Bulgarian Shale Gas Potential Estimate

Georgi V. Georgiev

Abstract On the base of comprehensive analyses of geological structure and sedimentary basins of Bulgaria, six organic-enrich dark-shale-dominated intervals have been identified. Besides Silurian and Etropole shales (earlier determined), another four newly defined shale intervals are Lower Carboniferous, Lower Jurassic, Oligocene and Oligocene–Middle Miocene. The optimum area for each of them is outlined. The shale gas estimate is made by up-to-date methodology with consideration of the determined critical parameters. From the estimated six targets, only the Lower Carboniferous shales (in the pointed western zone) and both Jurassic shaly intervals may present moderate shale gas interest.

Keywords Critical parameters, Estimation, Methodology, Resources, Shale gas

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1 Introduction

In Europe shale gas exploration is still in its early phase. In many European countries there is a strong interest in the identification of potential shale gas objectives. However, most of the countries have no resources, or estimation of a possible resource is poor, or the estimations have a very wide range of uncertainty. Often there are serious differences in methodology, fundamental assumptions, quality and quantity of the underlying geological information. By these reasons or by dread from fracking technology and harmful environmental impact in many countries the drilling for shale gas is banned. Only in 6 countries the shale gas exploration and development is presently permitted, in other 15 countries have no present activities and not expected in near future.

Bulgaria has a moratorium on unconventional hydrocarbon exploration since 2012. In June 2011 the Bulgarian government granted Chevron with 5-year shale gas exploration permit for the 4,400-km^2 Novi Pazar block in NE Bulgaria (Fig. 1). After that the public opposition to shale gas development has increased dramatically over fear of groundwater contamination in this Dobrudja agricultural region, which is very valuable for Bulgaria. In January 2012 the government banned all shale gas exploration and production, whether or not it involves hydraulic fracturing, and withdraws a granted exploration license to Chevron [1].

In Bulgaria some shale resource assessments were reported to be underway in the period 2011–2013 [2–9]. Two shale resource targets, namely Silurian shale and Jurassic Etropole shale, have been identified and assessed by Chevron, some national institutions, and IEA/ARI (2013).

For the 4,400-km^2 Novi Pazar block in NE Bulgaria (Fig. 1) have been publically announced shale gas resources of about 0.3–1.0 Tcm (11–35 Tcf) in the Silurian–Devonian silty shale, which is up to 2 km thick, 800–2,800 m deep and has 3.5% sapropelic organic content, as it is reported in the study of Shale Gas Research Group [3].

Risked, technically recoverable shale resources in the Moesian Platform region of Bulgaria are estimated by EIA/ARI in 2013 [8, 9] to be approximately 16 Tcf (0.45 Tcm) of shale gas and 0.2 billion barrels of shale condensate.

US-based TransAtlantic Petroleum, through its subsidiary Direct Petroleum Bulgaria, holds an exploration license at the 2,300-km^2 Lovech block, later reduced in Koynare concession block (650 km^2), located in the western part of North Bulgaria (Fig. 1) [4, 5]. Many years ago the well Peshtene 5 in Lovech block flowed gas at an unstimulated rate of 15,000 m^3/d from a conventional interval in the Middle Jurassic Etropole Fm. In 2011 Direct Petroleum drilled nearby a new Peshtene 11 exploration well to core and test the Etropole shale. The well was not fracture stimulated as Bulgaria has a ban in place [4, 5, 8].

Recently an up-to-date and comprehensive study for shale gas potential at Lower Carboniferous shales, but based on limited geological information, has been accomplished [10]. The technically recoverable shale gas resources (TRR) have been estimated rather optimistic to be approximately 58 Tcf (1.66 Tcm).

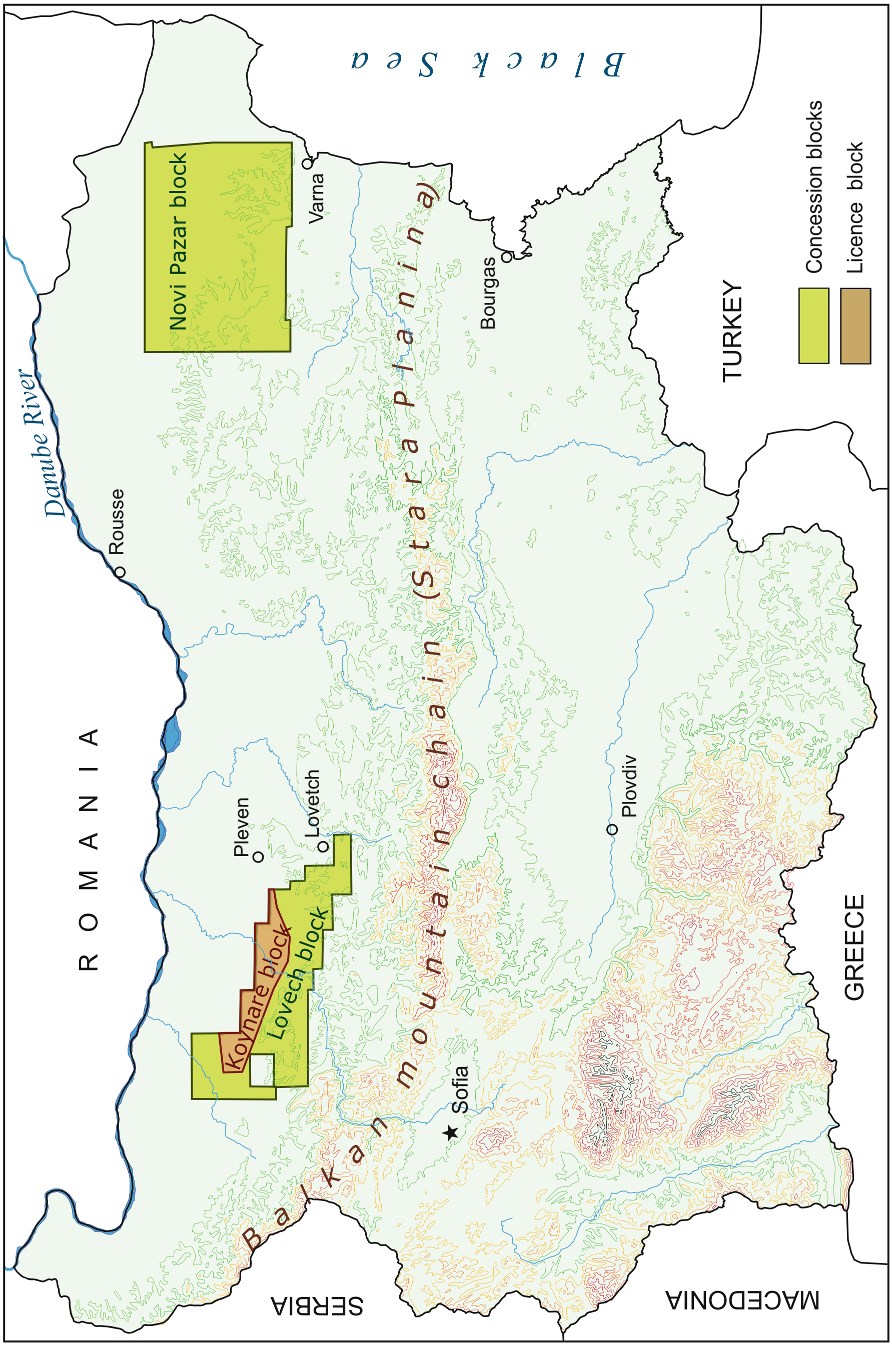


Fig. 1 General map of Bulgaria with location of some license and concession blocks

Obviously, the above mentioned assessments are based on (1) poor geological information and knowledge, (2) strongly exaggerated parameters (not proved by available geological, geophysical, and analytical data), and (3) general approaches and methodologies. They also do not comprise all possible organic-enriched dark-shale intervals in the sedimentary successions of Bulgaria. Therefore, the announced reserves are not realistic.

The present shale gas potential estimate of Bulgaria is based on (1) all available geological–geophysical data from hydrocarbon exploration, (2) analytical results from core-cutting analyses and (3) up-to-date assessment methodology [11], especially taking into consideration some additional critical parameters for shale gas resources, described below.

