Tandarei and Radauti Formations: Future Unconventional Exploration Gas Plays in Romania*

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Search and Discovery Article #80369 (2014)**
Posted March 31, 2014

*Adapted from oral presentation at the AAPG Europe Regional Conference, Tbilisi, Georgia, 26-27 September 2013

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Summary

Although the Silurian gas-prone shales are different in a number of respects in Moesia and East European Craton, the Tandarei and the Radauti black mudstones and their counterparts in Bulgaria, Moldavia, and Ukraine show a significant depositional and paleontological similarities. Recent work (Veliciu and Popescu, 2012) evaluated the gas potential resources of the Silurian- Lower Devonian mudstones in the Romania foreland basins. They revealed good petrophysical and geochemical characteristics, sensibly comparable to those already producing gas in the US: Barnett or Marcellus.

Emphasis in the studies was on the description of the lithostratigraphy and the depositional environment covering the Ediacaran Vendian-Devonian mega-sequence. It contains the Silurian gas-prone mudstones which appear related to the flexural bending close to the major crustal Teisseyre-Tornquist fault zone (TTZ). The TTZ is major lineament, and together with Sorgenfrei –Tornquist (STZ) and Elbe lineaments, is a fundamental lithospheric boundary in Europe, the Trans-Europe Suture Zone, or TESZ (Pharaoh et al., 2006). Establishing the trace of the TTZ in Romania was one of the major problems we had to solve for defining the eastern Romania and southern Moldova pro-foreland basin extension, as well as the position of the wedge separating it from the southern Romania and northern Bulgaria retro-foreland basin. It is proposed that a wedge, now located in outcrop and near-surface in the northern Tulcea Unit, mark the deformation front between the two terranes. This entity could had been periodically submerged; this, among other factors, may make it simpler to explain the reasons of the often reported mixtures of Gondwana and Baltican faunas from the larger TESZ development area.

-The Radauti shales accumulated in eastern Romania on an approximate N-S-trending pro-foreland basin over the TTZ, between Siret and Solca faults. From there, the Radauti Formation curves to the east, south of the Vaslui and Bistrita fault couple. Shale deposition, located on a Baltican basement, extends onto the flexural, convergent margin of the Caledonian orogeny (Tari et al., 2012) that included the TTZ.
-A deepwater turbidite facies wedge is partially cropping out in the North Dobrogea Inversion’s Tulcea Unit (e.g., Seghed, 2012). It was deformed in the late Caledonian and early Variscan compression phases. The now, southward contiguous Macin Unit displays shallow-water Silurian and Early Devonian facies.

-The Tandarei Formation is developed at some distance SW of TTZ, more precisely west of the Central Dobrogea's Danube Fault, in Eastern and Western Moesia. Tandarei mudstones were deposited in sub-basins on an Avalonian-Cadomian basement (Balintoni et al., 2010) that could represent the retro-foreland basin zone.

The assessment of the Silurian-Lower Devonian organic-rich mudstones (Veliciu and Popescu 2012) revealed they were buried under as much as 4000 m of Paleozoic, Mesozoic, and Cenozoic sediments. Also, both formations show similarly reservoir, organic carbon content and maturation parameters, as tabulated below.

Name of Shale Play	**Țăndărei Fm.**	**Rădăuti Fm.**	**Barnett Shale**	**Marcellus Shale**
Depth (ft)	3,000 to 14,500	1,300 to 12,500	5,000 to 8,000'	4,000 to 9,000'
Thickness (ft)	30 to 400'	100	100 to 500'	<10 to 300'
Porosity (%)	2 - 10	1 - 8….	1 - 9	2 - %
Permeability (mD)	n.a.	n.a.	0.00009 to 0.001	0.00001 to 0.01
TOC (%)	1.0 to 1.5	0.6 to 2.4	4 to 8 type II	0.1 to 13 type II-III
Ro (%)	0.4 to1.5	0.35 to 3.6	1.2	1.6 to 3.5

The resource evaluation shows that the technically recoverable resources amount to some 0.95 TCM, i.e., 60 years of production at the present-day output levels .The study of the gas potential of Tandarei and Radauti formations is in the early stage of geological and engineering understanding. Primarily there is a poor knowledge of kerogen maturation dynamics, physical rock properties, mineralogy, subtle facies changes, or natural formation fracturing.

In Romania, the start of modern investigation of these parameters by western oil companies is imminent, with the spud of a first well in the Radauti Formation within the year.

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Acknowledgments

The Tectonic Map of the Carpathian Foreland was drafted by, and with contributions of, Jimmy Micu. Some of the cartoons were drafted by Emilia Ranete. They are especially thanked by the authors.

