehole Cores	ASTM D5192/D5192M-22 - Standard Practice for Collection of Coal Sample from Core

[1]In the ASTM system there is an alternative method for the determination of Moisture in the analysis sample.

[2]In the ASTM system there are various alternative methods for the determination of Gross Calorific Value.

Coalbed/ Layer	Sample	Total moisture (%, by mass)	Moisture in the analysis sample (% by mass)	Proximate analysis (db, % by mass)		
				Ash	Volatile matter	Fixed carbon
Barro Branco	CR1	7.33	1.42	40.93	23.37	35.70
	CR 3	2.36	0.68	41.67	21.59	36.74
	CR 4	3.93	0.74	31.04	27.78	41.18
	CR 6	5.63	1.53	22.66	29.59	47.75
Bonito	CR 2	2.25	1.10	44.57	21.73	33.70
	CR 5	2.81	1.12	54.34	17.05	28.61
	CR 7	2.88	1.05	50.11	17.43	32.46
Upper Candiota		16.7	7.8	38.72	25.16	36.12
Lower Candiota		15.9	5.2	52.64	19.62	27.74
Lower Leão		12.6	9.6	29.87	30.31	39.82

db - "dry" basis

Coalbed/ Layer	Sample	Ultimate analysis (db, % by mass)					SO_3 in ash (db, % by mass)	Gross Calorific Value (aa, Btu/lb)
		C	H	N	O	St		
Barro Branco	CR1	48.09	3.73	1.05	1.59	4.61	0.275	8221
	CR 3	47.84	3.42	1.17	<0.10	5.80	3.261	8087
	CR 4	51.24	3.78	1.30	<0.10	12.53	0.341	9135
	CR 6	62.90	4.56	1.55	0.23	8.10	0.287	10735
Bonito	CR 2	41.82	3.07	1.16	<0.10	9.28	3.105	7195
	CR 5	37.84	2.83	0.84	<0.10	4.06	1.842	6226
	CR 7	42.90	3.03	0.91	<0.10	3.57	1.647	7018
Upper Candiota		48.67	2.97	0.60	8.38	0.66	2.48	7691
Lower Candiota		35.53	2.33	0.73	7.92	0.85	0.60	5808
Lower Leão		53.44	3.32	0.95	7.46	4.97	3.09	8616

db - "dry" basis; aa - "as analysed" basis = ad - "as determined" basis

Coalbed/ Layer	Sample	$\bar{R}r \pm \sigma$ (%)	Maceral groups analysis (mf, % by volume)		
			Vitrinite	**Liptinite**	**Inertinite**
Barro Branco	CR1	0.66±0.08	62	17	21
	CR 3	0.87±0.08	60	12	28
	CR 4	0.66±0.04	74	13	13
	CR 6	0.64±0.06	83	10	7
Bonito	CR 2	0.70±0.05	45	28	27
	CR 5	0.68±0.07	47	23	30
	CR 7	0.70±0.06	39	29	32
Upper Candiota		0.46±0.03	39	17	44
Lower Candiota		0.45±0.04	38	7	56
Lower Leão		0.43±0.03	51	16	33

