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SHALE GAS POTENTIAL OF THE ROMANIAN PLATFORM UNITS

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Potentially gas bearing shales and argillites are connected to the foreland Carpathians, in the platform units, at depth exceeding 2500–3000 m (south of Moldavian Platform, Scythian Platform (Bârlad Depression), and Moesian Platform with its extension in South Dobrogea. The formations developed in the sediment dump of the **Moldavian Platform**, containing sequences of clay rocks which are richer in organic matter and implicitly those of gas shale (GS) type, are bituminous argillites and black clay rocks from the Paleozoic (Vendian – Silurian Period). Black clay formation from the Middle Silurian exists at depths of 400–2300 m, was deposited under accumulation conditions corresponding to a dysoxic-anoxic marginal basin and its thickness exceeds 30–40 m. TOC values (0.35 and 1.6) and vitrinite reflectance (Ro between 0.35 and 1.6), reveal a remarkable potential. **Bârlad Depression**, which is part of the Scythian Platform, has formations of particular concern for shale gas production, dating back to the Silurian – Devonian sedimentation cycle. The relevant formations developed at depths between 900 and 3800 m, in a basinal-pelagic depositional environment, and the organogenetic parameters have average values between 1.0 % and 2.4 % for TOC and between 0.60 % and 3.5 % for vitrinite reflectance. Upper Cambrian – Westphalian, Permian – Triasic and Toarcian – Senonian cycles from the four sedimentation cycles of **Moesian Platform** overlay have an important shale gas potential. The main formations with a proven gas production potential are Ţăndărei Clay Formation, **C**ălăraşi Formation, Vlaşin Formation and Balş Formation where of Silurian formations in the graptolite argillite facies have the most important shale gas generation potential (TOC = 1.0–1.9%, Ro = 0.40–1.40%).

Keywords: Moldavian Platform, Scythian Platform, Moesian Platform, oraganic matter.

INTRODUCTION[1]

Potentially gas bearing shales and argillites are connected to orogenic units (in formations with surface exposure, but which also extend to the deep areas of the Eastern Carpathian – Săndulescu, 1994) and in the foreland Carpathians, in the platform units, at depth exceeding 2500–3000 m (south of Moldavian Platform, Scythian Platform (Bârlad Depression), and Moesian Platform with its extension in South Dobrogea (Anastasiu, 2012).

REGIONAL SETTING

The Moldavian Platform represents the south-western part of the grand East-European Platform, known within the Romanian territory under this name between Carpathian and Prut or in Moldova Republic, between the Carpathians and Nistru (Brânzilă, 1999) (Fig. 1).

Basement was intercepted by a series of drillings at different depths: Todireni (–950 m), Bătrâneşti (–1008 m), Popeşti (–1370 m), Iaşi (–1121 m). Data regarding the absolute age indicate values of 1280–1593 Ma.

The ***sedimentary cover*** includes sedimentary deposits accumulated on the Late Vendian – Meotian interval the stratigraphic thickness of which ranging between 2500–6100 m. The stratigraphic analysis of the deposits allowed the identification of three main sedimentary cycles, separated by large or shorter breaks: I. Late Vendian – Devonian, II. Cretaceous – ? Eocene – ? Oligocene, Badenian-Meotian (Brânzilă, 1999). The lithostratigraphic formations developed in the sediment pile of Moldavian Platform which contain sequences with shales richer in organic matter and, implicitly, those of *gas shale* (GS) type

are located at great depth (Paleozoic) or closer to the surface, as the Neozoic ones (Grasu, 2007):

– Vendian **bituminous** argillites;

– Black argillites and sandstone in Early Cambrian;

– **Black shale** in Middle and Late Silurian.