TANDAREI and RADAUTI formations future unconventional gas plays in Romania

by

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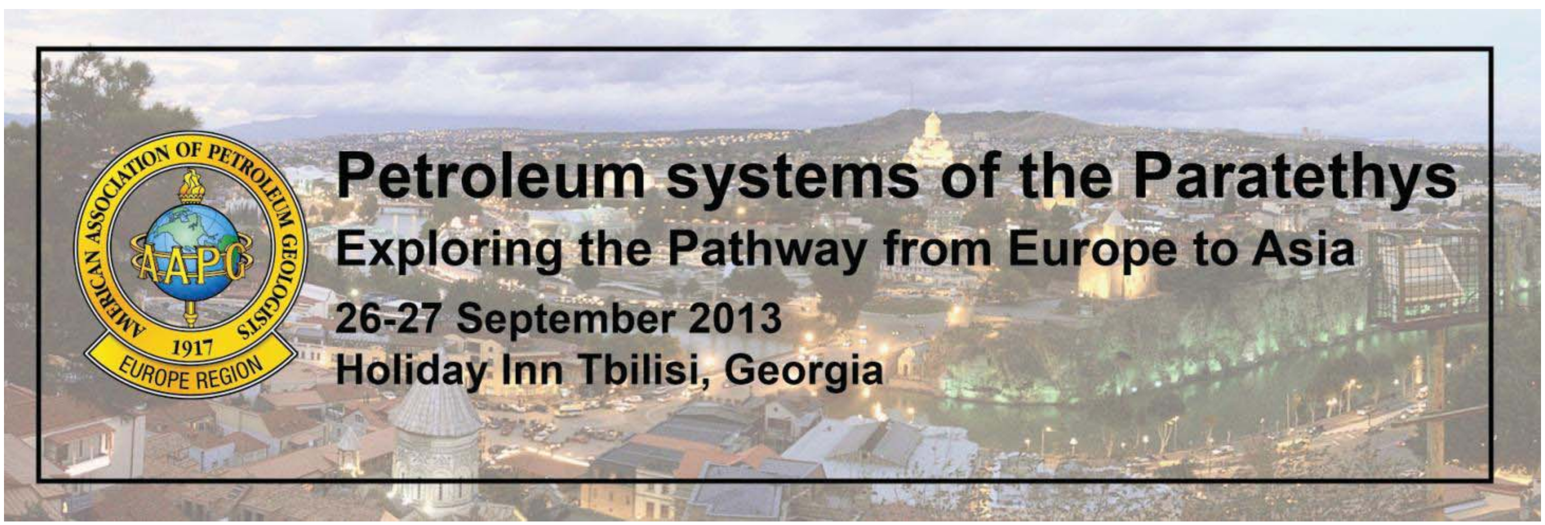
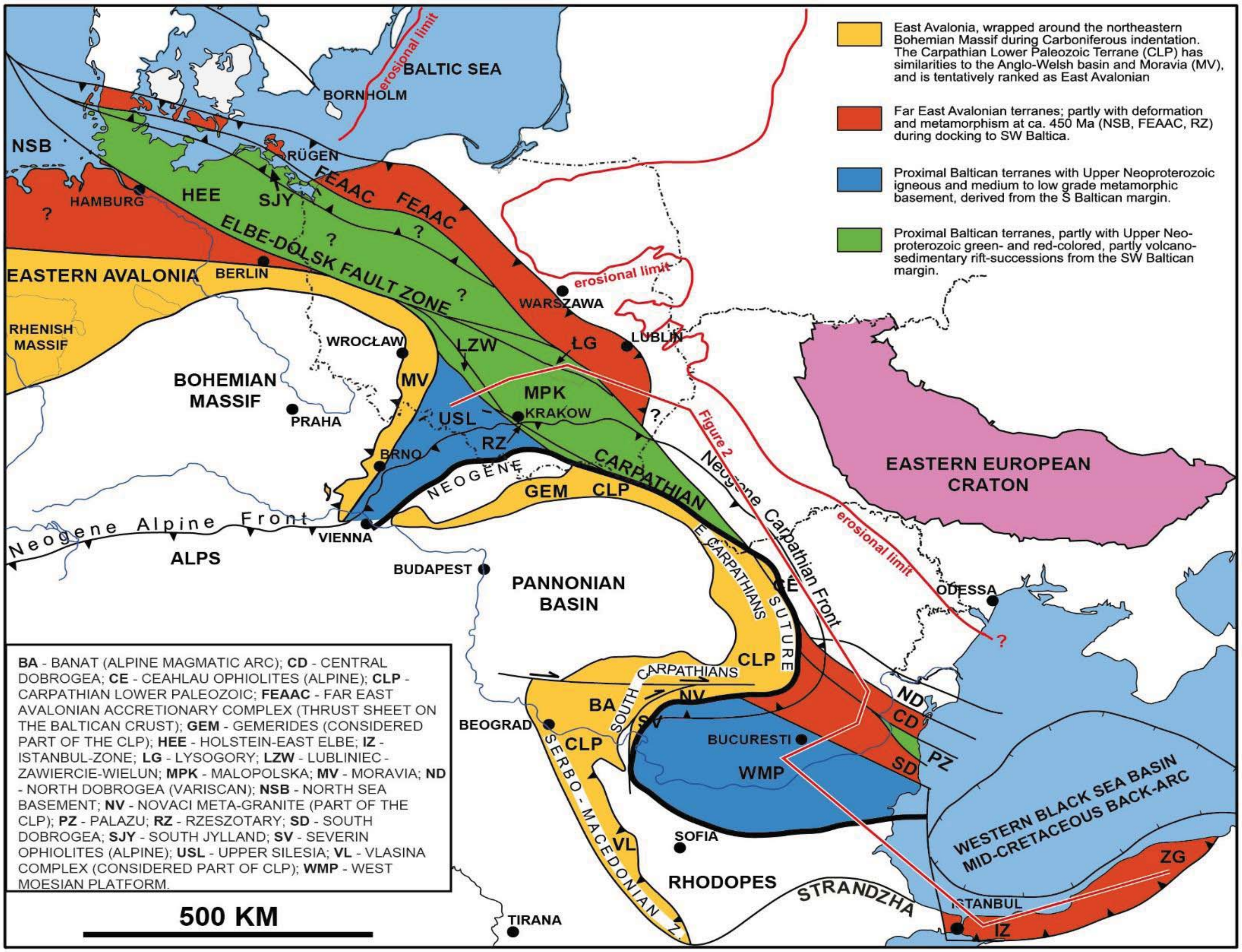
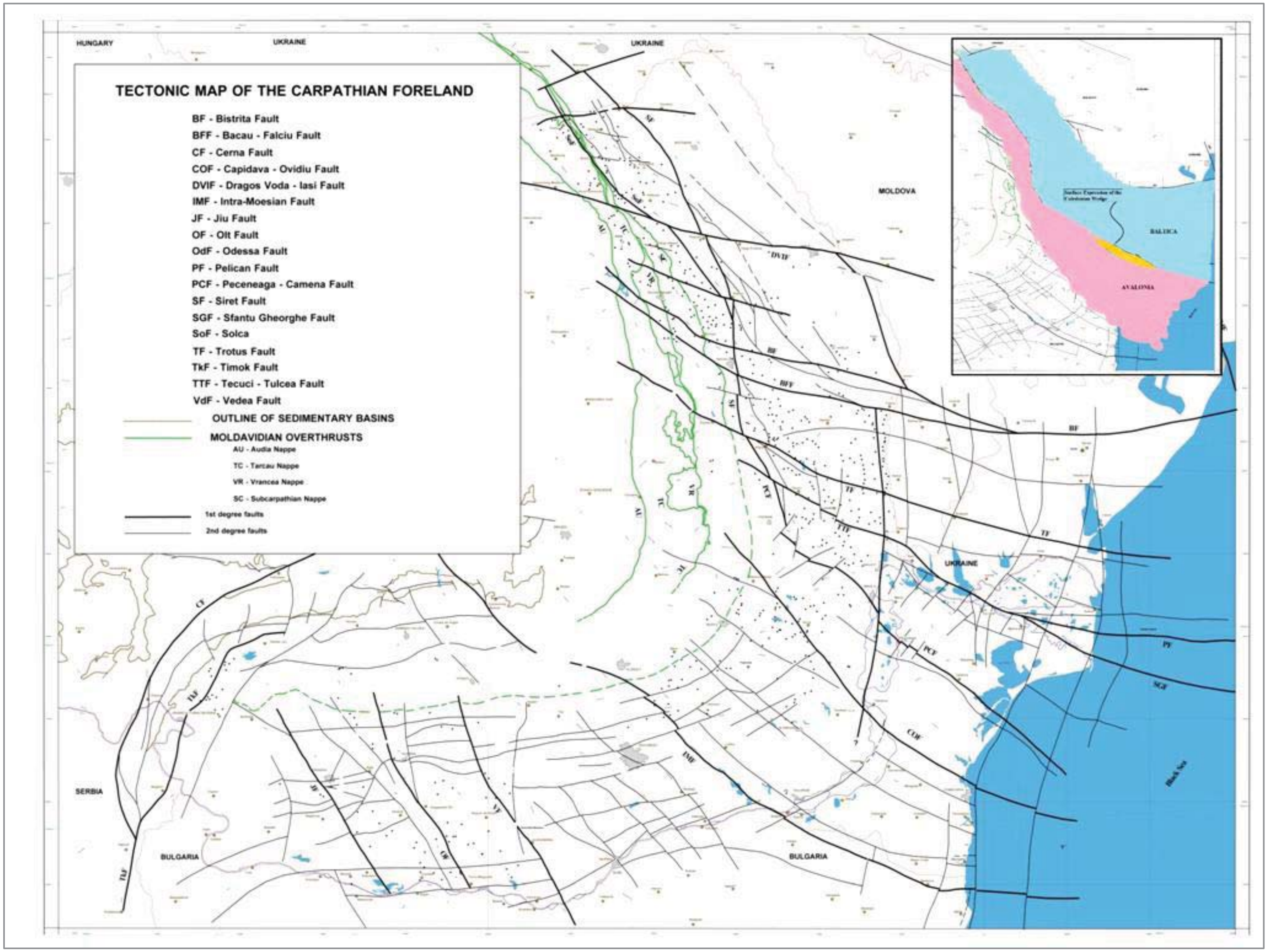


Caledonian terranes on the southwestern margin of the East European Craton (from Tari et al., 2012)