2 Geological Overview

Bulgaria is located on the European continental margin and covers parts of the northern periphery of the Alpine orogen and its foreland (Fig. 2).

Bulgaria has an extremely varied geology mostly developed as a result of the Alpine orogeny [12–15] and related to the Mesozoic and Cenozoic history of the northern Tethyan margin in the eastern Mediterranean region.

Two major geological domains or tectonic units are differentiated in the onshore territory of Bulgaria (Figs. 2 and 3):

- The Moesian Platform, covering the northern half of the country, dominated by thick (4–13 km) Phanerozoic sedimentary succession and block-faulted uplifts and depressions, horsts, and grabens of different ranks
- The Alpine orogenic belt that extends along the southern half of the country, dominated by igneous and metamorphic rocks and represented by mountain ranges and internal lowlands arranged in a WNW-ESE direction

The Moesian Platform forms part of the northern Peri-Tethyan shelf system. In southeastern Bulgaria, in the area of the eastern Srednogorie–Balkan zone, the southern margin of the Moesian Platform was repeatedly affected by Mesozoic rifting cycles; these were interrupted and followed by compressional events, causing strong shortening of this margin, and ultimately it is overprinting by the Alpine orogen [16].

The Moesian Platform is a foreland basin that stretches between Southern Carpathians and Balkans (Fig. 1). The Platform is overthrusted by the Balkan thrust system to the south, while the Carpathian thrust system forms the northern boundary; both are Cenozoic features related to Alpine tectonics. The orogeny of the Balkanides ceased in the Eocene, whereas the Carpathians stopped their collision in the Miocene, when the platform was finally shaped [16]. To the NE the Moesian Platform is separated from the Scythian Platform by the North Dobrogea Orogen. The easterly platform part is downwarped to the Black Sea. In contrast to

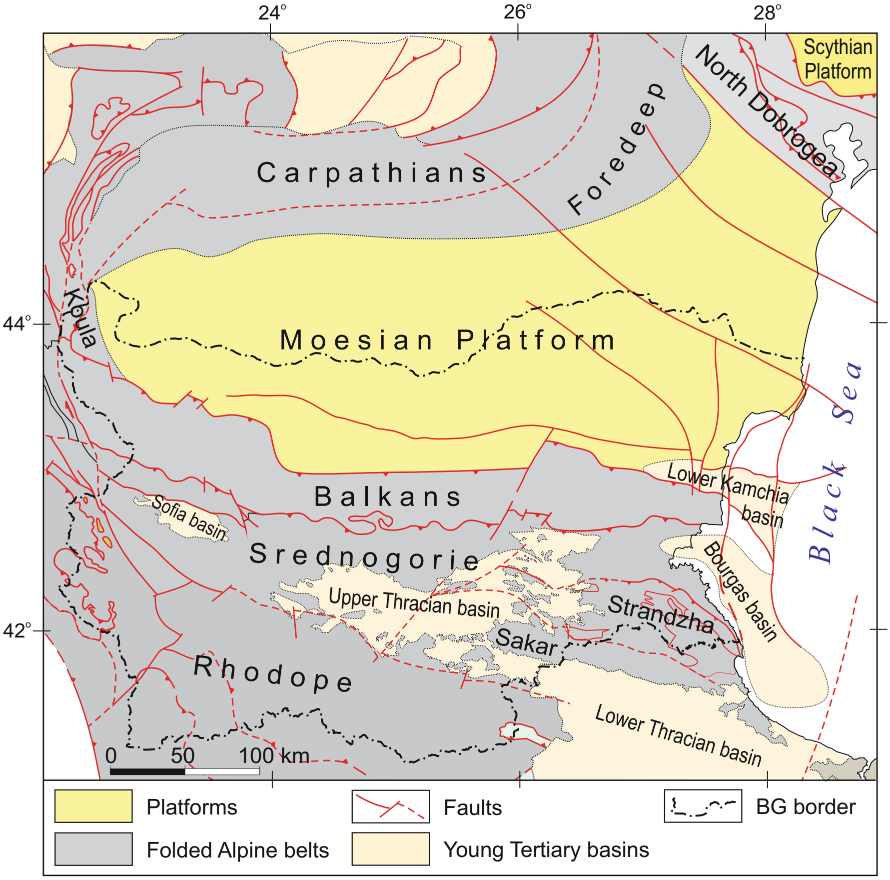


Fig. 2 Simplified regional tectonic sketch, showing Moesian Platform location (modified from Dabovski and Zagorchev [28])

surrounding thrust-fold belts, the Moesian Platform has a flat topography with typical elevation only up to 200 m above sea level. The geological boundary of the platform is well defined by the leading edge of the surrounding Alpine thrust belts.

Only the southern part of the Moesian Platform belongs to Bulgaria, much of it is situated in Romania.

The Moesian Platform is a stable continental block, comprises subhorizontal Paleozoic, Mesozoic, and Neozoic sediments with a total thickness of 4–13 km overlying a pre-Paleozoic metamorphic basement. It consists of several superimposed basins: Cambrian–Early Devonian, Middle Devonian–Permian, Triassic, Early–Middle Jurassic, Late Jurassic–Mid-Cretaceous, Late Cretaceous Paleogene, and Neogene–Quaternary. The structural pattern over the platform is

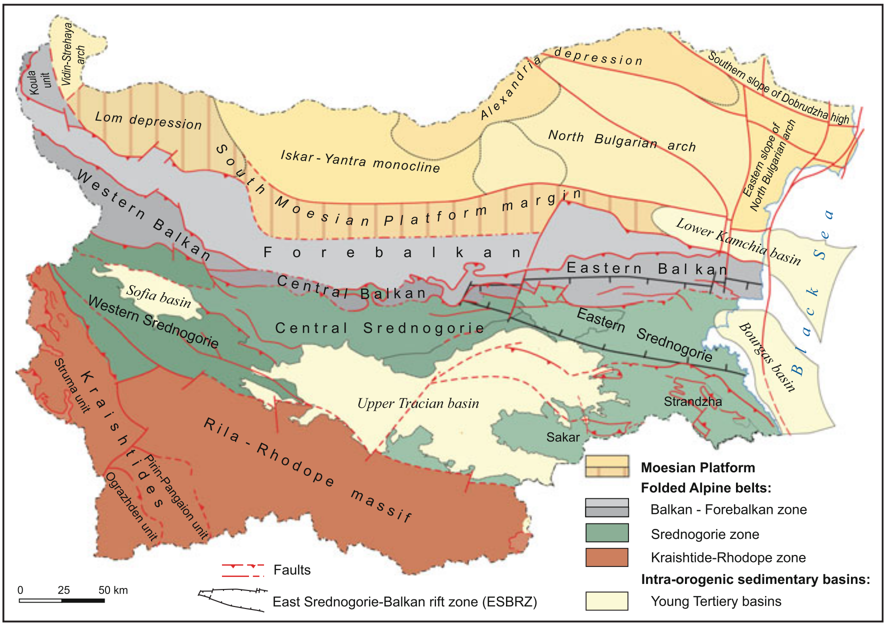


Fig. 3 Simplified tectonic sketch of Bulgaria (by Georgiev and Dabovski [43]; Dabovski et al. [15]; modified)

typical of cover deformation over reactivated basement block faults. In the southern platform, margin deformation appears to be similar to, but less intense, that in the adjacent Alpine thrusts belt: the main structures are reverse faults or not so steep to sloping thrusts and associated uplifts.

The complete Phanerozoic sedimentary succession in the Bulgarian part of the Moesian Platform thicken from about 4 km in NE Bulgaria to about 12–13 km in NW Bulgaria (Fig. 2). Major unconformities occur at the base of the Triassic, Middle Jurassic, Mid-Cretaceous, and Middle Eocene which are correlated with the main compressive events of the Alpine fold-and-thrust belt. The compression culminated toward the end of the Early Cretaceous and during the Middle Eocene [16].