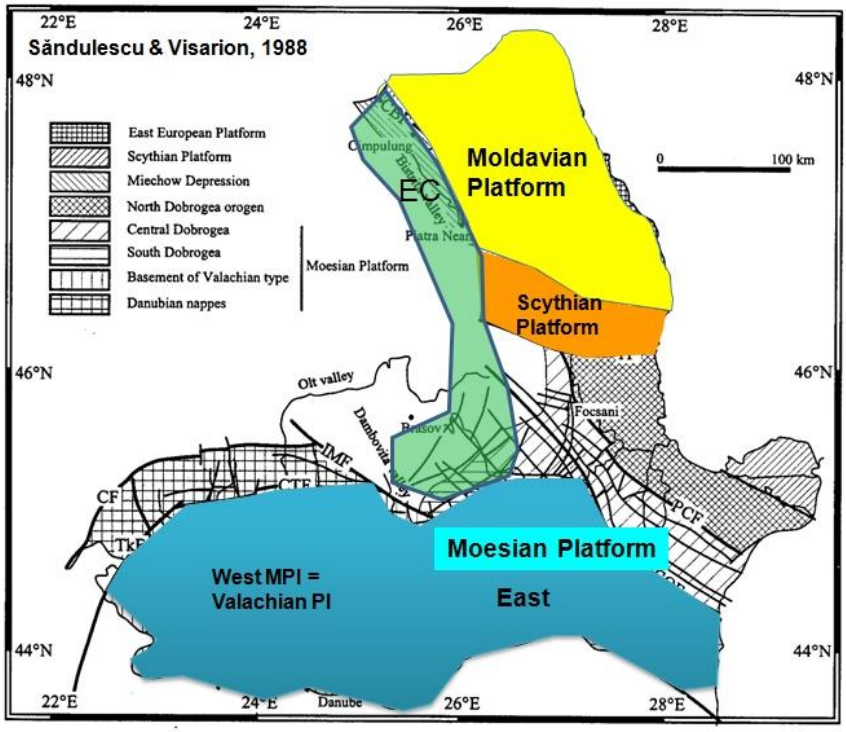


Fig. 1. Simplified structural map of the Carpathian foreland
(Săndulescu & Visarion, 1988; Visarion, 1988, modified by Anastasiu):
SiF – Siret Fault; ScF – Solca Fault; CBF – Câmpulung-Bicaz Fault; VF – Vaslui Fault; BF – Bistriţei Fault; TF – Trotuş Fault; PCF – Peceneaga-Camena Fault; COF – Capidava-Ovidiu Fault; IMF – Intra-Moesian Fault; CTF – Călimanești-Tg.-Jiu Fault; TkF – Timok Fault; CF – Cerna Fault; MF – Motru Fault; JF – Jiu.

	Cycle-age	Formation	Thickness – m (max. – west)		Locality	Lithology
Cycle I	Vendian (Pcb)		300		Bătrânești	sandstones-argillites
Cycle I	Cambrian	Naslavcea Beds	130		Bătrânești	sandstones-**argillites**
Cycle I	Late Ordovician		6			sandstones
Cycle I	Middle-Late Silurian		30	1300		sandstones-**black shales**
Cycle I	Early Devonian		100			sandstones, **shales with graptolites**
Total thickness			**566**			

The first cycle – Vendian – Devonian – has a potential for gas shales.

Vendian – Devonian Cycle

Based on the phytocenosis, the associations of Foraminifera and even based on macrofauna, in the sediment pile, the presence of the following ages was attested: Late Vendian, Cambrian, Late Ordovician, Middle and Late Silurian, Early Devonian (Fig. 2).

a. ***Late Vendian*** (terminal Precambrian): The deposits of this interval were intercepted in the Bătrânești drilling, were they reach a thickness of 300 m. The lithology is given by conglomerates, sandstones, and bituminous argillites. As intercalations, there are numerous tuffs.

b. ***Early Cambrian:*** The deposits have approximate 130 m and were intercepted in Bătrânești drilling also and include

conglomerates and sandstone over which follows an alternation of argillites and black sandstones. The deposits related to the Early Cambrian are known in literature as **Naslavcea beds**.

c. ***Late Ordovician:*** It is very thin, with a thickness of only few meters (2–6 m), and includes mainly sandstones with numerous remains of brachiopods and echinoderms.

d. ***Middle and late Silurian:*** The deposits of this interval can be found on the entire platform, except the south-western border and was also observed in other drillings with variable not uniform thickness, 30 m to the east – over 1300 m in the drillings near the Carpathian orogeny, in the Rădăuţi area. Lithology includes black shales (Rădăuţi Formation), followed by carbonatic deposits – limestones and calcareous sandstones – rich in associations of corals, bryozoan and brachiopods (Bătrâneşti Formation).

e. ***Early Devonian:*** It is the last term of the first sedimentation cycle, with uniform development, deposits especially to the west of quartz sandstones, shales and blackish calcareous. Their total thickness is of approximately 100 m. The age is indicated by associations of ostracods and some Foraminifera, but mainly graptolites.

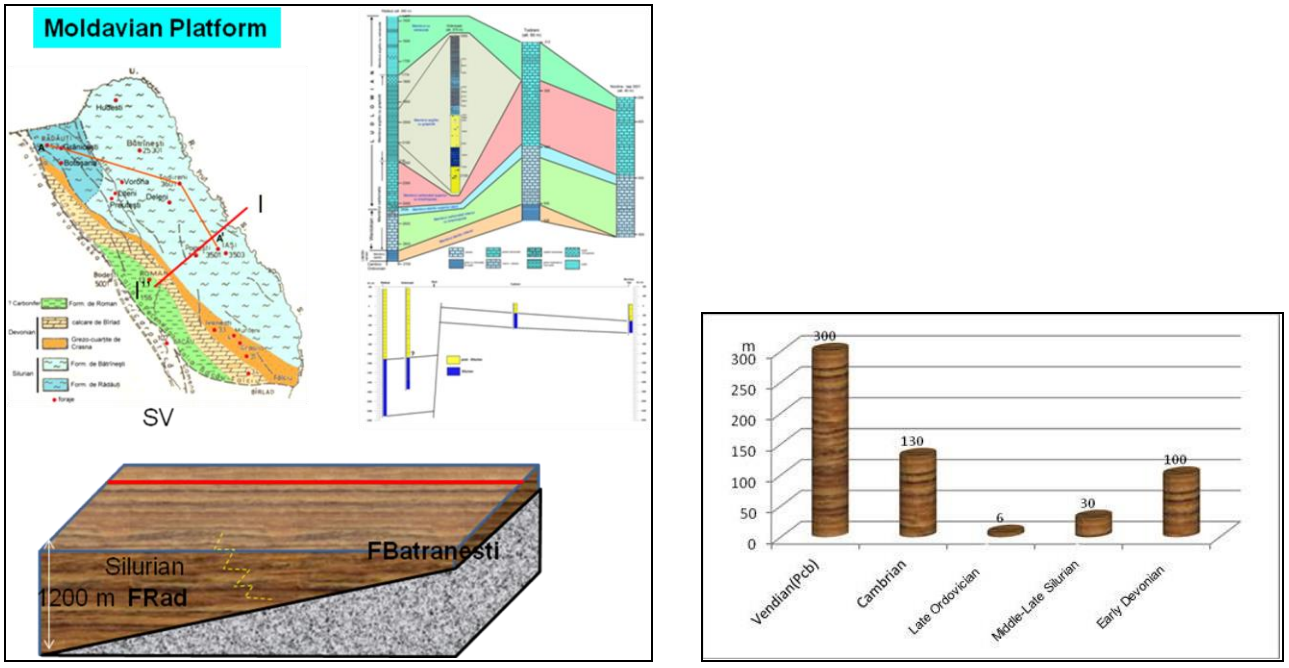


Fig. 2. Moldavian Platform – thickness of formations – Cycle I.