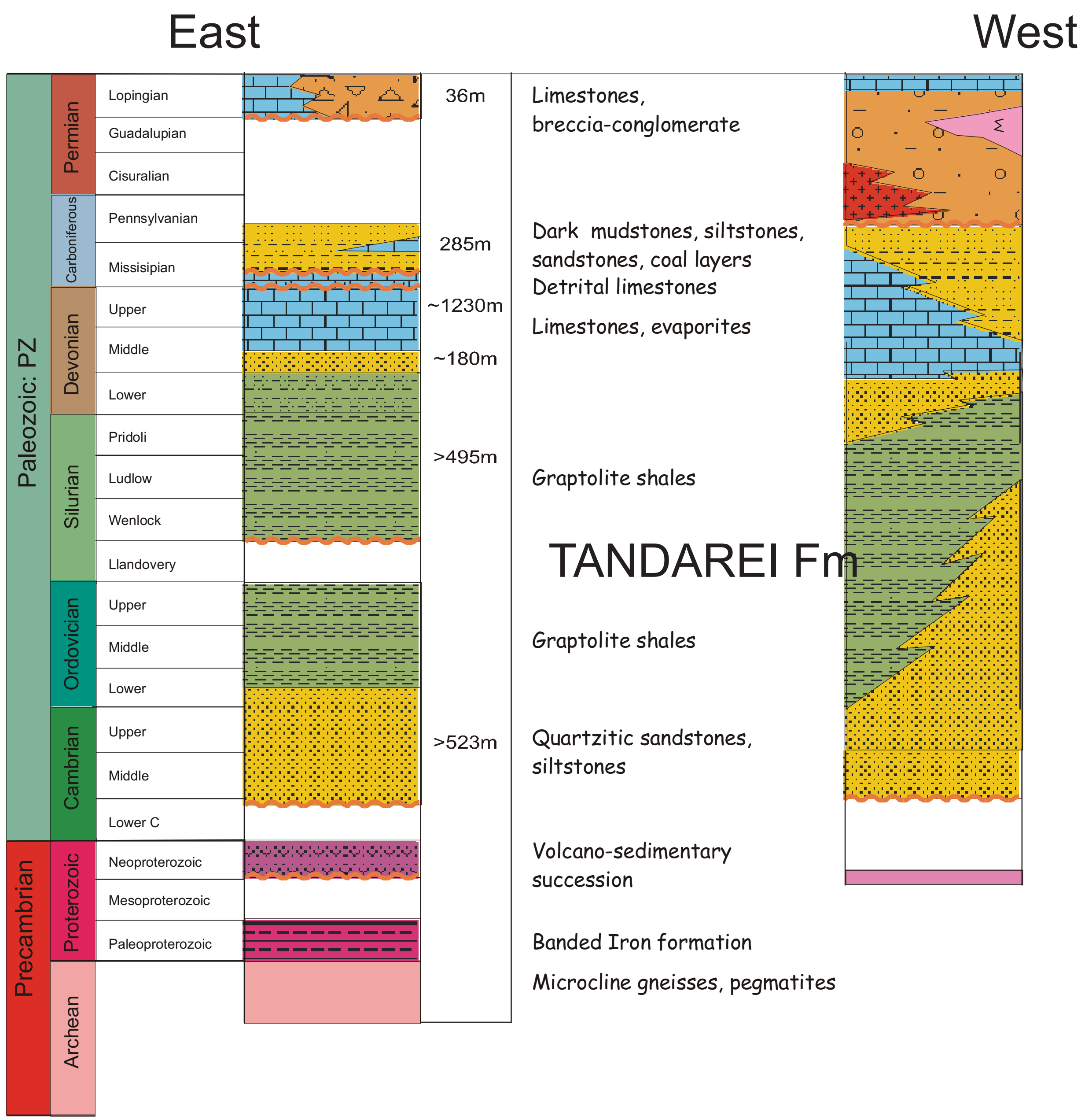
Presenter's notes: The tectonic sketch of the Carpathian foreland shows the contact between Far East Avalonian terranes (pink) the Baltican terranes (blue) and, between these major terranes, the partially outcropping expression of the Caledonian deformational pro-wedge (brown) that belongs to the Teisseyre-Tornquist Zone (TTZ) .

TANDAREI PLAY

Late Ordovician-Early Devonian

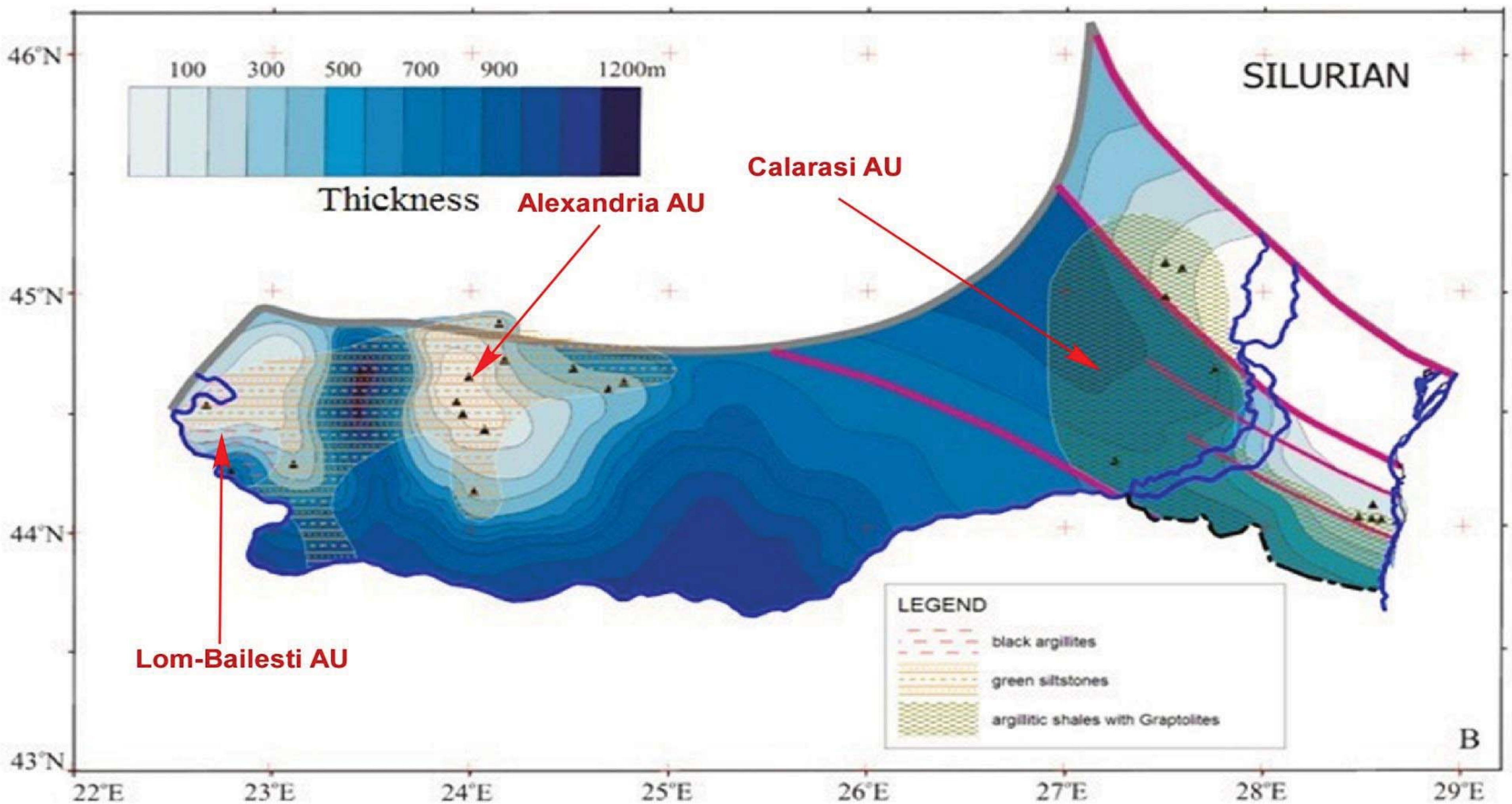
Lithostratigraphic charts of Moesia Paleozoic

(after Paraschiv et al 1983, Iordan 1987, 1992)