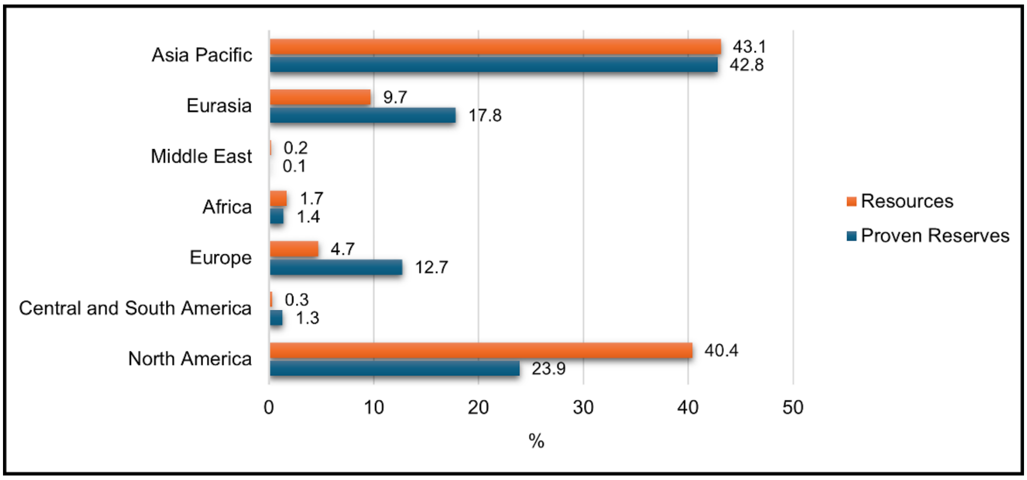
mf - mineral free

Coalbed/ Layer	Sample	Vitrinite reflectance ($\bar{R}r$ %)	Vitrinite content (mf, % by volume)	Ash yield (db, % by mass)	Classification		
					Rank	Petrographic composition	Ash yield
Barro Branco	CR1	0.70	62	42	Bituminous C	Moderately high vitrinite	High ash
	CR 3	0,90	59	43	Bituminous C	Medium vitrinite	High ash
	CR 4	0.70	74	32	Bituminous C	Moderately high vitrinite	High ash
	CR 6	0.60	83	23	Bituminous C	High vitrinite	Moderately high ash
Bonito	CR 2	0.70	45	46	Bituminous C	Medium vitrinite	High ash
	CR 7	0.70	39	51	Bituminous C	Low vitrinite	High ash
Upper Candiota		0.50	39	39	Subbituminous	Low vitrinite	High ash
Lower Candiota		0.50	38	53	Subbituminous	Low vitrinite	High ash
Lower Leão		0.40	51	30	Subbituminous	Medium vitrinite	Moderately high ash

mf - mineral free; db - "dry" basis

Coalbed/ Layer	Sample	"Mineral matter free" basis					"Ash free" basis				
		Fixed carbon (dmmf, % by mass)	Volatile matter (dmmf, % by mass)	Gross calorific value (mmmf)		Classification	Fixed carbon (daf, % by mass,)	Volatile matter (daf, % by mass,)	Gross calorific value (maf)		Classification
				Btu/lb	MJ/kg				Btu/lb	MJ/kg	
Barro Branco	CR1	66	34	13232	30.77	High volatile B bituminous coal	60	40	12450	28.96	High volatile C bituminous coal
	CR 3	68	32	14136	33.26	High volatile A bituminous coal	63	37	13404	31.18	High volatile B bituminous coal
	CR 4	66	34	13447	31.78	High volatile B bituminous coal	60	40	12598	29.31	High volatile C bituminous coal
	CR 6	65	35	13614	31.66	High volatile B bituminous coal	62	38	13087	30.44	High volatile B bituminous coal
Bonito	CR 2	67	33	13532	32.29	High volatile B bituminous coal	61	39	12601	29.30	High volatile C bituminous coal
	CR 7	71	29	14494	34.22	Medium volatile bituminous coal	65	35	13419	31.20	High volatile B bituminous coal
Lower Leão		59	41	11542	26.84	High volatile C bituminous coal	57	43	11272	26.22	Subbituminous A coal

dmmf - "dry, mineral matter free" basis; mmmf - "moist, mineral matter free" basis; Moist refers to Bed moisture, i.e. Total moisture (or Moisture Holding Capacity / Equilibrium moisture)
daf - "dry, ash free" basis; maf - "moist, ash free" basis



Coal (billion tonnes)	Proven Reserves		Resources	
	Billion tonnes	**%**	**Billion tonnes**	**%**
North America	257	23.9	8 387	40.4
Central and South America	14	1.3	60	0.3
Europe	137	12.7	980	4.7
Africa	15	1.4	343	1.7
Middle East	1	0.1	41	0.2
Eurasia[1]	191	17.8	2 015	9.7
Asia Pacific[2]	460	42.8	8 950	43.1
World	**1 075**	**100**	**20 776**	**100**

[1]Caspian regional grouping and the Russian Federation (Russia).

[2]Southeast Asia regional grouping and Australia, Bangladesh, Democratic People's Republic of Korea (North Korea), India, Japan, Korea, Mongolia, Nepal, New Zealand, Pakistan, The People's Republic of China (China), Sri Lanka, Chinese Taipei, and other Asia Pacific countries and territories.