The angular unconformity developed at the Triassic–Jurassic boundary is important from a tectonic and petroleum point of view [17]: below it, the Triassic successions are weakly deformed everywhere into open folds and faulted block structures, which were interpreted [18] as ramp folds above shallow-dipping thrusts in the frontal parts of a Late Triassic orogen. The overlying Jurassic, Lower and Upper Cretaceous sediments are nearly horizontal (dips of 1–4°), and normal faults, horsts and grabens dominate the structural pattern.

In the Bulgarian part of the Moesian Platform are recognized eight structural elements (Fig. 2). Some of these structures extend and have a wider development in Romania. The major tectonic units are North Bulgarian arch, Iskar–Yantra monocline and southern platform margin including Lom depression also. The most relevant are described below:

The North Bulgarian arch formed as a result of continuous Mesozoic and Cenozoic uplift (at least since Late Triassic). The arch is outlined by the Upper Jurassic–Lower Cretaceous carbonate complex, which crops out directly on the surface. The Upper Jurassic–Lower Cretaceous carbonate succession in the central arch is underlain by very thin Middle Jurassic clastic sediments that rest with angular unconformity upon weakly folded Devonian, Carboniferous and Permian rocks [19]. In the eastern arch slope, known as Varna monocline, the Upper Jurassic–Lower Cretaceous complexes dip gently to the east and southeast under a thick cover of Paleogene and Neogene deposits. Block faulting, stairs, terraces, horsts and grabens of different ranks are typical structural features of the arch.

The Lom depression comprises an almost continuous succession of Jurassic, Cretaceous and Tertiary sediments with a total thickness of over 5 km. They consist of shallow to relatively deep marine sediments that record a continuous subsidence of the western part of the Moesian Platform throughout post-Triassic Mesozoic and Cenozoic times.

The Iskar–Yantra monocline is a slope transition zone between North Bulgarian arch and Lom depression, about 140 km long. It is featured by the Upper Jurassic–Lower Cretaceous carbonate complex, which develops a wide, gentle monocline dipping to the west and south. The monocline complex covers unconformably the complex mosaic of folded, faulted, and eroded in different extent Triassic and Upper Paleozoic sediments.

The Alexandria depression developed during the Middle–Late Triassic. Only a small SE part of it spreads into NE Bulgaria.

The Southern platform margin includes the south-dipping downfaulted slope of the Moesian Platform in front of and below the thrust slices of the Alpine thrust front (Fore-Balkan). The Mesozoic section comprises a thick Triassic to Upper Cretaceous clastic and predominantly carbonated rocks; locally, the Upper Jurassic–Lower Cretaceous shallow marine sediments interfinger with deeper-marine foredeep successions. They are locally overlain by Paleogene and Neogene deposits. The structural pattern is dominated by a southward-dipping monocline, locally (and gently) deformed by north-verging thrusts.

The Lower Kamchia basin is filled up by Tertiary sediments with a total thickness of 3–5 km. Only a small part of its westernmost periphery spread onshore, whereas to the east, the basin widens, deepens, and accumulates younger sediments offshore in the Black Sea. The tectonic setting of this basin is a subject of debate: a marginal foredeep in front of the Alpine orogen, or a deep western Tertiary embayment jutting out of the Western Black Sea basin [20, 21].

Five tectonic units in the Bulgarian part of the Moesian Platform show an increase in sedimentary thickness: the Southern Moesian Platform Margin (SMPM); the Lom depression, which is considered lately as the westernmost zone of SMPM [14, 22]; the Varna monocline (eastern slope of the North Bulgarian arch); the Lower Kamchia basin; and the Alexandria depression.

The Alpine orogenic belt consists of predominantly north-verging thrust sheets and fold structures that resulted from multiphase collisions and related compressional events in the Late Triassic, Middle Jurassic, Mid-Cretaceous, Late Cretaceous, and Middle Eocene time. These were followed by crustal extension, collapse of the orogen, and development of a system of Mesozoic–Tertiary intraorogenic rift-type basins.

The Alpine orogenic system occupies in Bulgaria the area southward of the Moesian Platform. It is subdivided into three tectonic zones: the Balkanides, the Srednogorie, and the Kraishtide–Rhodope zone (Figs. 2 and 3). Cenozoic intraorogenic basins occur within the Srednogorie and Kraishtide–Rhodope zones, and its continental and shallow marine sediments extend along restricted areas.

The Balkanides form the northern external part of the Alpine orogen. To the north it overthrusts the Moesian Platform. The southern boundary with the Srednogorie zone is likewise a system of north-verging Middle Eocene reverse faults and thrusts, largely covered by Tertiary deposits of the Sub-Balkan graben system. The typical features of the Balkanides are (1) wide occurrence of Triassic and Jurassic–Lower Cretaceous platform carbonates in continuity with the Moesian Platform, (2) development of Upper Jurassic–Lower Cretaceous and Upper Cretaceous–Paleocene flysch sedimentation, (3) almost full absence of Mesozoic magmatic products, and (4) main and final compressional events toward the end of the Middle Eocene, preceded by Late Cretaceous, Mid-Cretaceous, and weak Triassic deformations.

The Balkanides are subdivided into two tectonic zones: Forebalkan and Balkan range.

The Forebalkan occupies the northern frontal part of the Balkan zone. Its principal structural elements are north-verging folds and associated reverse faults. The Mesozoic sections begin with Peri-Tethyan (Balkanide) Triassic type, followed by Lower and Middle Jurassic continental to shallow marine sediments and Upper Jurassic–Lower Cretaceous carbonate and flysch sedimentary rocks. The younger rocks are exposed mainly in the central and eastern parts of the zone. The deformation phases are synchronous with those in the Balkan unit but are much less intensive. The main compressional events are recorded in Mid-Cretaceous and Middle Eocene times. In the Forebalkan three longitudinal units are distinguished by differences in sedimentary succession and tectonic and morphologic features [23]. They are separated by transversally oriented small depressions. The Western Forebalkan is typically a post-platform orogen [24], thrusted during the Middle Eocene (Illyrian phase). In the Central Forebalkan, a very thick Upper Jurassic flysch sequence (up to 3 km) conditioned the thrust-tectonic processes in Mid-Cretaceous (Austrian phase) and Middle Eocene (Illyrian phase). In the Eastern Forebalkan, Mid-Cretaceous (Austrian phase) salt tectonics occurred, facilitated by a thick succession (above 1,000 m) of Upper Triassic evaporites [25].

The Balkan range is the easternmost Alpidic chain of SE Europe. It is strongly folded and overthrusted to the north. The sedimentary strata of this fold belt become younger toward the east: plutonic and volcanic rocks and of crystalline schists in the western part, Paleozoic in the central zone and Mesozoic-Early Tertiary in the eastern part. The Balkan fold belt is subdivided into three tectonic units: West Balkan, Central Balkan and East Balkan.

The West Balkan has a largely exposed Vendian–Cambrian greenschist basement (ophiolite, island-arc and olistostrome assemblages). It is locally overlain by sediments with large stratigraphic range: Ordovician–Eocene. The main compressional deformation events have a Late Cretaceous age. The northern boundary of the unit records Middle Eocene thrusting over the Moesian platform.

The Central Balkan unit has a pre-Mesozoic basement mainly exposed in the southern, uppermost thrust slices. These are overlain by Permian–Early Cretaceous sedimentary successions, locally overlain by Upper Cretaceous–Paleocene carbonates and Lower–Middle Eocene continental sediments. Specific feature is the presence of a thick Late Jurassic–Early Cretaceous flysch succession that was deposited in a foreland basin. This unit experienced intense Mid-Cretaceous and Middle Eocene folding and thrusting.

The East Balkan unit differs considerably from the other Balkan parts because of the large development of sedimentary sequences and a lower tectonic style [16]. It is composed mainly of Upper Cretaceous to Middle Eocene clay-carbonate and clastic flysch sequences that were deposited in a foreland basin which developed in front of the northward advancing Alpine thrust belt. These series are underlain by Lower Cretaceous, Jurassic and Triassic sediments which are exposed in the narrow Kotel belt that is associated with the frontal thrust of the East Balkan unit. Lower–Middle Jurassic black shales, exposed only in this part of the country, are typical of this belt. In some localities, they are closely associated with thick Upper Triassic flysch-like deposits. The main folding and thrusting have a Late Bathonian age, but during Middle Eocene times, the whole unit experienced renewed compressional deformations, which resulted in north-verging folding and thrusting.