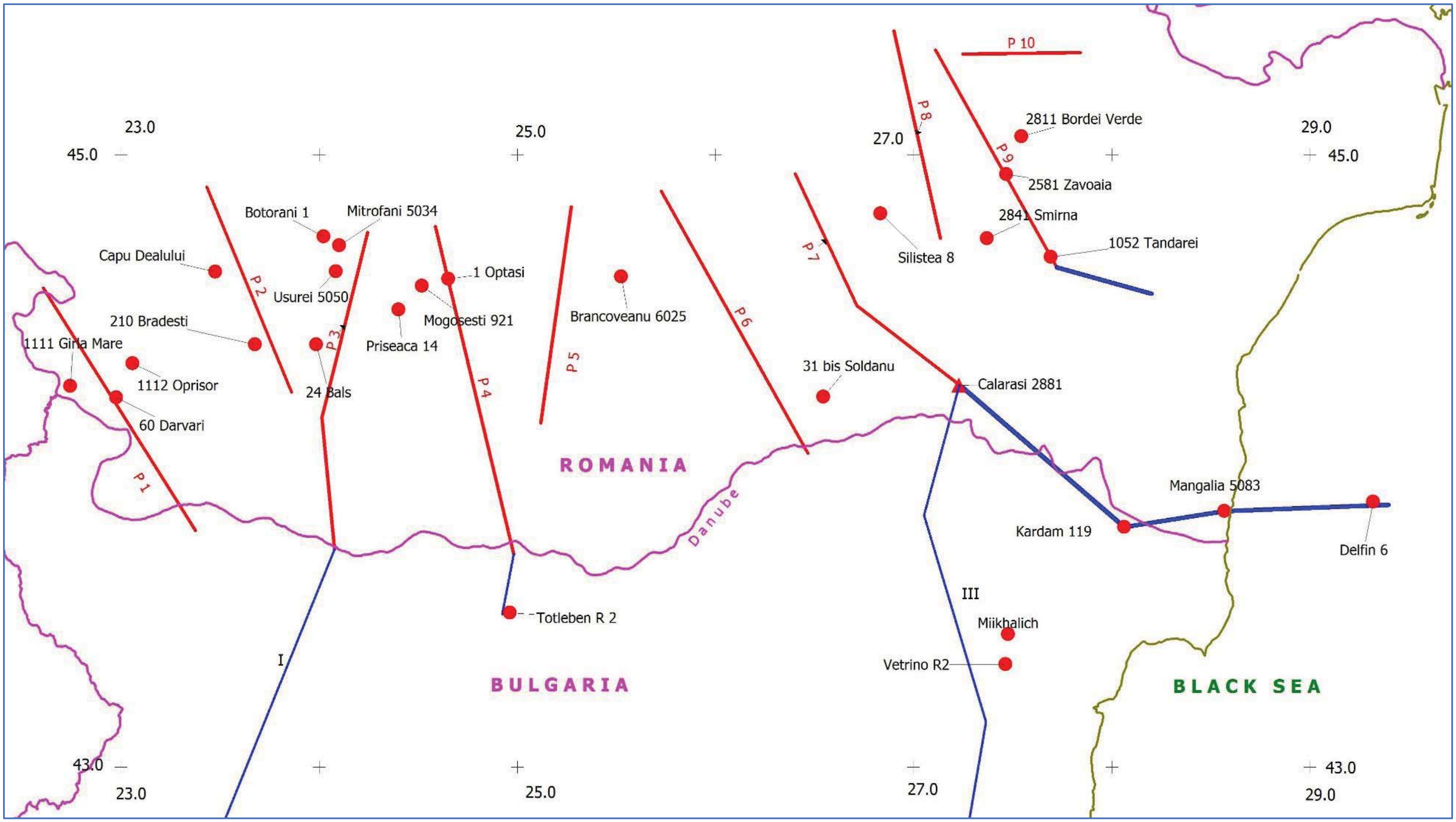


Moesian Platform – Isopach and facies of the Silurian Tandarei Fm showing areas of assessment units

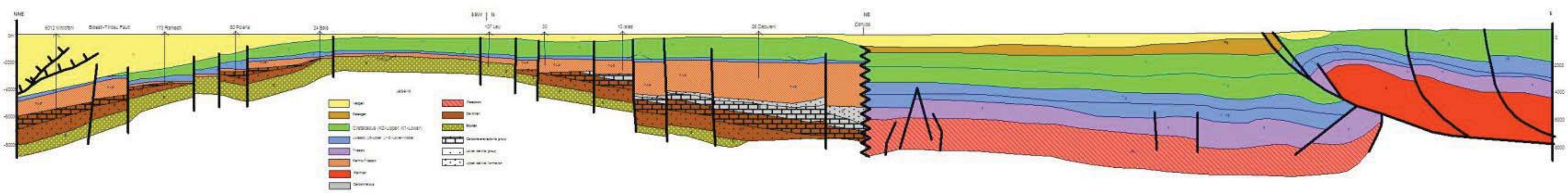
(modified from Seghedi 2005)

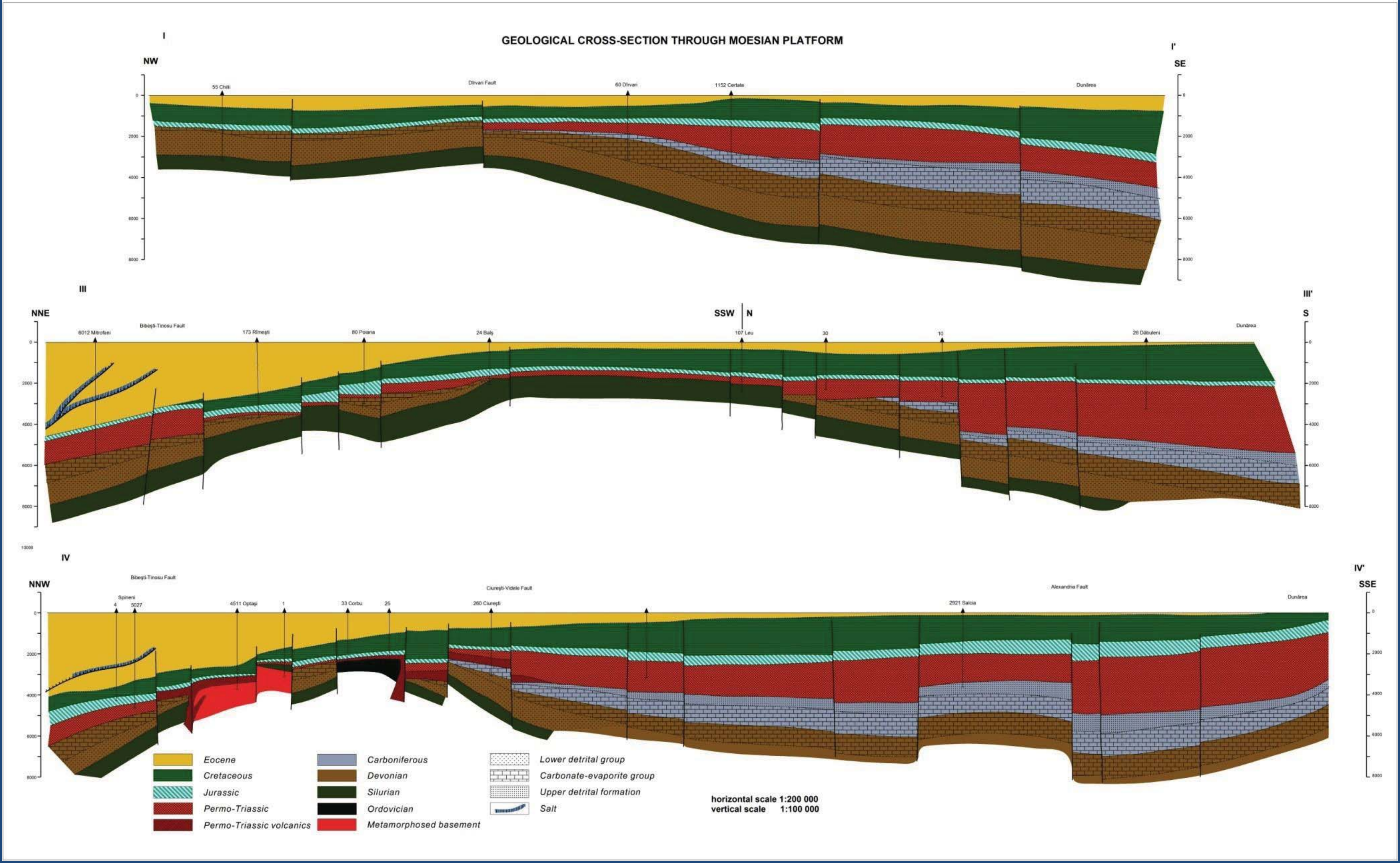


Moesia - Location of cross-sections



Moesia: Regional cross-section Romania/Bulgaria (III-III')