Fig. 2

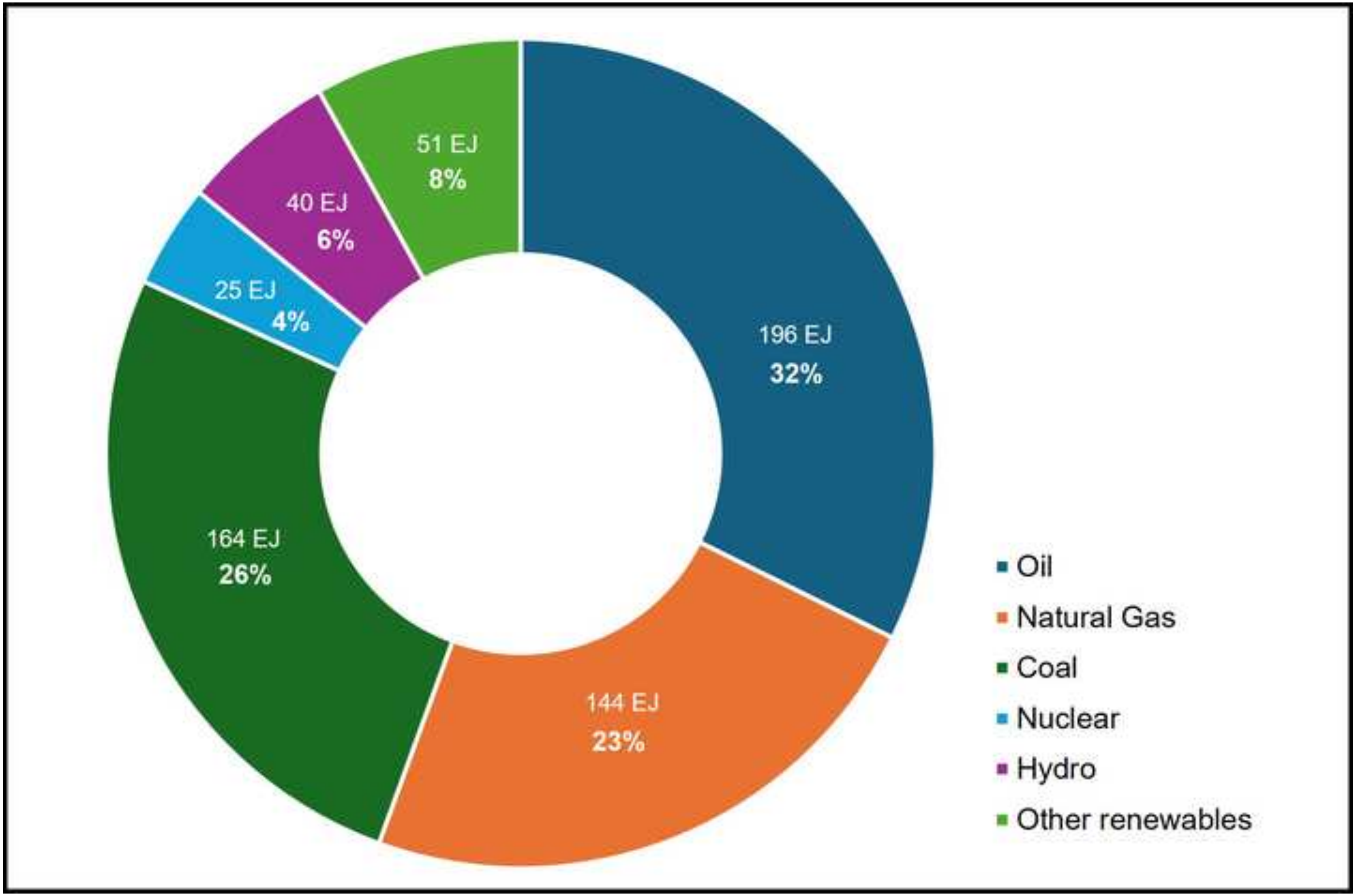