The Srednogorie zone has traditionally been considered as a first-order tectonic unit based on the wide distribution of Upper Cretaceous volcano-sedimentary succession and plutonic bodies [26]. Its northern boundary with the Balkan zone is traced by north-verging Middle Eocene reverse faults and thrusts, whereas the southern boundary with the Morava–Rhodope zone is a system of faults (Maritsa fault zone) with uncertain age and relationships. The main compressional events took place toward the end of the Late Cretaceous times, followed by Middle Eocene north-verging thrusting in the northern parts of the zone. Based on tectonic relationships and specific features of the pre-Mesozoic and Mesozoic successions, three subzones are distinguished: Western Srednogorie, Central Srednogorie, and Eastern Srednogorie [27]. The specific feature for eastern Srednogorie is the presence of older Mesozoic mostly marine sediments overlapped by Late Cretaceous volcanoclastic sequences and molasses totally over 3,000 m thick.

The East Srednogorie–Balkan rift zone (ESBRZ – Fig. 3) is preserved within the thrust sheets of the eastern Srednogorie and East Balkan units. Its northern and southern border faults are deeply buried beneath the frontal thrusts of the East Balkan and Strandzha units.

The Rila–Rhodope massif and the Kraishtides Morava–Rhodope zone are situated in the internal parts of the Balkan orogenic system, south of the Srednogorie zones. This zone includes fragments of several tectonic units: Struma, Pirin–Pangaion, Ograzhden and Rila–Rhodope, each of them with relatively independent pre-Late Cretaceous history. These units are integrated into one zone [28] based on the following common features: (1) widely exposed high-grade metamorphic basement complexes typical of the internal parts of orogenic belts, (2) frequent Late Cretaceous and Tertiary intrusive bodies of different sizes, (3) development of small isolated Paleogene basins of graben type with continental and shallow marine sediments that are associated with predominantly acid and intermediate volcanic rocks, (4) main Mid-Cretaceous compressional deformations followed by Late Cretaceous–Tertiary extension and exhumation, and (5) thick continental crust (50–52 km), thinning to 34–37 km in the SE and NW directions.

In Southern Bulgaria there are numerous, small, young, intra-mountain Tertiary sedimentary basins, very restricted in area and thickness. Only Upper Thracian and Sofia basins are larger and deeper.

The Upper Thracian Tertiary sedimentary basin (Fig. 3) is 185 km long and up to 30–40 km wide. It is mostly a fault bounded graben-like depression, which developed on the central southern parts of the Srednogorie tectonic zone and partially on the northern border of the Rhodope tectonic zone. As a consequence of the aforementioned general evolution, the Upper Thracian basin has a rather complicated structure and evolution. It is filled by Eocene–Oligocene, Neogene and Quaternary deposits. During the Paleogene, the basin had a more active basement with faster and more differentiated subsident zones. During the Neogene, the structure was smoother as a result of a considerably slower rate of subsidence. The most subsiding areas are related to three small depocenters, in the total Paleogene–Neogene sedimentary thickness ranges between 1,000 and 2,000 m and outlines three small depocenters in the basin.

The Sofia basin (Fig. 3), 60 × 20 km in size, contains over 800 m Neogene (mainly Pliocene) to Quaternary clastics. Lignite and oil shale occur also in this seismically active basin.

The Bulgarian offshore covers the easternmost fragments of the Moesian Platform and Balkanides, as well as the western periphery of the Western Black Sea basin and part of the young Bourgas Tertiary basin.

The Bourgas basin is developed mainly offshore (Fig. 3). Only a very small part of its northwesternmost periphery covers onshore a very small area of 35 × 20 km. The basin developed over Upper Cretaceous volcano-clastic sequences of the Eastern Srednogorie zone [21, 22].

3 Methodological Estimation Approach

Shale gas deposits are considered unconventional gas resources that can be found in organic-enriched shale with very low permeability. These shales act at the same time as source rocks and reservoir rocks. Shale formations are typically from anoxic basins that consist of sedimentary seams with low permeability and saturated in gas. Usually, shale formations are rather heterogeneous and present a very complex stratigraphic architecture as a consequence of the numerous physical, chemical and biological processes that take place during sedimentation [33].

Technological advances related to horizontal drilling and well stimulation by hydraulic fracturing (injection into the shale a mixture of water, sand and chemicals at a high pressure) permit profitable production, moving considerable resources of unconventional gas reservoirs into the category of reserves.

Typical composition of the fracturing fluid is between 95 and 98 % water (not necessarily fresh), under 5 % of sustaining sands and less than 1 % chemical products. Until recently, companies were not making public the composition of used chemicals and this was a major reason for *concern* within the population against the use of this technique. *Other concerns related to:*

- Induced seismicity (fault movements, induced salt tectonics) and methane emissions
- Potential pollution of freshwater aquifers both from fracking fluid or methane (through usual vertical migration, or along faults, or absorption from earth surface)
- Possible radioactivity of return waters
- Damage of well construction (casing) from the very high pressures, especially on greater depths

All these aspects have to be seriously taken into account during the estimation, exploration and exploitation of shale gas resources.

The usual methodology for assessment of shale gas resources [11] are based on consideration of next main parameters:

- *Regional extent, thickness, and depth of potentially shale gas formations.* The presence of organic-enriched shales must be with large areal extent in the marine sedimentary basin (at least several thousands of square kilometers), with greater thickness, not less than 20 m, but it is as better as to be more (several scores and hundred meters) and buried depth between 1,000 and 4,500–5,000 m. Areas shallower than 1,000 m have lower reservoir pressure and thus lower driving forces for gas recovery [11]. In addition, the shallow shale formations have risks of higher water content in their natural fracture systems, piercing in not consolidated seal and vertical migration both of fracking fluid or methane. Areas deeper than 4,500–5,000 m have risks of reduced permeability, damages in well construction (casing) in conditions of very high pressures (near to 1,000 bars) and much higher drilling and development costs.

- *Organic type and richness*. Total organic content (TOC) needs to be a minimum of 2 % for generation of economical gas volumes. Organic type III produced dry gas, type II wet gas, and type I shale oil, condensate and wet gas.
- *Organic maturation.* It is needed to break down organic matter into hydrocarbons; this is what happens in mature stage of the organic matter. The main maturation indicator is Ro, which values must be between 0.65 % and 1.35 % (hydrocarbon window). For immature formations Ro is less than 0.55 % and for postmatured ones Ro is above 1.35 %).
- *Gas in place* (*absorbed and free*). It is a very important index for realized hydrocarbon generation and that the produced products (gas, condensate, oil) are in place.
- *Permeability*. Minimal values are needed for successful stimulative hydraulic fracturing and for gas production.
- *Pore pressure*. It has to be higher than normal formation pressure in depth.
- *Shale brittleness and mineralogy*. They are important indicators for successful stimulative hydraulic fracturing.

However, the estimations of shale gas resources by such methodology have a very wide range of uncertainty and often the mismatch between the hope and reality for shale gas resources is dramatic. To avoid this some *critical parameters* have to be considered additionally, which are often missed in the assessments. In our view they are with decisive meaning for a successful shale gas exploration.

Such *critical parameters* are:

- *Age of shale formation and buried depth*. The age of shale formation determines how long the generated shale gas must be saved in the source shales. As the age is older as the probability the generated shale gas to be saved is less. The younger organic-enriched shale formations (with Tertiary age) are the most promising for shale gas exploration. Concerning the buried depth in geological history and at present – as depth is less as better. Up to about 3,000–3,500 m, the geological conditions for shale gas in general are good. However, with increasing of buried depth above 3,000–3,500 m, the conditions for saving of produced shale gas rapidly get worse, what related with transformation of clay minerals from montmorillonite to hydromica. That process increases the micropore system and permeability of the shale formations.
- *Faulting, fracturing, and erosion of shale formations*. Intensive faulting and fragmentation in blocks, or strong earthquakes, could cause intensive fracturing in shale formation that make worse the conditions for shale gas, because the generated gas quickly leaves the shale sediments and migrate out of them. The same happens if the shale formation is exposed on erosion surface during the geological history as a result of inversions.
- *Presence of gas shows during the drilling*. It is an extremely important indicator for presence of gas in place. The absence means that it is not generated or it has left the source shales.
- *Effective sealing of shale formation in geological history and presently*. It is important to have an effective sealing above the source shales all time during

and after the gas generation (hydrocarbon window). Usually the clay seals worse efficiency in depth above 3,000–3,500 m, the same happens with evaporate seals in shallow depth (less than 1,200–1,000 m).