GEOLOGICAL CROSS-SECTION THROUGH MOESIAN PLATFORM
I
I'
NW
SE
55 Chilli
Dîrvari Fault
60 Dîrvari
1152 Certate
Dunărea
III
III'
NNE
SSW
N
S
6012 Mitrofani
Bibeşti-Tinosu Fault
173 Rîmeşti
80 Poiana
24 Balş
107 Leu
30
10
26 Dăbuleni
Dunărea
IV
IV'
NNW
SSE
Bibeşti-Tinosu Fault
Spineni
4
5027
4511 Optaşi
1
33 Corbu
25
Ciureşti-Videle Fault
260 Ciureşti
2921 Salcia
Alexandria Fault
Dunărea
Eocene
Cretaceous
Jurassic
Permo-Triassic
Permo-Triassic volcanics
Carboniferous
Devonian
Silurian
Ordovician
Metamorphosed basement
Lower detrital group
Carbonate-evaporite group
Upper detrital formation
Salt
horizontal scale 1:200 000
vertical scale 1:100 000

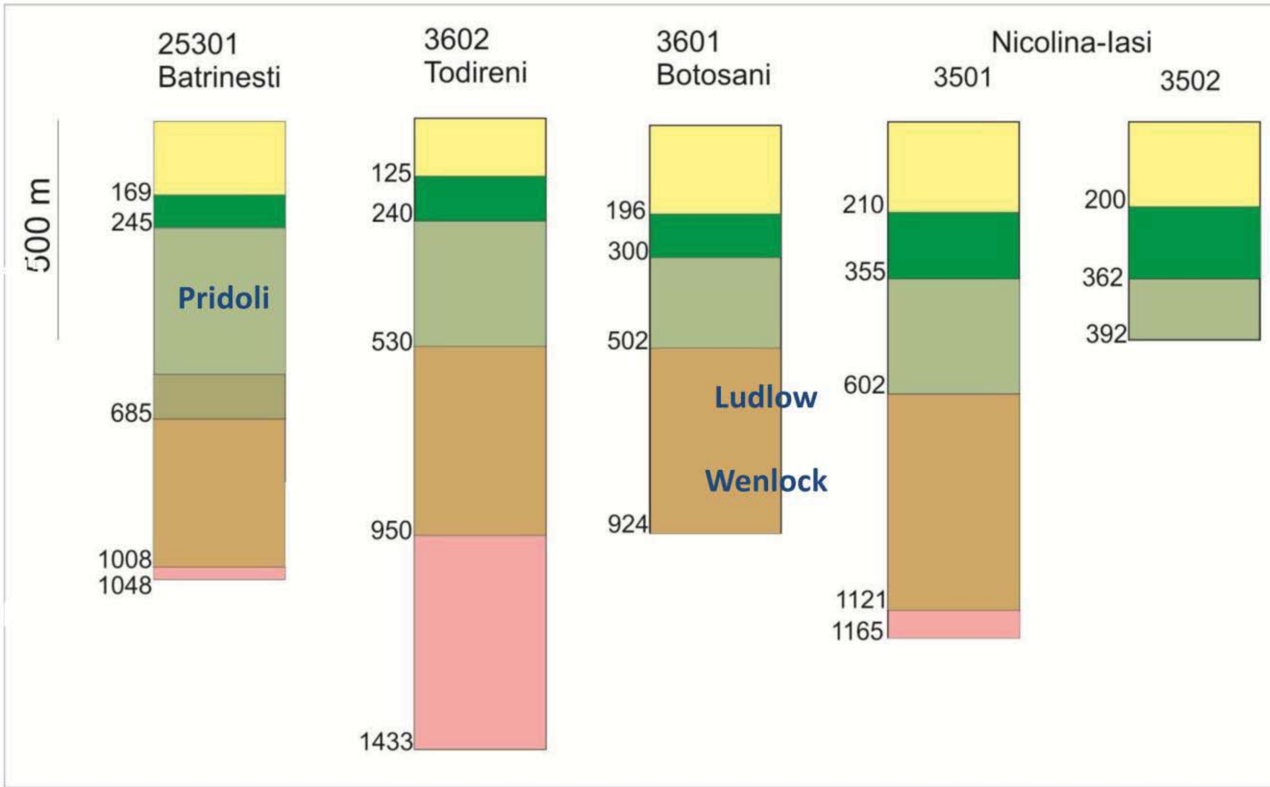
Shale Gas Reservoirs Properties of the Paleozoic Formations in Moesia

	Plays	Lom - Bailesti	Alexandria	Calarasi
	Shale formations	black shales, argillites	black shales, argillites	shales, argillites
	Geological age	Silurian - Lower&Middle Devonian	Silurian - Lower&Middle Devonian	Silurian - Lower&Middle Devonian
Physical extent	Prospective Area (acres**km^2**)	196.307**794**	2,098,981**8,494**	2,953,543**11,952**
	Depth at the top of formations organically rich (ft.)	10,000 - 14,500	6,600 - 8,200	3,000 - 12,500
	Average thickness of organically rich reservoirs (ft.)	1.132	2.457	1.217
Reservoir properties	Pressure (Mpa)	35	30	28
	Temperature (Rankin)	663	654	636
	TOC (wt. %)	0.428 - 0.966	0.800 - 1.500	0.728 - 1.457
	Thermal maturity (% Ro)	0.74 - 1.90	0.85 - 1.40	1.00 - 1.50
	Volume factor Bg	0.0037	0.0043	0.0049
	z - factor	0.9922	10,000	11,000

RADAUTI PLAY

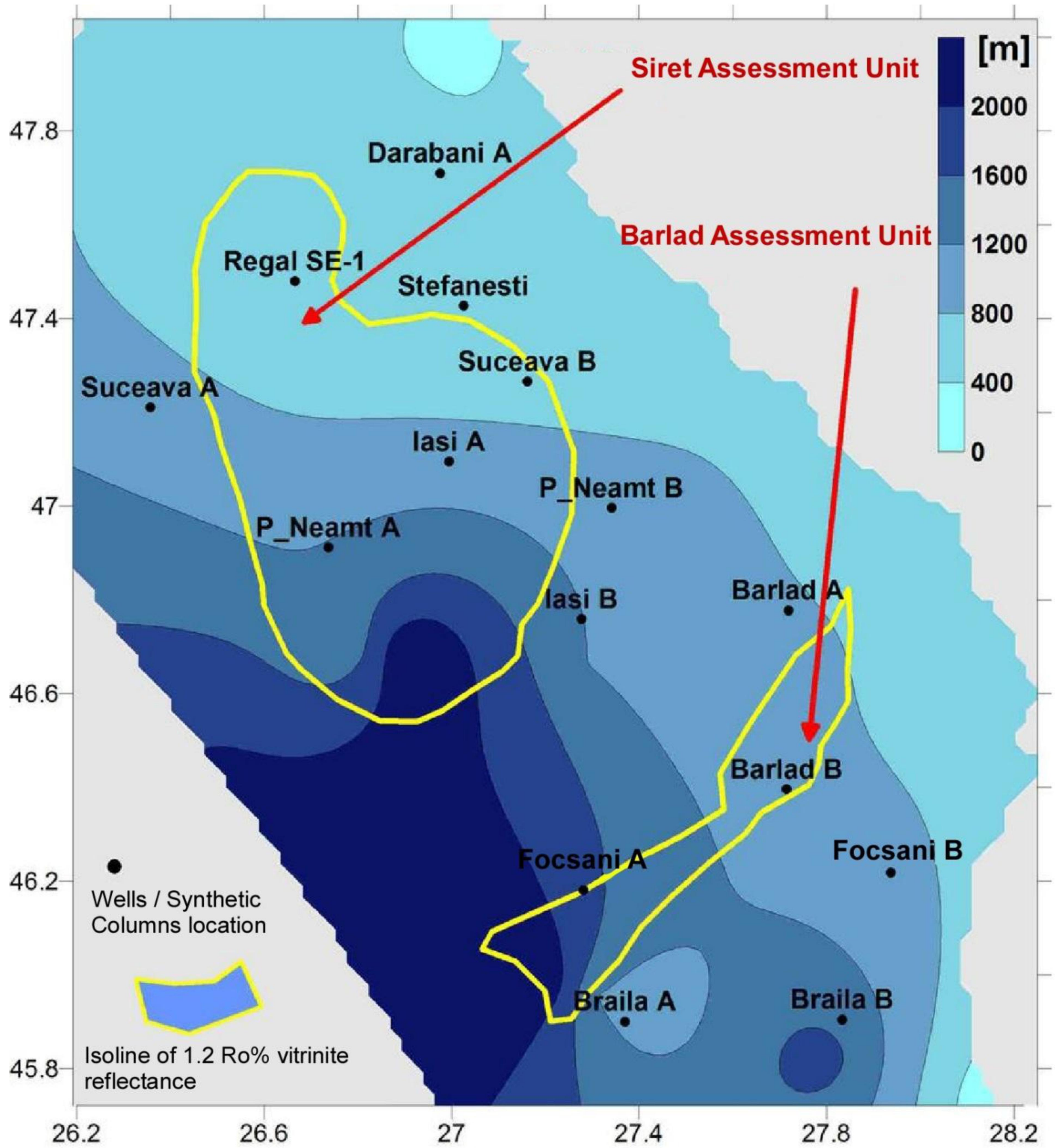
Silurian

Wells drilled through Silurian carbonate-terrigenous facies on the Romanian sector of Dniester Pro-foreland Basin (after Iordan, 1974)