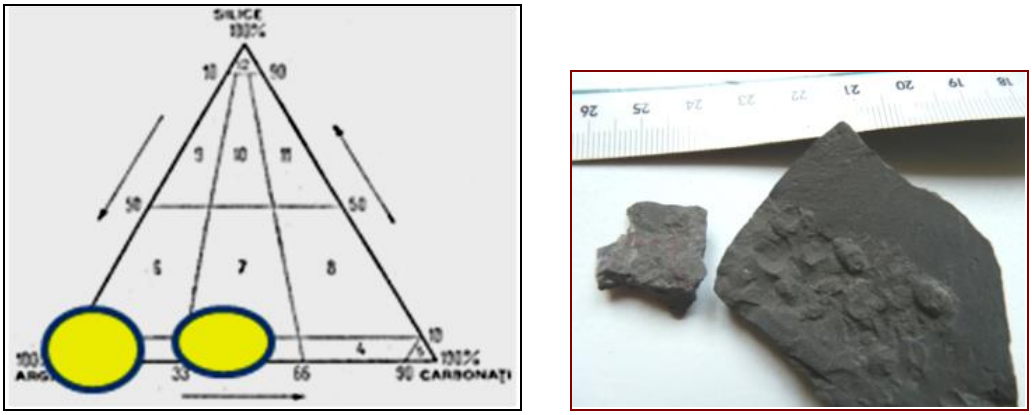


Fig. 3. Petrofacies of the shale formation from vendian-devonian cycle.

Scytian Platform (Bârlad Depression). Bârlad Platform may be considered a typical platform and represents the western extremity of the Scythian Platform. In the specialized literature, Bârlad Platform is also known as: Bârlad Depression as a sector of Predobrogean Depression, or even Moldavian Depression, being considered as a sector of the Moldavian Platform, Scythian Platform (Săndulescu, 1984) (Fig. 4).

Basement. It has a heterogeneous nature, including lower folded Paleozoic deposits in which, even older pre-Cambrian, metamorphosed formations can be found. The study of formations, at the level of the basement, and even of the sedimentary cover, was very difficult, many results being obtained by indirect methods.

Due to the complicated tectonics, the pre-Jurassic basement was intercepted by wells at very different depths on the entire area of the depression: from only –664 m) at Oancea, in the south-eastern extremity, to (–1130 m) at 30 Prut, in the north-eastern part, where it is represented by Paleozoic deposits of *East European type*.

In Bârlad, the same Paleozoic (Devonian) deposits, also of East European type were reached at (–1350 m). In the north-western part of the depression, in Bacău, platform Devonian sits on a *basement of green shale* and was intercepted at a depth of (–2939 m).

In the southern extremity, *the basement is of North-Dobrogean type* and was intercepted at: Conţeşti (–3950 m), Nicoreşti formation, of Carboniferous age; at Burcioaia (–3850 m) epimetamorphites of Boclugea type, of Cambrian-Ordovician age and at Crăieşti (–1150 m) – Post-Carapelitic deposits.