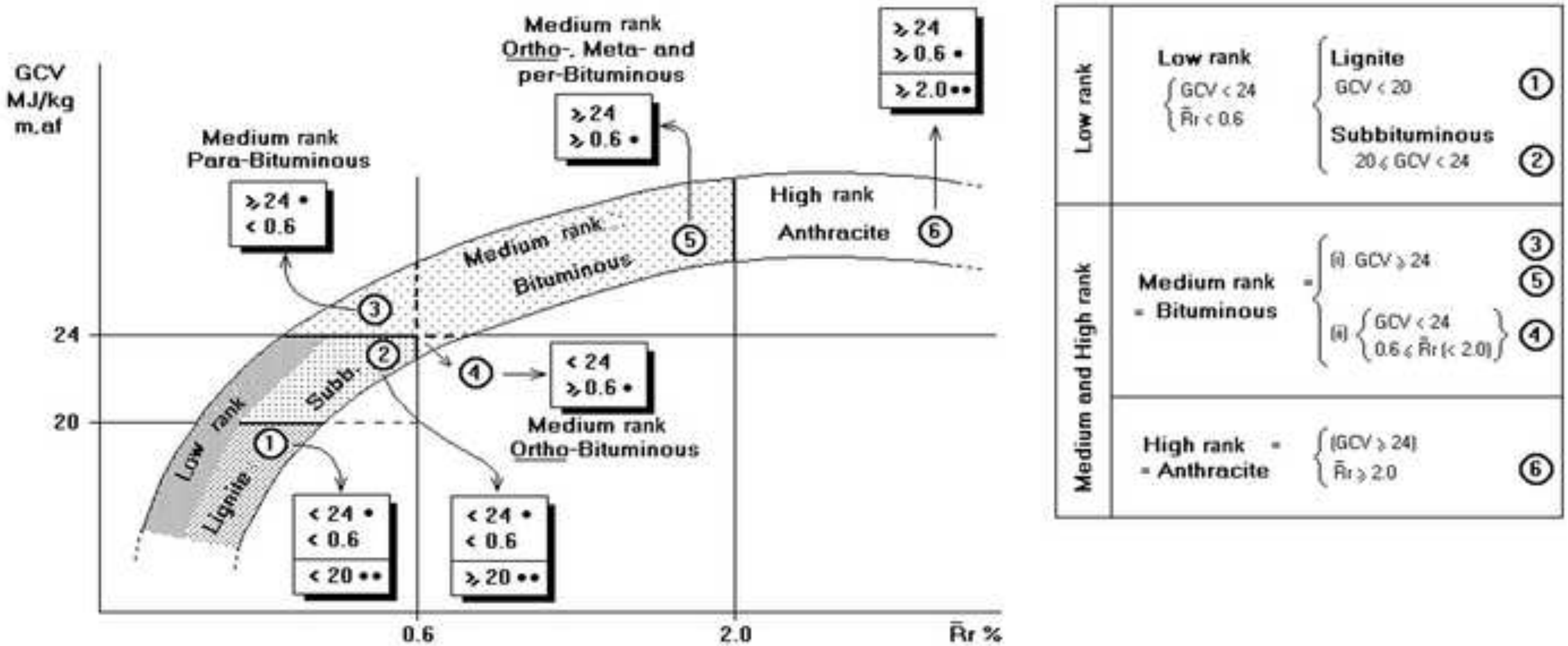