Presenter's notes: During the Silurian, west of the Siret line, a foreland basin fore-bulge (DeCelles and Giles, 1996) developed; it separates the two sub- basin types of the pro-foreland Dniester basin:

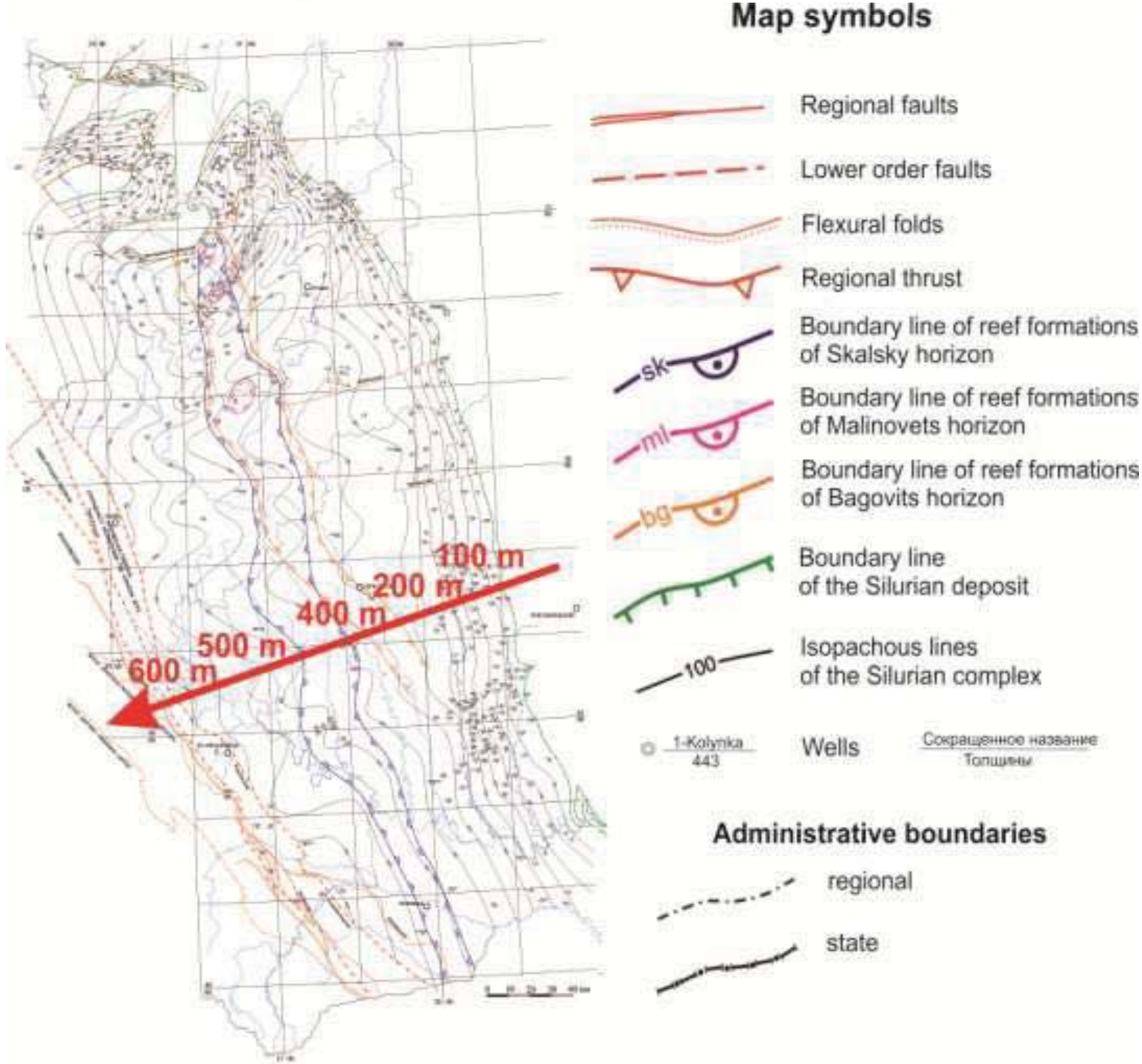
- to the west, the flexural basin that accommodates the Silurian, mostly thick anoxic sediments and ,
- to the east, the Cernauti thermal (?) sag sub-basin filled mostly with thinner terrigenous and carbonate sediments.



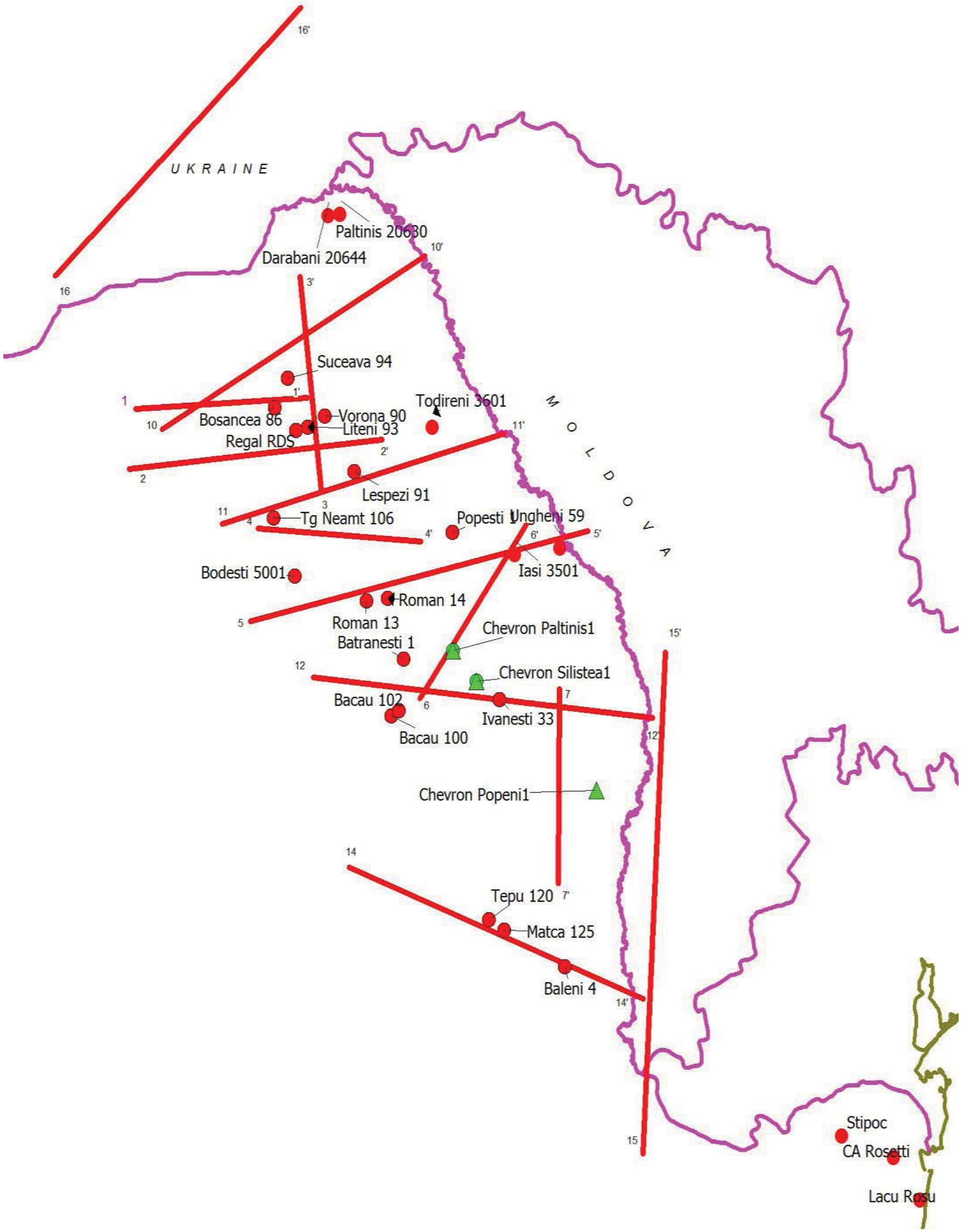
Dniester Basin- Isopach Map of Silurian Radauti Fm. showing the areas of assessment units