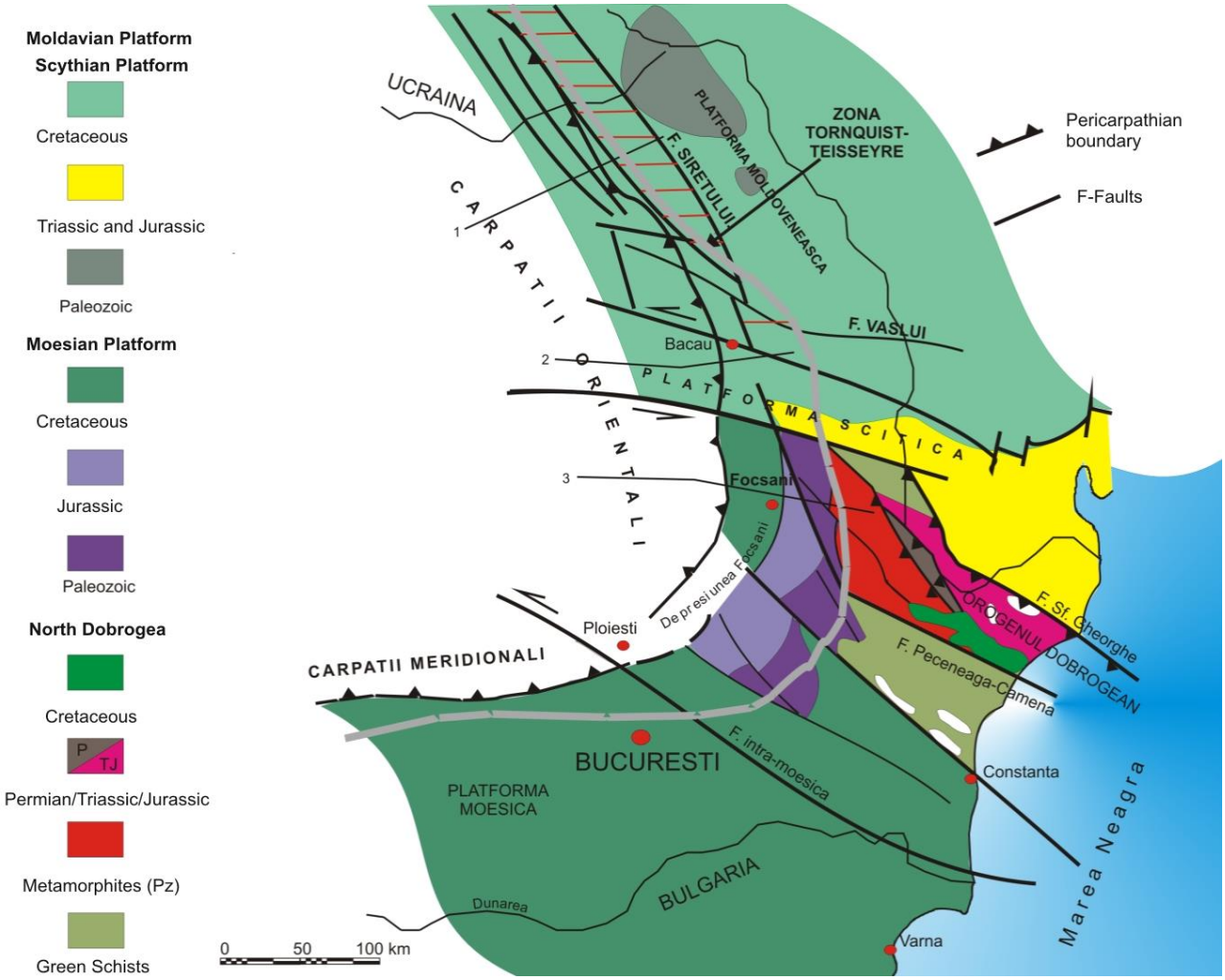
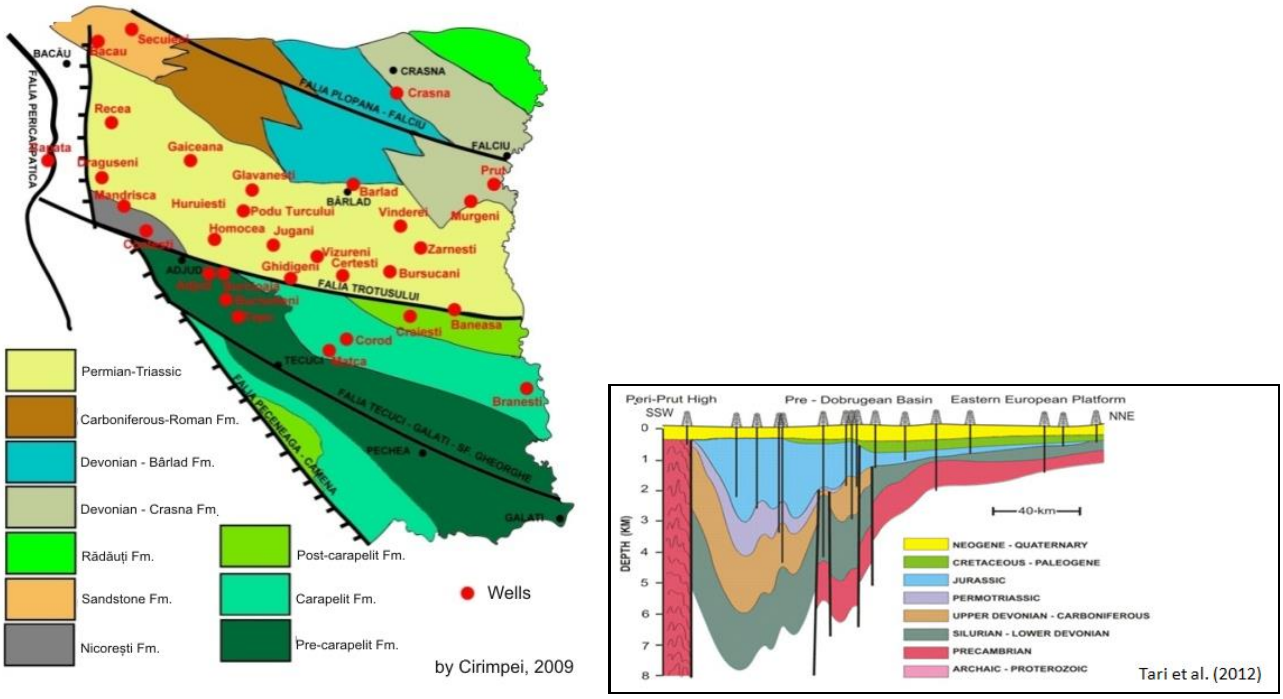


Fig. 4. Geological map of the Moldavian Platform and Scythian Platform (Bădescu, 2005).

Cycle	Age	Formation	Thickness – m (max. – west)		Locality	Lithology
Silur-Devon Cycle			**155**			
Silur-Devon	Silurian		50	?		
Silur-Devon	Devonian	Coarse arenitic formation	45		Prut	microconglomerates
Silur-Devon	Devonian	Crasna sandstone and quartz formation	60		Murgeni	sandstones
Perm-Tr	Permian-Triassic	Lacu Rosu Form. – Rosiori Form. (Moes P))	**900**		Murgeni-Oancea	sandstones, red shales



a **b**

Fig. 5. Geological map – **a**, and cross section – **b** – of the Pre-Jurassic basement of Bârlad Depression (Cirimpei, 2009, Tari *et al.*, 2012).