196 EJ
32%
144 EJ
23%
164 EJ
26%
25 EJ
4%
40 EJ
6%
51 EJ
8%
Oil
Natural Gas
Coal
Nuclear
Hydro
Other renewables

Fig. 3a

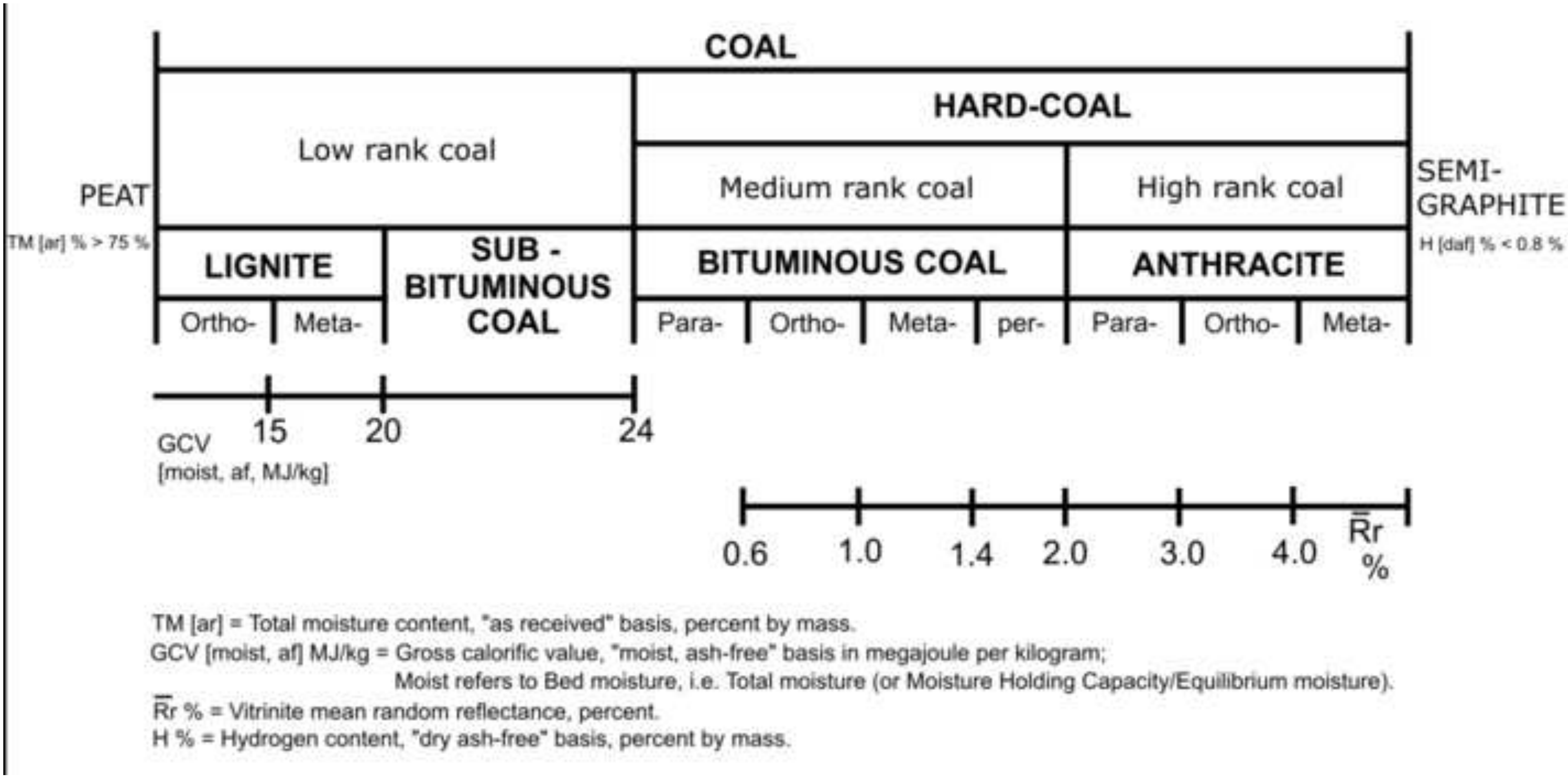
Click here to access/download;Figure;Fig. 3a.tif



TM [ar] = Total moisture content, "as received" basis, percent by mass.
GCV [moist, af] MJ/kg = Gross calorific value, "moist, ash-free" basis in megajoule per kilogram;
Moist refers to Bed moisture, i.e. Total moisture (or Moisture Holding Capacity/Equilibrium moisture).
R̄r % = Vitrinite mean random reflectance, percent.
H % = Hydrogen content, "dry ash-free" basis, percent by mass.