Western Ukraine – Thickness of the Silurian

(after Rudko 2013)



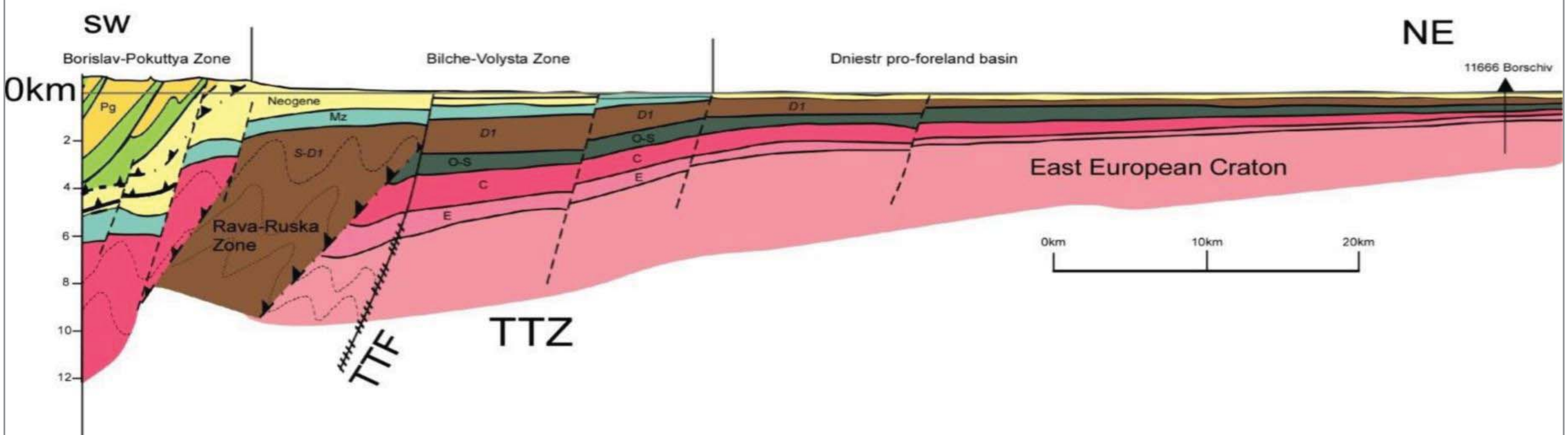
Dniester Basin - Location of cross-sections
(1-1' to 7-7', 10-10' to 12-12', & 14-14' to 16-16')



Cross-section North of Romania/Ukraine border (16-16’)

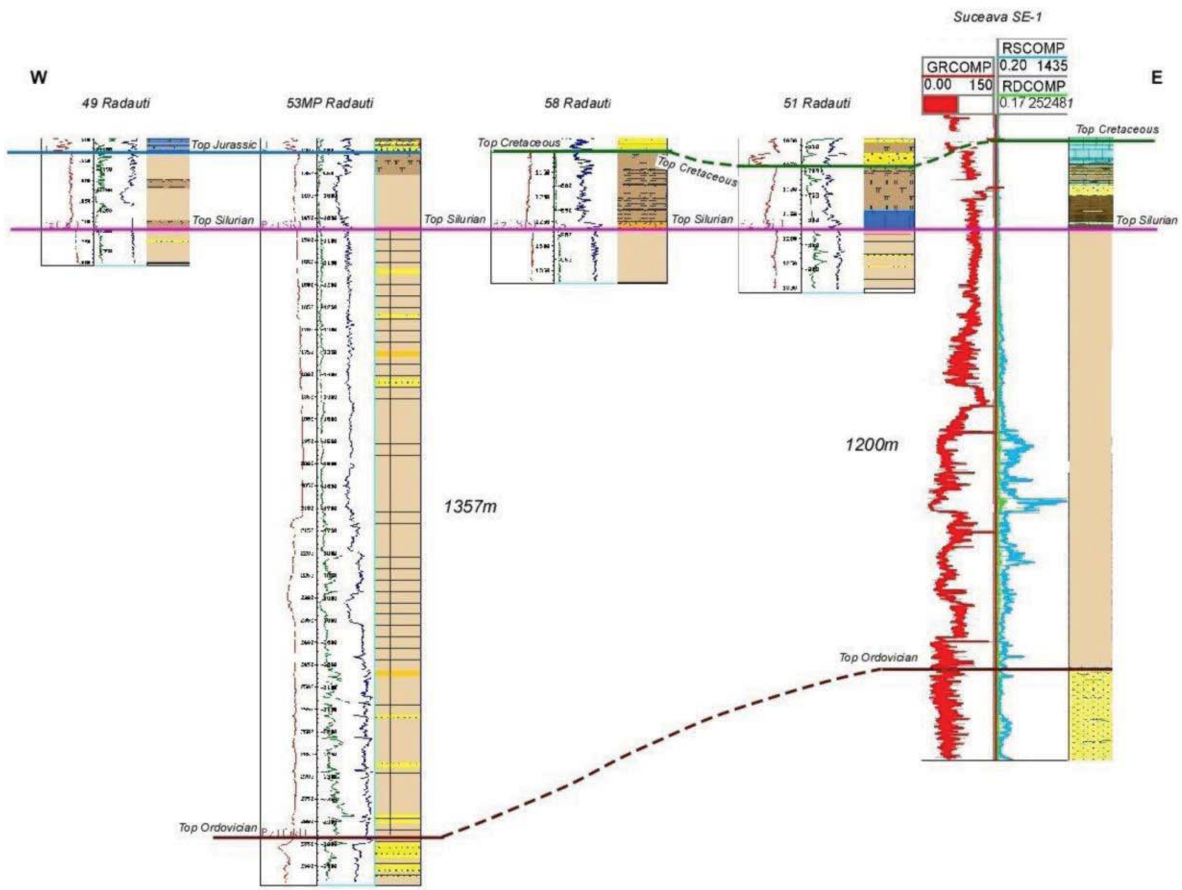
(adapted from Western Ukraine Tectonic

Map)



Presenter’s notes: The Bilche-Volitsa Zone includes both the TTZ and the Rava-Ruska (Russian-Rava) Zone.