The axial area of the platform is submerged from east to west. Thus, the pre-Jurassic basement is known at: (–2170 m) – Vinderei, (–4616 m) – Homocea, (–4864 m) – Bereşti and (–4930 m) – Mândrişca. To the west, the wells no longer intercept the basement up to the depth of (–5087 m) at Drăguşani and (–5502 m) at Capăta, where the wells stopped in Jurassic deposits.

Cover. The oldest deposits which probably belong to the cover are Silurian-Devonian, and the youngest are Romanian and Quaternary. Although the Paleozoic and Triassic deposits are less known, after the sediment pile analysis, several sedimentation cycles can be outlined (Fig. 5).

METHODS AND RESULTS

Oil generating and gas bearing potential of shale formations in Moldavian Platform and Scythian Platform

The lithostratigraphic formations developed in the sediment pile of Moldavian Platform which contain sequences with shales richer in organic matter and, implicitly, those of *gas shale* (GS) type are located at great depth (Paleozoic) (Fig. 6) or closer to the surface, as the Neozoic ones (Grasu *et al.*, 2007):

– Vendian **bituminous** argillites;

– **Black argillites** and sandstone in Early Cambrian;

– **Black shale** in Middle and Late Silurian;

– Fălticeni-Boroaia Formation (Volhynian);

– Formation with *Cryptomactra* (Basarabian);

– Bârnova-Muntele Formation (Basarabian).

Table 1

Comparative presentation of lithology, spatial extent and oil generating and gas bearing potential of Ordovician – Devonian shale formation in the Moldavian Platform and Scythian Platform (Veliciu and Popescu, 2012)

	Structural unit	Moldavian Platform	Scythian Platform
Basic data	Lithology	Shales (20–30 %);	Shales (20–30 %);
		Limestones (30–50 %); sandstones (30 %)	Limestones (30–50 %); sandstones (30 %)
	Geological age	Silurian-Ordovician	Devonian-Silurian-Ordovician
The extent of organic matter rich formation (m)	Perspective area (km^2)	8223	1102
	Depth at which the upper part of organic matter rich formation is encountered (m)	400–2,350	900–3800
	The average thickness of organic matter rich formation (m)	30	25
Properties	Pressure (Mpa\psi)	35	30
		3481	5366
	Temperature [Rankin]	684	691
	TOC (wt %)	1.1–1.6	1.0–2.4
	Thermal maturity (%Ro)	0.35–1.6	0.58–3.6
	Bg volume factor	0.0048	0.0033
	Z factor	0.860	0.900

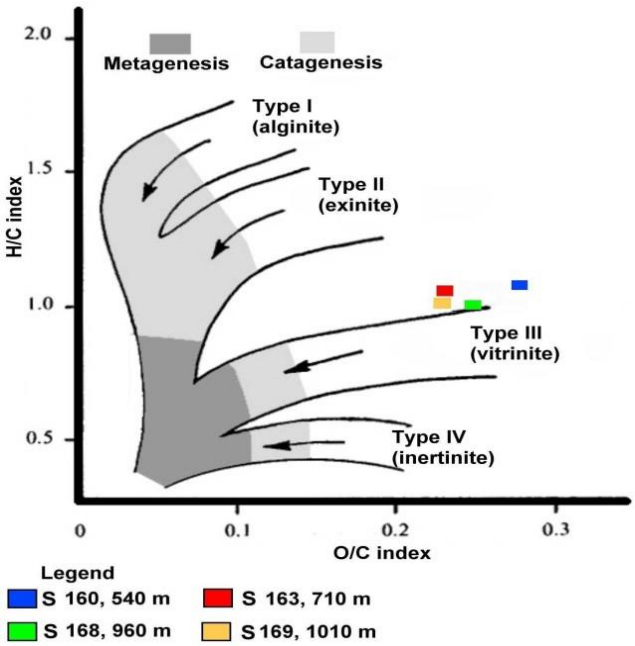


Fig. 6. Oil generating and gas bearing potential of some shale formations in the Moldavian Platform.

Moesian Platform. The sedimentation of the Moesian Platform was performed in four main cycles: Late Cambrian – Westphalian, Permian – Triassic, Toarcian – Senonian and Late Badenian – Pleistocene (Seghedi *et al.*, 2005) (Fig. 7).

Its interval included the largest part of Paleozoic, during which marine deposits have been accumulated (sandstones, ***shales***, marls, limestones, dolomites) with an approximate thickness of 6500 m (Table 2). The main potentially gas-bearing formations are:

Table 2

The thickness of formation of the Moesian Platform in the four main sedimentation cycles: Late Cambrian – Westphalian, Permian – Triassic, Toarcian – Senonian and Late Badenian – Pleistocene

Age	Formation	Thickness (m)
Permian	Rosiori_1 Formation	1000
Carboniferous (Namurian)	**Vlasin Formation**	800
Devonian (Eifelian-Giventian)	Smirna Formation	370
Early Devonian	**Călăraşi formation**	875
Silurian	**Tandarei Formation**	1200
Ordovician	**Tandarei-pelitic Formation**	275
Cambro-Ordovician	Mangalia Formation	900