- *Maturation level of shale formation*. For dry gas prospective areas, the maturation indicator Ro is greater than 1.3–1.35 %; for wet gas and condensate prospective areas, it is between 1.0 % and 1.3 %; and for oil-prone prospective area the values are between 0.65 % and 1.0 %.

Usually, the immature and transition mature shales (Ro < 0.55–0.65 %) are considered as nonprospective for shale gas because of poor gas generation. However, if shales are enough organic enriched, they can generate bigger volumes of *biogenic gas* that forms sometimes conventional economic gas fields (as Galata gas field in Bulgaria). In such cases the immature shales may be of interest for shale gas exploration.

Postmature shale formations could save shale gas potential if they are effectively sealed, usually by salt–anhydrite deposits. Postmature stage can be indicated by clay mineralogy - the absence of montmorillonite is typical.

Improper appreciation of pointed critical parameters in the assessments of shale gas prospects can bring to dramatic mismatch between the assessed resources and received exploration results. That happens often during the last years.

4 Shale Gas Potential Estimate

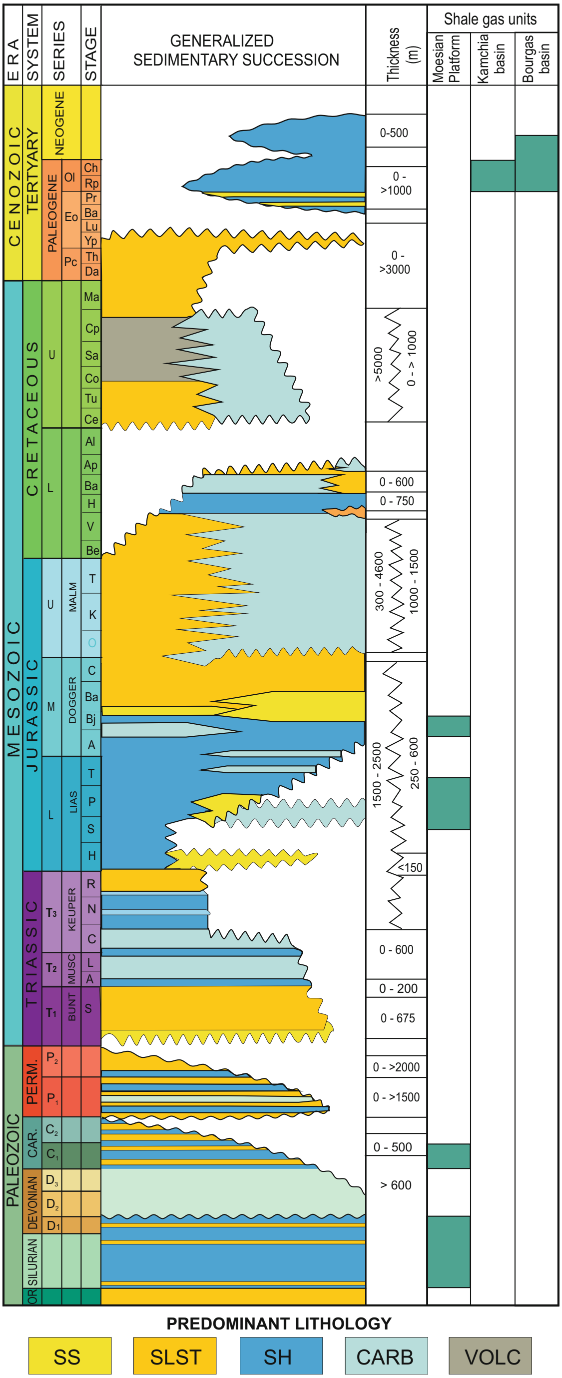
Six organic-enrich dark-shale-dominated intervals have been identified in the sedimentary successions of Bulgaria, which would be of interest for shale gas (Figs. 4 and 5). They are:

1. Silurian–Lower Devonian(?) shales
2. Lower Carboniferous shales – Trigorska and Konarska formations
3. Lower Jurassic shaly sediments – Ozirovo Formation (Bucorovo and Dolnilucovit Mbs)
4. Middle Jurassic shales – Etropole Formation (Stefanets Mb)
5. Oligocene shales – Ruslar Formation
6. Oligocene–Middle Miocene shales – Danisment and Kirazli Formations

The Middle Triassic dark shales in the Moesian Platform (Mitrovo Formation) have been ignored in this selection, because of lack of appropriate hydrocarbon generative parameters [29, 30]: average TOC – <0.5 %, gross thickness usually 40–60 m, limited area of extend.

The first four of the defined units are related to Moesian Platform basin, the fifth is spread in the Kamchia basin, and the sixth extend in the Bourgas basin (Figs. 3, 4, and 5).

Fig. 4 Schematic lithostratigraphic chart for sedimentary successions in Bulgaria with the identified potential shale gas units (based on Georgiev and Dabovski [43])



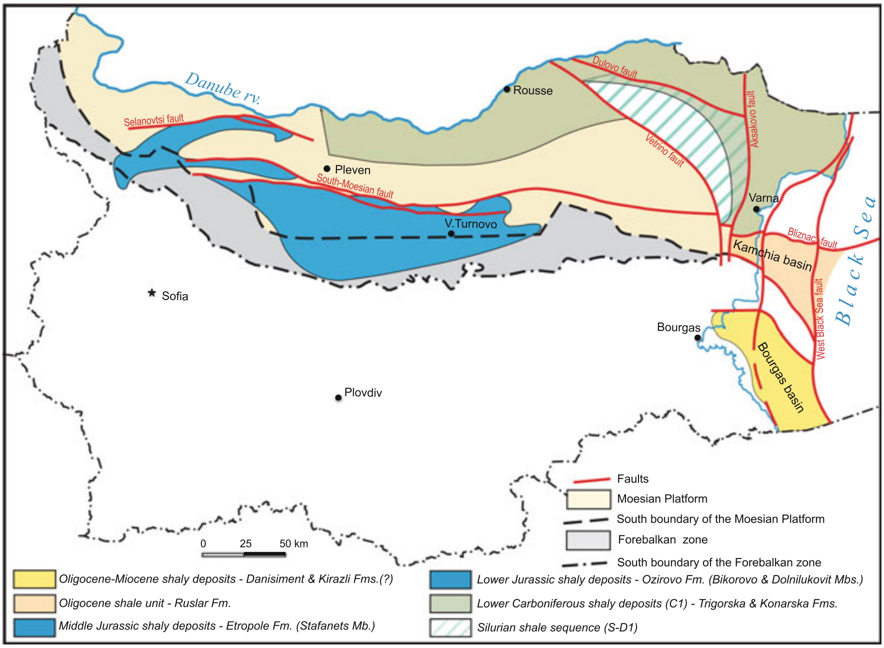


Fig. 5 Spreading of potential shale gas deposits in Bulgaria

The shale gas prospects estimate is made by up-to-date methodology [11] with taking into consideration of described above critical parameters for shale gas resources.

4.1 Silurian–Lower Devonian(?) Shales

The known extent of this shale unit related with area of 1,250 km^2 in the easternmost uplifted Vetrino block of North Bulgarian arch, bounded by Aksakovo fault to the east, by Vetrino fault to the west, and by Dulovo fault to the north (Fig. 6), [19, 31, 32]. These shales are drilled until now only by two boreholes: Vetrino 2 drilled the full section and Mihalitch 2 penetrated only the upper 700 m. Obviously, the areal spreading of Silurian shale is expected to be much larger than the outlined one. However, outside of the marked area, the buried depths are greater than 4–5 km. The drilled gross thickness is about 2,000 m, but organic-rich thickness averages about 500–550 m (gross). Silurian shales are at buried depths of 1,000 to above 3,500 m (Fig. 6), but the available data are very scant. The TOC is in the range of 0.4–3.35 % (average no more 1.5–2 %), type II–III (mainly gas prone). Porosity is usually less than 3.5–4 %. Thermal maturity of 1.3–2.2 % Ro ranges from wet to dry gas.