Fig. 3b

Click here to access/download;Figure;Fig. 3b.tiff



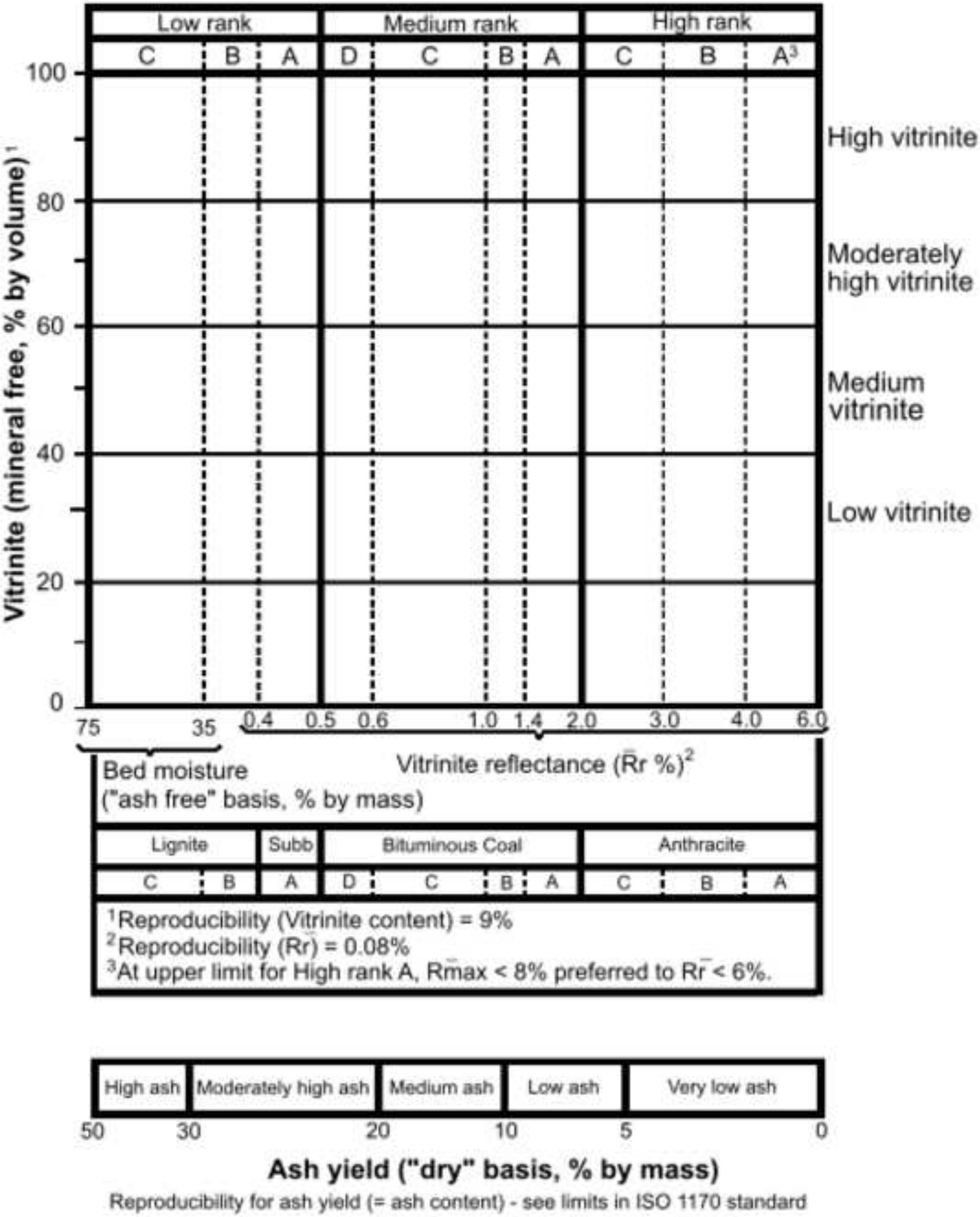

Low rank
Medium rank
High rank
C B A D C B A C B A3
High vitrinite
Moderately high vitrinite
Medium vitrinite
Low vitrinite
Vitrinite (mineral free, % by volume)1
100
80
60
40
20
0
75 35
0.4 0.5 0.6 1.0 1.4 2.0 3.0 4.0 6.0
Bed moisture ("ash free" basis, % by mass)
Vitrinite reflectance (R̄r %)2
Lignite
Subb
Bituminous Coal
Anthracite
C B A D C B A C B A
1Reproducibility (Vitrinite content) = 9%
2Reproducibility (R̄r) = 0.08%
3At upper limit for High rank A, R̄max < 8% preferred to R̄r < 6%.
High ash
Moderately high ash
Medium ash
Low ash
Very low ash
50 30 20 10 5 0
Ash yield ("dry" basis, % by mass)
Reproducibility for ash yield (= ash content) - see limits in ISO 1170 standard