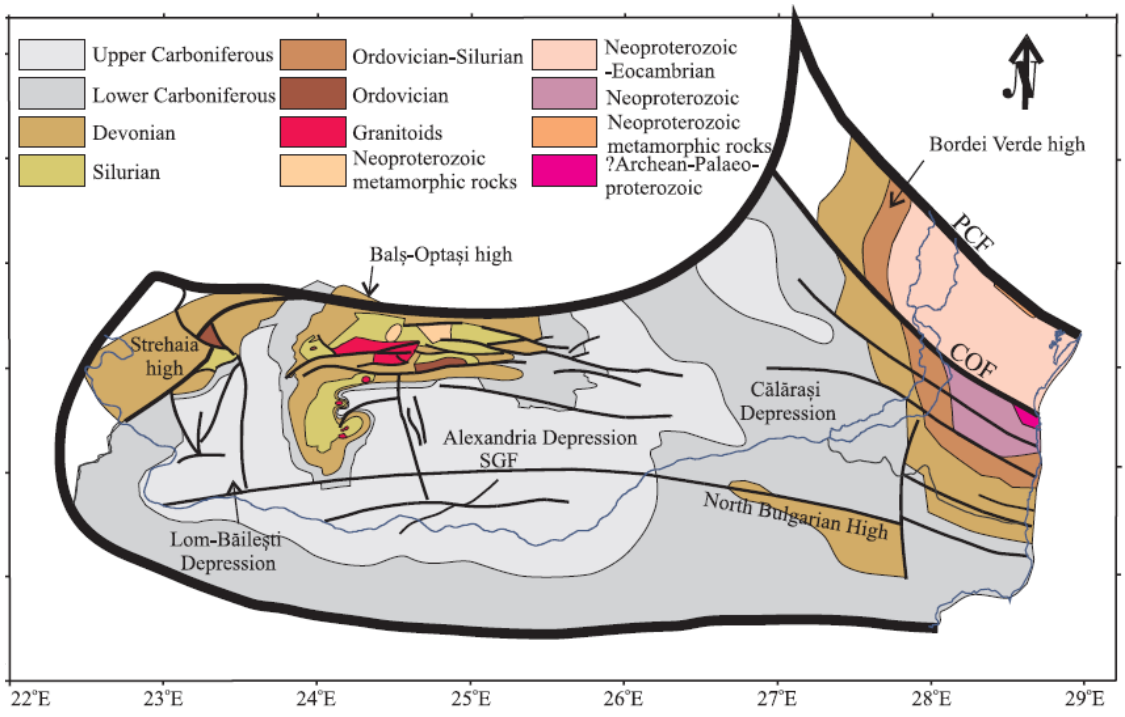


Fig. 7. Map of the distribution of Permo-Triassic deposits in the subsoil of the Moesian Platform and the structure of its first structural level (Paraschiv 1974; Iordan 1981; Seghedi *et al.*, 2005).

Ţăndărei shale Formation (Ordovician-Silurian-Early Devonian). Geochemical indices of the east and west part of the platform indicate that this formation is included in the category of effective source rocks outside the oil window, located in the stage which also generate condensate and dry gas (metagenesis study). The generating potential of ***Călăraşi Formation*** (Early Devonian) is debatable, after analyzing the results of examined cores of the Argetoaia, Chilii, Dârvari, Brădeşti, Râmeşti, Lişcoteanca wells (organic carbon – 0.12–1.7 %; soluble organic extract – 0.008–0.042; extract of hydrocarbons – 32–75 %; rocks of hydrocarbon – 32–468; traces of pyritic sulphur – 0.30; traces of FeO – 4.40; pH – 8.6–9.6) the hypothesis of the pronounced nature of source rocks of these deposits remaining open. ***Balş Formation*** (*Toarcian-Dogger Cycle*). Taking into account the petrographic (**dark grey shales**, marls, marly-limestones and sandstones and predominantly

siliceous sandstones) and geochemical features (organic carbon – 0.33–3.11 %; bitumen A – 0.011–0.47 %; total sulphur – 0.24–2.14 %; pH 7.5–9.5), the existence of associated hydrocarbon accumulation and the stratigraphic framework, the Pelitic Jurassic deposits ("*Posidonia schilts*") have been considered possible generating rocks even from the first stages of the study of the platform (Anastasiu et al, 2011, Paraschiv, 1979).

In the eastern sector, **Călăraşi-Ţăndărei Depression** – the thickness of Silurian is very variable, from 713 m, in Ţăndărei (East) to 380 m, in Optaşi (West). (Drillings and organofacies – data, tables from Patruti, 1961, Paraschiv, 1979, Vinogradov, 1998, Seghedi, 2005).

Silurian is complete in Călăraşi and Ţăndărei. Reducing, euxinic, basinal environment for schilts with graptolites and then, on the shelf, based on the fauna composed of bivalves, gastropods, tentaculites, brachiopods etc.

The gas-bearing potential of the argillitic facies of Moesian Platform differs according to the age and basinal sector, as follows.

Formations with a higher potential occur especially at the level of Silurian and Early Devonian (Ţăndărei- schilts with graptolites) and subordinated, at the level of Carboniferous and Jurassic (Vlaşin Formation and Balş Formation). At the level of Late Devonian-Early Carboniferous, Călăraşi Formation covers carbonatic and dolomitic facies, less significant for gas shale type accumulation.