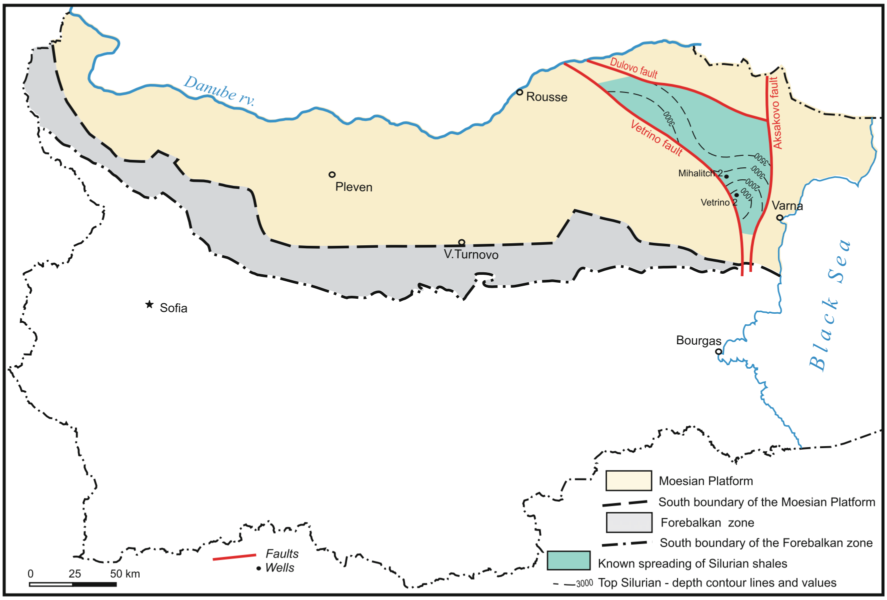


Fig. 6 Silurian shale sequence – spreading and depths

Very critical for Silurian shale gas potential is the total absence of gas presence during the drilling. The most uplifted part of North Bulgarian arch (Figs. 3, 5, 6), where are spread the reachable for drilling Silurian–Lower Devonian (?) shales, is intensively faulted and fragmented in blocks with vertical displacement of up to 2,000 m and more, as well many inversion and erosion periods took place in the geological history [19, 31, 32]. In the marked area (Fig. 6) the Lower Valanginian–Upper Jurassic carbonates crop out on the earth surface, and a very large stratigraphic gape in the sedimentary succession took place – the thin Bathonian sediments cover unconformably the Middle Devonian carbonates, that means lack of deposits from about 200-million-year-long geological period. Parts of absent sediments are eroded, and others are not deposited [19]. Before the Late Paleozoic–Early Mesozoic hiatus, the burial depths of Silurian shales were enough for development of hydrocarbon generation in them. However, during the intensive tectonics and erosional processes in Late Paleozoic–Early Mesozoic time, the generated gas (modest in volumes by TOC) had escaped the Silurian shales and *they are degasified at present*.

4.2 Lower Carboniferous Shales: Trigorska and Konarska Formations

Lower Carboniferous dark-to-black shale has been drilled by several wells in northern and eastern parts of NE Bulgaria (Fig. 7). The most impressive results have been received from drilled several years ago deep borehole Jernov (Fig. 7), which penetrated very thick Lower Carboniferous section (>2,400 m). Three intervals in the section are dominated by dark shales with total thickness of about 1,100 m (Fig. 7). The upper interval, about 140 m thick, related to Konarska Formation [34, 35], contains few coal seams [36]. The middle (850 m) and lower (115 m) shale intervals are related, respectively, to the upper and lower parts of Trigorska Formation [34, 35], with thickness above 2,200 m. Generally, all these shales are still poorly geochemically investigated. The recently accomplished up-to-date and comprehensive study comprises only 70–80 m from shales in Konarska Fm [10].

The Lower Carboniferous shales extend on area of 12,000 km^2, which comprises two zones separated by Vetrino fault (Fig. 7).

The western more elongated and narrow zone covers an area of about 4,000 km^2. The Lower Carboniferous thicknesses grow fast toward Danube River to 3,000 m and more (Fig. 7). Buried depths of Lower Carboniferous range between 2,700 and above 5000 m. Shale TOC values tend to be good and very good (up to 3–4 % and more). Kerogen type is II–III, maturation ranges from transition to postmature

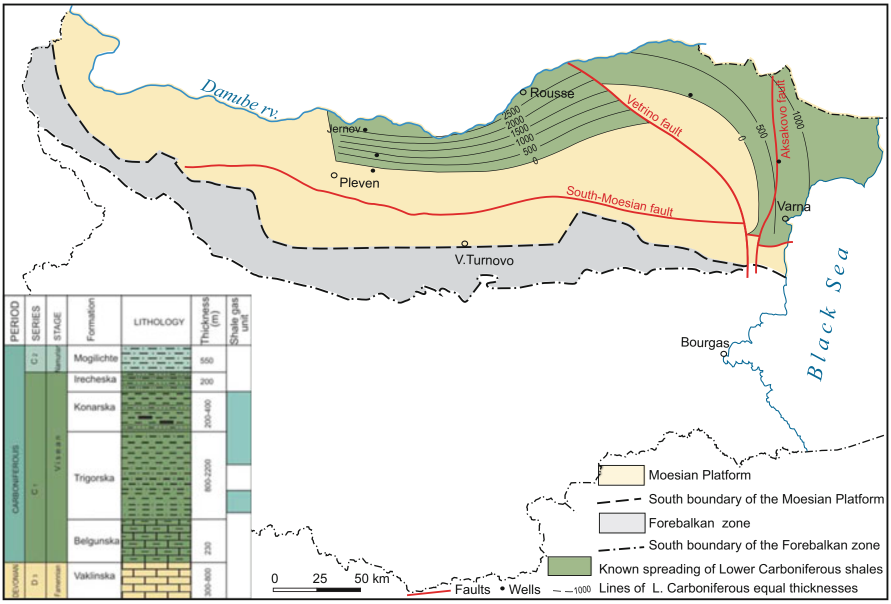


Fig. 7 Lower Carboniferous shale sequence – spreading and thicknesses

(0.6–1.9 % Ro), some anthracite inclusions have been observed [36]. In the shales there is absorbed gas with methane content of 3.5–50 % [10]. The available geological and especially geochemical data are very scant for estimation of shale gas potential. But there are moderate-to-good preconditions if the total Lower Carboniferous thicknesse is above 400–500 m. The *most critical parameters* are *the big depths and the very old age* (320–350 My).

The eastern uplifted zone (eastward of Vetrino fault) is two times larger, about 8,000 km^2 in area (Fig. 7). The Lower Carboniferous sequence occurs on shallower depth, between 850 and 3,100 m. The total and shale thicknesses are, respectively, above 1,000 and 400 m. The organic content of shales has the next parameters: TOC is up to 2–3 % (average less 2 %), kerogen tends to be type III, maturity is high – up to anthracite level [37, 38], as it is for Upper Carboniferous coals in Dobroudja field [39]. By these characteristics shale gas potential may be estimated to be fair.

However, *critical for this zone* is the absence of gas presence during the drilling, as it is also in Dobroudja coal field. The intensive faulting and fragmentation in blocks with high vertical displacement and many inversions and erosions in the geological history [19, 31, 32] have caused escaping and vertical migration of the generated gas (modest in volumes by TOC). So the Lower Carboniferous shales in this zone *are strongly degasified at present*.