Fig. 5

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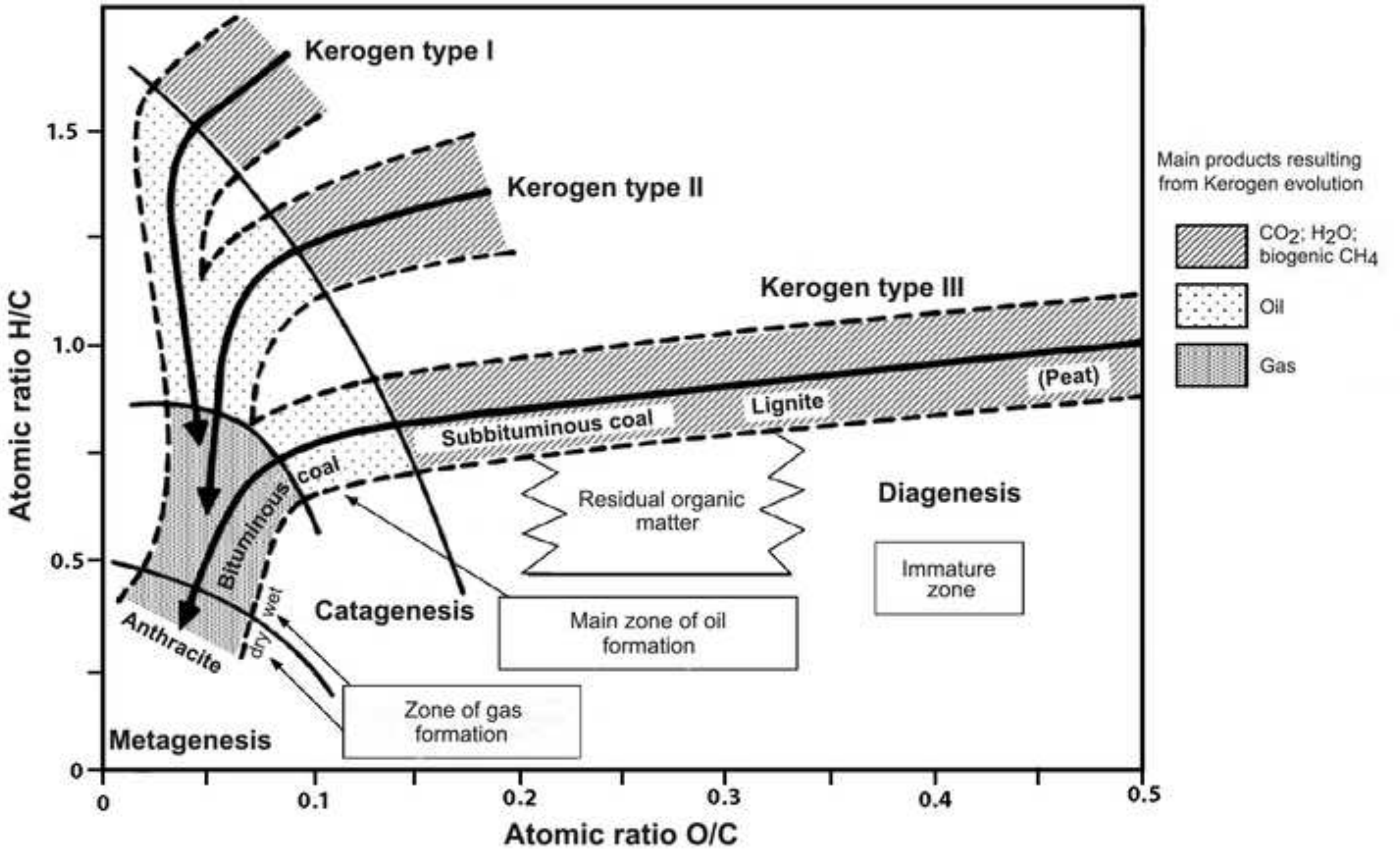
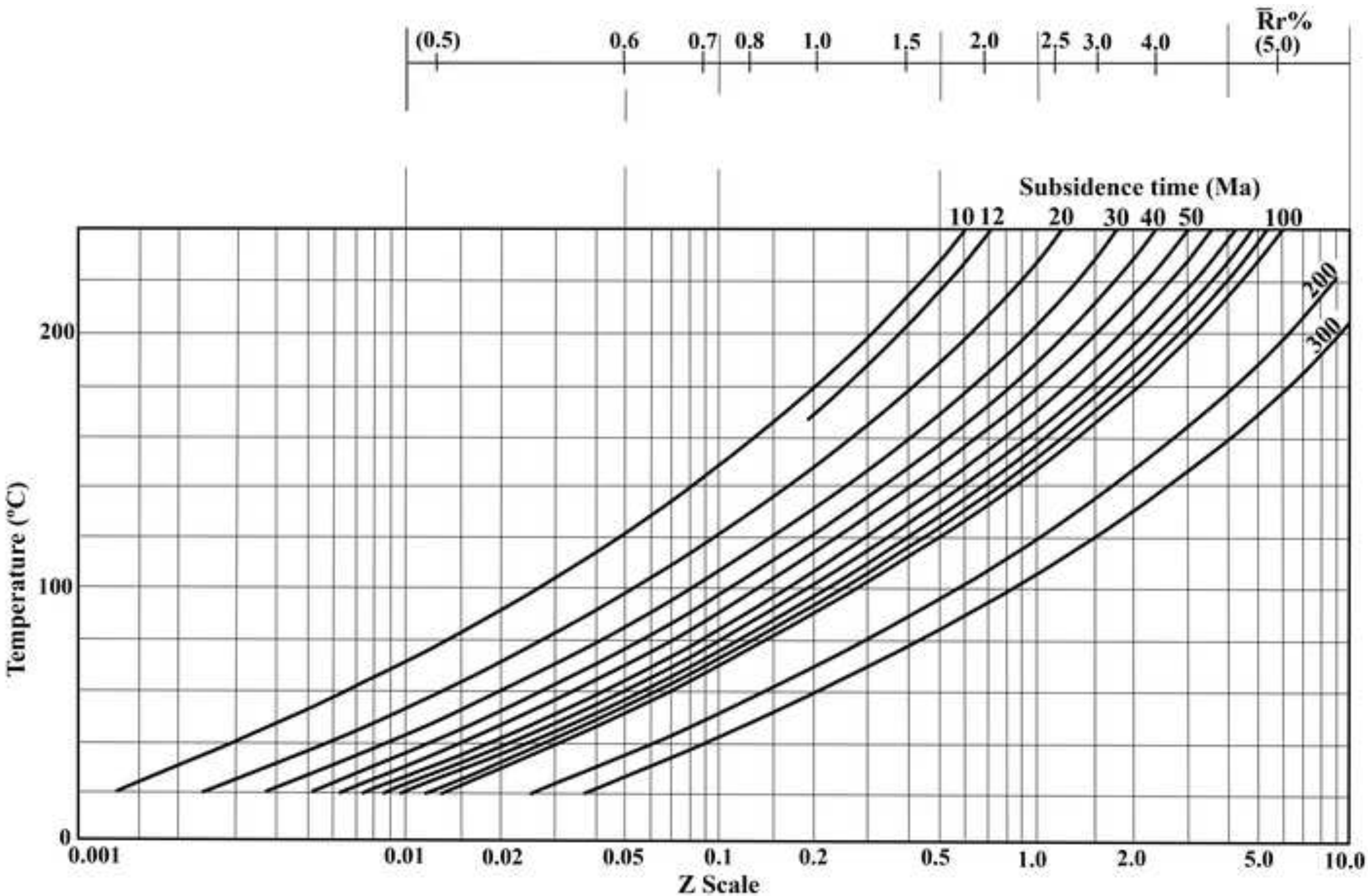


Fig. 6


R̄r%
(0.5)
0.6
0.7
0.8
1.0
1.5
2.0
2.5
3.0
4.0
(5.0)
Subsidence time (Ma)
10 12 20 30 40 50 100
200
300
Temperature (°C)
0
100
200
0.001
0.01
0.02
0.05
0.1
0.2
0.5
1.0
2.0
5.0
10.0
Z Scale