Table 3

Oil-bearing potential of the formations located in the eastern sector of Moesian Platform

Age of studied formation	No. of drilling/depth of core sampling	Organic matter %	RO – average values	TOC – average values	LOI-rr (CO2) total burning	TOC – LOI-rr
	F8001-m5250	3.89			5.86	1.01
	F8001-m5560	2.89			4.76	0.75
	F8001-m5790	4.29			17.81	1.12
Devon-Givetian	F2881-m3950	4.33	0.80	0.73	6.56	1.13
Devon-Lochovian	F2881-m3950		0.60	0.9		
Silurian-Prid-Lland	F2881-m3950		0.90	1.5		
	F2811-m2818	1.65			4.48	0.43
	F2841-m3670	1.43			36.75	0.37
	F2841-m4045	2.19			3.68	0.57
	F2581-m3063	1.68			8.25	0.44
	F2506-m2655	4.35			12.21	1.14
	F2803-m2232	3.34			45.9	0.87

In the **western sector**, Gârla Mare-Oprişor (Lom-Băileşti Basin) wells intercepted argillitic, siltic, with bivalve fauna in prodeltaic, deltaic and neritic facies with low perspectives for obtaining, by metagenesis, the dry gas window. (Drillings and organofacies – data, tables from Patruti, 1961, Paraschiv, 1979, Iordan, 1985, Vinogradov, 1998, Seghedi, 2005).

In the eastern sector, many drillings intercepted Silurian, in the facies of argillites with graptolites. The thickness of Silurian is very variable, from 713 m, in Ţăndărei (East) to 380 m, in Optaşi (West). The initial sediments reached the metagenesis stage. The depositional facies are basinal, of ruxinic conditions. (Drillings and organofacies – data, tables from Patruti, 1961, Paraschiv, 1979, Iordan, 1985, Vinogradov, 1998, Seghedi, 2005) (Fig. 8).

The comparative examination of the vitrinite reflectance (Ro%) and IH (mgOil/gTOC) of the formations in the eastern (Călăraşi-Ţăndărei) and western sectors (Lom-Gârla Mare-Oprişor Basin) indicates important variations of these parameters (under the area of mature-dry gas, for Oprişor and Călăraşi and, in the area of dry gas window, by reaching the maturity necessary for thermal gas, in Ţăndărei, Mangalia, Ianca, Făurei drillings) (source: Veliciu şi Popescu, 2012) (Fig. 9).

Table 4

Oil-bearing potential of the formations located in the western sector of Moesian Platform

Age of studied formation	No. of drilling/ depth of core sampling	Organic matter %	RO – average values	TOC – average values	LOI-rr (CO2) total burning	TOC-LOI-rr
Devon (Givetian)	F1111-m3560	2.65	1.38	2	4.65	0.69
Silurian			1.40	1.50		
	F1112-m2175	2.55			3.88	0.67
	F1112-m4000	1.49			3.52	0.39

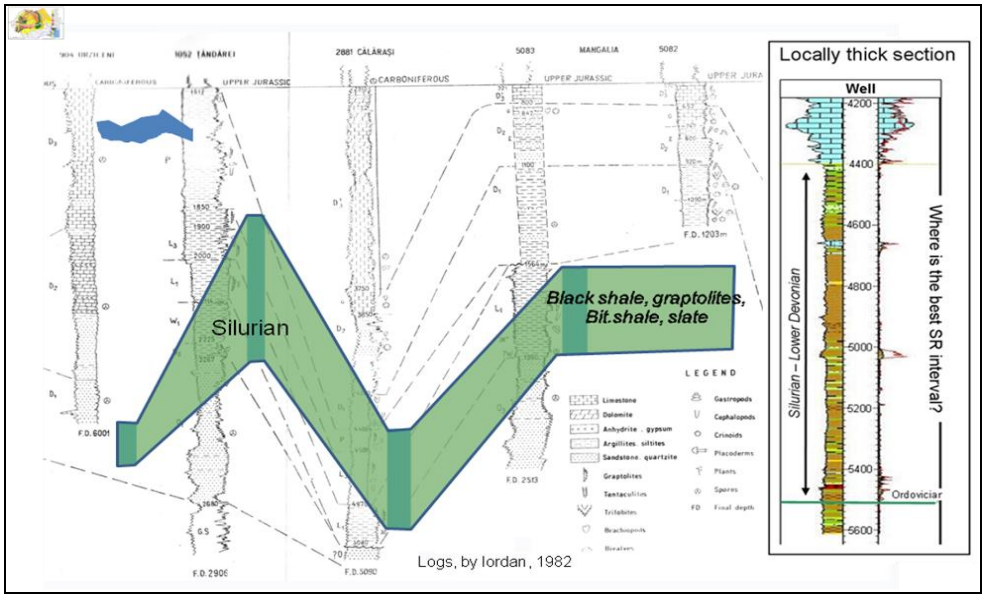


Fig. 8. Silurian Formations between Mangalia and Tandarei drills (by M. Iordan 1995, and Anastasiu 2012).