4.3 Lower–Middle Jurassic Shaly Sediments

By lithological, log, and geochemical features, two potentially shale gas intervals have been detected in the Lower–Middle Jurassic sedimentary succession of Moesian Platform basin [40]. They are, respectively, related to Bucorovo and Dolnilucovit members within Ozirovo Formation and to Stefanets member within Etropole Formation [41, 42] (Fig. 8). Usually, their source features improve when the total thickness of Lower–Middle Jurassic sequence is above 350–400 m, as much as better. In addition, all oil–gas discoveries in central North Bulgaria (Dolni and Gorni Dubnik, Dolni Lucovit and others) have been chemically linked back to the Etropole and Ozirovo shaly sediments [40, 43–45]. The areal extension of the thicker Lower–Middle Jurassic sequence has been mapped by a lot of well and seismic data and cover the area of about 10,000 km^2 (Fig. 5, 8), [43].

4.3.1 Lower Jurassic Shaly Sediments: Ozirovo Formation (Bucorovo and Dolnilucovit Members)

The shaly middle part of Ozirovo Fm comprises Bucorovo member and the upper part of Dolnilucovit member. This shaly unit manifests fair-to-good hydrocarbon generative features [40]. The thicknesses vary between 200 and 500 m in the western part of the outlined area, but eastward they reduce to 40–50 m (Fig. 8). Total organic content is usually between 1 % and 2 %, rarely more. Organic type is

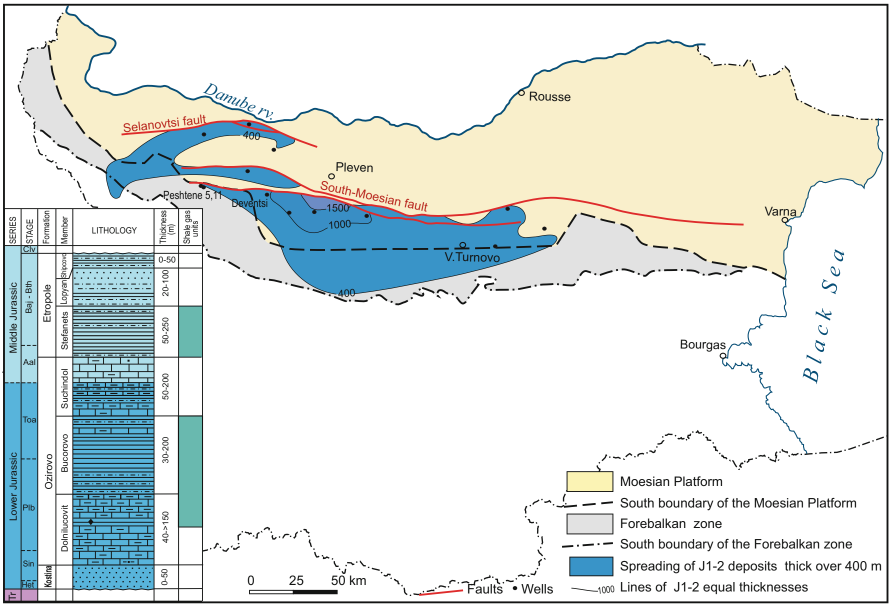


Fig. 8 Lower–Middle Jurassic stratigraphy and spreading in gross thicknesses of above 400 m

I–II, its transformation rate increases southward from peak to late maturity stage (by Ro and T_{max} values) together with fast rising of the thicknesses and burial depths from 2,600 to 4,500 m.

Borehole Devensi, drilled in the southwestern part of outlined area by Direct Petroleum Bulgaria, tested good gas-condensate flow from Dolnilucovit member [4, 8].

Critical for Ozirovo shaly sediments is the thickness, when it is less than 100 m and not so sufficient organic enriches.

4.3.2 Middle Jurassic Shales: Etropole Formation (Stefanets Member)

The organic-enriched shales in the lower portion of Etropole Formation, represented by Stefanets member, are prospective within the outlined 10,000 km^2 area in central part of Northern Bulgaria (Fig. 8). Stefanets member contains carbonate-rich (40–50 %) black shale that was deposited in a marine environment with thickness from 250 m to the southwest up to 50 m to the east. Total organic content ranges from 0.7 % to 2.95 %, kerogen type II predominate [3, 4, 8, 40, 43, 45]. The Stefanets shale generally ranges from 2,500 to above 4,250 m deep and is overpressured in much of the western zone, with an elevated pressure gradient of 0.78 psi/ft. [4, 8]. Thermal maturity falls in the oil window in the north, increasing to wet and dry gas in the south near the Balkan thrust belt (Ro 1.0–1.5 %). Porosity is assumed to be moderately high (3–4 %). Gas recovery rates also could be favorable based on the inferred brittle lithology.

The located to southwest in the area old well Peshtene 5 tasted many years ago gas-condensate flow at an unstimulated rate of 15,000 m^3/d from conventional carbonate-clastic interval within the Etropole Formation. In 2011 a new exploration well Peshtene 11 was drilled nearby by Direct Petroleum Bulgaria to core and tests the Etropole shale. This well penetrated about 350 m of Etropole shales with numerous gas that shows (C1–C3) at a depth of 3,500–3,800 m. The well was not fracture stimulated as Bulgaria has a ban in place [4, 5, 8].

The insufficient organic enriches and the big buried depths to above 4,000 m are critical for Etropole shales, because they aggravate the exploration technical and price conditions.

4.4 Oligocene Shales: Ruslar Formation

This shale unit named Ruslar Formation [46] is spread in the Kamchia basin, which extend mainly offshore in the western Black Sea (Fig. 9). However, the western basin periphery is exposed onshore and has been an oil–gas exploration target over 60 years.

Many authors considered in a long time the Kamchia depression as a post Early Eocene foredeep, based mainly on the onshore position and geometry. However, the eastern offshore prolongation shows that the basin gradually deepens and

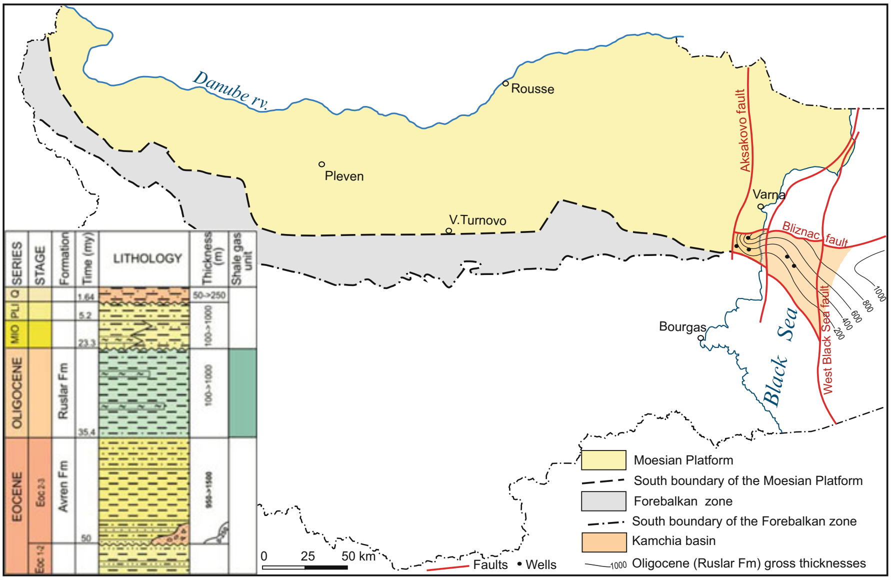


Fig. 9 Kamchia basin stratigraphy and Oligocene shale (Ruslar Fm) gross thicknesses

expands eastward and merges with the Western Black Sea basin (WBSB) floor. Hence, the Kamchia elongated basin represents westward wedging branch of the WBSB [47]. The Eocene–Oligocene sequence represents the major sedimentary fill in the western shallower periphery of the basin, while the Neogene thickness increases notably toward the WBSB floor [47]. The onshore basin area, called Kamchia depression, is small (about 200 km^2) with sedimentary feeling above the Illyrian unconformity up to 1,300–1,400 m. But to the eastward offshore, the basin gradually enlarges up to 60–70 km and deepens to 7,000 m, with area of extend near to 2,000 km^2.

The Ruslar Formation is considered to be a primary hydrocarbon source in the Kamchia basin. This sequence comprises mainly shale and claystone, occasionally grading to siltstone, with a total thickness of 100–400 m in the southern basin slope to more than 1,000–1,500 m northward to the basin axial zone and eastward to the WBSB. It is an equivalent of the Maykop Fm, which is the basic source unit in the larger Black Sea–Caspian domain.

The organic matter content is good to very good (1.4–2.8 %), dominated by amorphous kerogen type II [48]. At the drilled depth intervals, the formation is immature (0.27–0.35 % Ro) and generates only biogenic gas. However, the generated volumes form four small gas fields – Kamchia one onshore and Galata, Kavarna and Kaliakra ones offshore. Additionally, all drilled sections manifest the presence of absorbed methane in increased values.

Overall, the Ruslar shales have fair-to-good gas source potential mostly offshore. The onshore basin part and the slant drilling from the cost are good opportunity for modest shale gas exploration.

4.5 *Oligocene–Middle Miocene Shales: Danisment and Kirazli Formations*

This shale unit extends in the small Bourgas sedimentary basin, located mainly offshore in the southwestern zone of Black Sea [47]. Only a very small part of the northwestern basin periphery exposes onshore in the Bourgas area (Fig. 10).

The Bourgas basin has half-graben geometry, bounded to the east by the endmost Balkan unit and the Western Black Sea fault. The basin prolongation in the Turkish offshore, as well as its connection with Thrace basin to south of Strandzha, are not enough clear.

Mostly Middle–Late Eocene (Ravnets Fm), Oligocene (Danisment Fm), and Miocene (Kirazli Fm) clay deposits with many thin clastic layers and coal seams fill up this basin [47]. Seismic data indicate basin deepening toward the Bulgarian/Turkish offshore border, where the sedimentary filling reached more than 4 km. In the Bulgarian offshore zone of this basin has no drilling, but in its Turkish zone several wells were drilled.

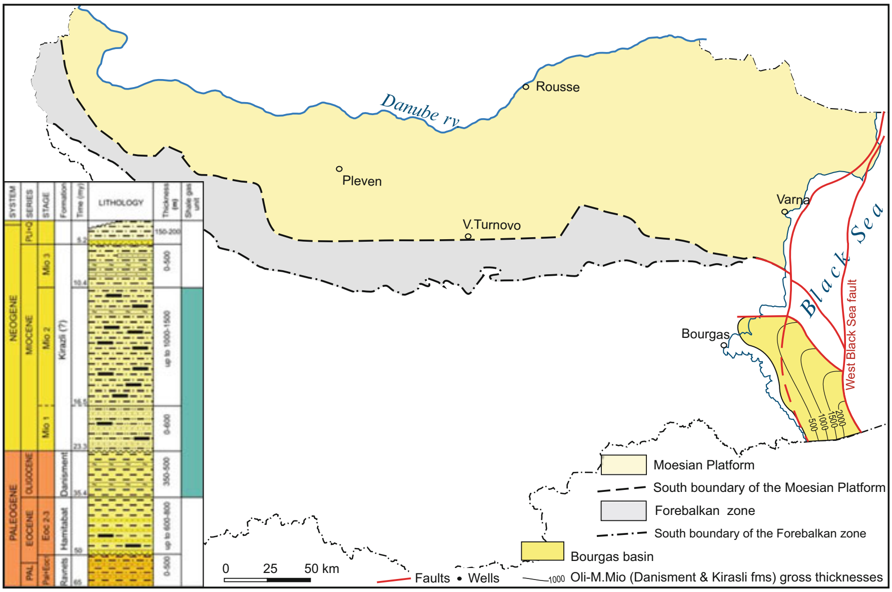


Fig. 10 Bourgas basin stratigraphy and Oligocene–Middle Miocene (Danisment and Kirazli Fms) gross thicknesses

The Oligocene–Lower–Middle Miocene shales (Danisment and Kirazly Formations) have a total thickness up to 1,500 m in basin central parts [47]. The lacustrine lignite coals and shallow to marginal marine shale, drilled in the Turkish zone, showed good source parameters – TOC in average 1.5–2 % mainly type III on immature stage (0.35 % Ro), PY up to 41.6 kg/t, and HI up to 387. The buried depths rise toward Bulgarian/Turkish border up to 2,200–3,000 m; hence, an increasing organic maturity up to early oil generation can be expected.

Overall, this source unit is mainly gas prone and generate mainly biogenic gas, which amount is expected to be significant. The drilling in Turkish offshore manifest reach saturation with absorbed and solved methane. Offshore basin location is *the most critical element* for shale gas exploration, although the main target is reachable by slant drilling from the coast.

5 Main Results and Conclusions

The accomplished shale gas estimate of Bulgaria analyze only the geological data and conditions; the environmental impact has not been subject of the study.

Some very optimistic prognoses and assessments from 2011 to 2013, including the Silurian and Etropole shales [3, 5, 7, 8, 10], have been not supported by available geological–analytical results and present-day geological conditions.

Besides Silurian and Etropole shales, another four newly defined organic-enrich and dark-shale-dominated intervals that are related to Lower Carboniferous, Lower Jurassic, Oligocene and Oligocene–Middle Miocene have been estimated.

The Silurian–Lower Devonian(?) *shales* have moderate fair generative gas abilities. However, along the Late Paleozoic–Early Mesozoic period, continued about 200 million years, the generated modest volumes gas had escaped the shales as a result of intensive tectonics, faulting and erosions. *At present they are degasified*, what is supported by total lack of gas shows during the drilling.

The Lower Carboniferous shale unit extend on large area of 12,000 km^2, separated by Vetrino fault into two differ zones. *In the western subsided zone*, the shales have moderate-to-good shale gas potential by organic peculiarities and contain absorbed methane in values of 3.5–50 %. Most critical parameters looks to be the big depths (2,700–5,500 m) and the old age (320–350 My). *In the eastern uplifted zone*, the shale organic characteristics define modest shale gas generation. However, the intensive faulting and block fragmentations, as well as the many inversions and erosions in the Late Paleozoic–Early Mesozoic geological history caused escaping and vertical migration of the generated gas.

In the Lower–Middle Jurassic succession are defined two shale gas targets: Ozirovo and Etropole formations, which have hydrocarbon source abilities, especially the lower one, only when the Lower–Middle Jurassic thickness is above 350–400 m, as much as better. All made oil–gas discoveries in central North Bulgaria genetically linked back to these two source intervals.

The Lower Jurassic shaly sediments (*Ozirovo Formation – Bucorovo and Dolnilucovit Mbs*), manifests fair-to-good hydrocarbon generative features. Thicknesses less than 100 m and not so sufficient organic enriches are critical.

The Middle Jurassic carbonate-rich marine black shales (Etropole Formation - Stefanets Mb) have good shale gas potential in the central–western zones of outlined prospective area. *Critical* are not so sufficient organic enrich and buried depth if it is above 4,000 m.

The defined two Lower Tertiary targets don't take place in traditional concepts for shale gas formations, because they are immature and are spread mainly offshore. However, in our view they have some shale gas potential, even though modest.

The Oligocene shales (*Ruslar Formation*) *are* developed in Kamchia basin mainly offshore and have a good to very good gas generative potential. The *Ruslar Formation is* equivalent of Maykop Formation. The shales are immature (0.27–0.35 % Ro) and generate biogenic gas. However, it formed four small gas fields – Kamchia onshore and Galata, Kavarna and Kaliakra offshore. All drilled sections manifest increased values of absorbed methane. *The onshore basin part and the slant drilling from the cost are good opportunity for modest shale gas exploration.*

The Oligocene–Middle Miocene shale sequence (*Danisment and Kirazli Formations*) is developed in the small Bourgas basin located mainly offshore in the SW Black Sea. The Danisment and Kirazly formations are mainly biogenic gas prone. The drilled sections in Turkish offshore manifest reach gas saturation. Most critical for shale gas exploration is offshore location, although the main target is reachable by slant drilling from the coast.

According to our estimatiom, the shale gas potential of Bulgaria is moderate to poor. From the estimated six targets for shale gas, only the Lower Carboniferous shales (in the outlined western zone) and both Jurassic shaly intervals may present moderate interest. The immature shales in Oligocene (Kamchia basin) and Miocene (Bourgas basin) are not for disparagement.

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