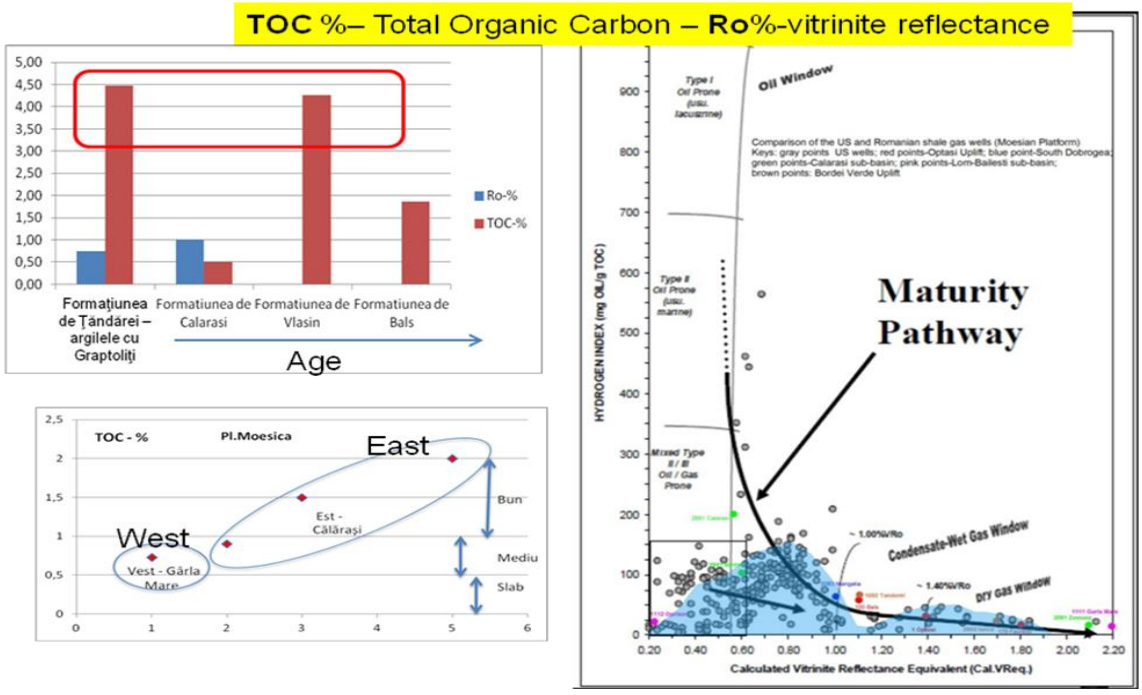


Fig. 9. TOC (%), and Ro(%) in Paleozoic and Mesozoic Moesian Formations;
right, a maturity pathway comparation with Barnett standard.

Table 5

Assessment of resources/reserves in Lom-Băileşti, Optaşi structures
(and Călăraşi-South Dobrogea, in three calculation hypothesis (Veliciu & Popescu, 2012)

Structure	Drilling	Formation/lithology	TOC %	Ro [%]
MP-West: Lom-Băileşti	1111 Garla Mare	Devonian Mediu (Giventian)/argillites	0.8–3.0	0.35–1.40
		Silurian/shale	1.0–1.9	1.40
MP-East Călăraşi		Devonian Mediu (Giventian)/argillites	0.73	0.75
	2881 Călăraşi	Early Devonian (Lochovian)/shale	0.8–1.0	0.4–0.8
		Silurian (Pridoli-Llandovery)/shale	1.50	0.40–1.36

	Lom-Bailesti			Optasi Elevation (Alexandria)			Calarasi-Dobrogea_South		
Assessment hypothesis	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic	Pessimistic	Average	Optimistic
OGIP Resources (Tcf)		29			687			579	
Reserves (Tcf)	0.3	0.6	0.9	6.9	13.7	20.6	5.8	11.6	17.4

The gas-bearing potential of the argillitic facies of Moesian Platform differs according to the age and basinal sector (Veliciu & Popescu, 2012).

CONCLUSIONS

- Many shales with *good petrophysical gas reservoir* parameters exist from the Paleozoic to the Tertiary. The best is Silurian (Paleozoic). There is a good understanding of the geological formations located between 0 and 3,500 m.
- The formations developed in the sediment dump of the **Moldavian Platform**, containing sequences of clay rocks which are richer in organic matter and implicitly those of gas shale (GS) type, are bituminous argillites and black clay rocks from the Paleozoic (Vendian – Silurian Period) as well as the Fălticeni-Boroaia Formation, the Cryptomactra Formation and the Bârnova-Muntele Formation dating back to the Neozoic. Black clay formation from the Middle Silurian exists at depths of 400–2,300 m, was deposited under accumulation conditions corresponding to a dysoxic-anoxic marginal basin and its thickness exceeds 30–40 m. TOC values (0.35 and 1.6) and vitrinite reflectance (Ro between 0.35 and 1.6), reveal a remarkable potential.
- **Bârlad Depression**, which is part of the Scythian Platform, has formations of particular concern for shale gas production, dating back to the Silurian – Devonian sedimentation cycle, when clay rocks developed significantly. The relevant formations developed at depths between 900 and 3,800 m, in a basinal-pelagic depositional environment, and the organogenetic parameters have average values between 1.0 % and 2.4 % for TOC and between 0.60% and 3.5% for vitrinite reflectance.
- Upper Cambrian – Westphalian, Permian – Triasic and Toarcian – Senonian cycles from the four sedimentation cycles of **Moesic**

Platform overlay have an important shale gas potential. Marine deposits with a thickness of around 6,500 m accumulated during such cycles. The gas-production potential of argillite facies in the Moesic Platform vary depending on age and basinal sector. The main formations with a proven gas production potential are Ţăndărei Clay Formation, Călăraşi Formation, Vlaşin Formation and Balş Formation whereof Silurian formations in the graptolite argillite facies have the most important shale gas generation potential. The thickness of Silurian formations, deposited in the basinal – euxinic facies varies from 713 m, in Ţăndărei (East), to 380 m, in Optaşi (West). Organogenetic parameters undergo significant variations, being located under the dry-mature gas window, for Oprişor and Călăraşi areas, and in the dry gas generating window, reaching the maturity required for thermal gas, in Ţăndărei, Mangalia, Ianca and Făurei areas.

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