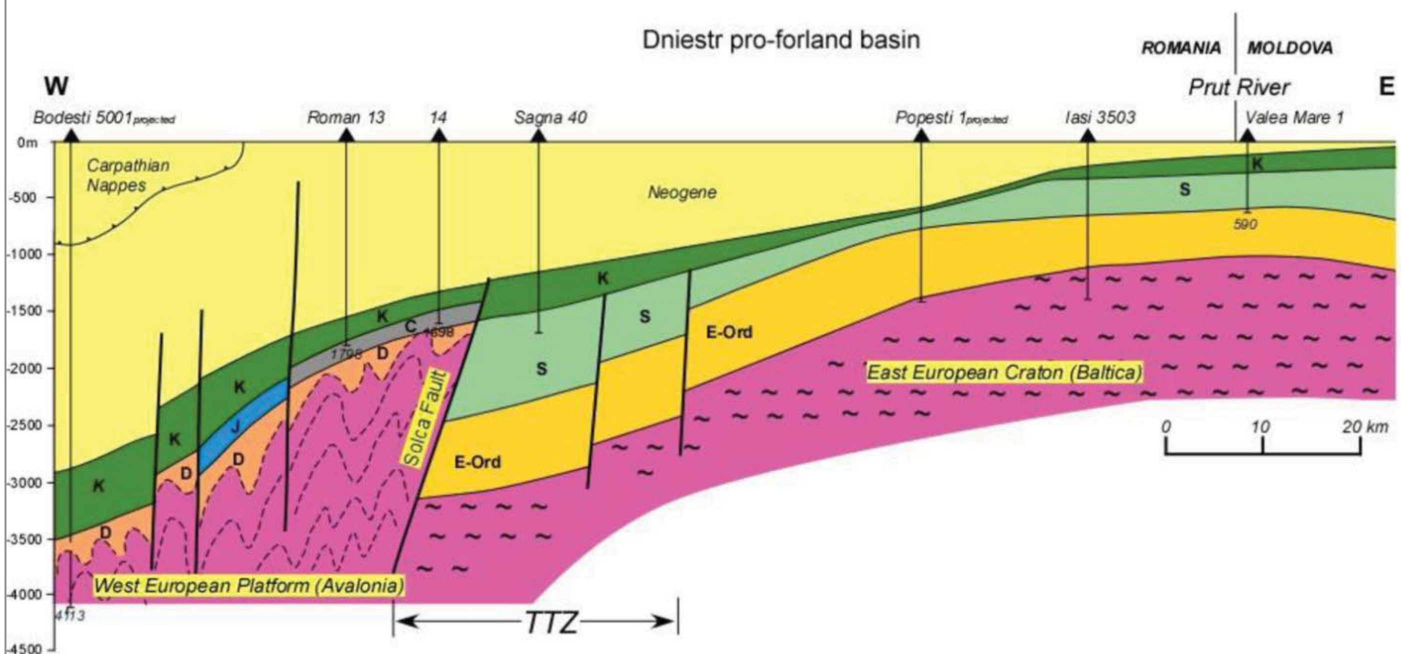
Development of Radauti mudstones in the TTZ south of the Romania/Ukraine border



Presenter's notes: Increase in thickness of the Silurian to the west; flexural bending indicated in the area of the Solca and Siret faults. Sand layers shown at various levels in the black mudstone packages possibly originated from the Far East Avalonian exhumed retro-wedge terranes.

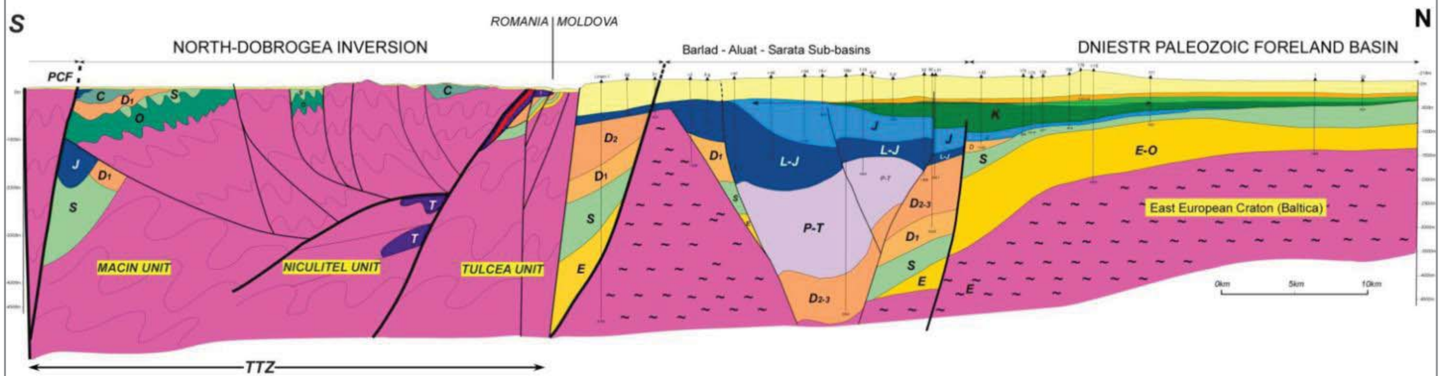
Cross-section North-Eastern Romania EEC (5-5')

(modified after Paraschiv 1986, Patrut & Danet 1987)



Presenter's notes: Note the fore-bulge drilled in the Popesti 1 and Iasi 3503 wells and the development to the east of the back-bulge (DeCelles and Giles, 1996), the Chisinau sag basin with Silurian clastic and carbonates facies.
West of the Solca Fault , correlated by Sandulescu (1984) with the Rava-Ruska Fault of W. Ukraine, the greenschist basement and the Vendian-Cambrian package are tightly folded. The unconformable, folded Devonian west of the Solca Fault develops into Old Red Sandstone facies (Paraschiv, 1986).

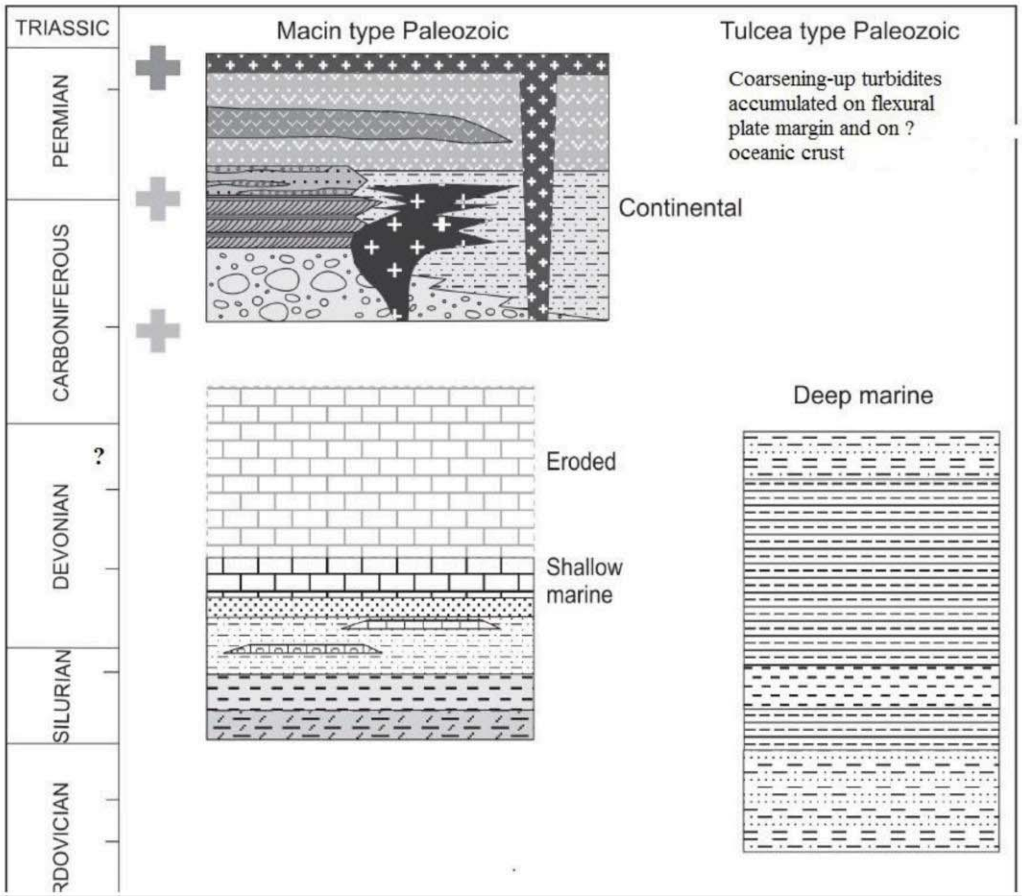
Cross section Moldova-Romania (15-15’)



Presenter’s notes: Tulcea unit is narrow, with sparse outcrops in the western part, close to Danube/Prut river junction where this section is located. Yet, it expands eastwards where a prominent gravimetric low was interpreted as an expression of the thick sediment pile (Rosca and Atanasiu 1993). We propose this minimum has the appearance of the deformational pro- wedge between the Baltican and Far Avalonian terranes. The whole North Dobrogea Paleozoic suite was reworked during the Variscan movements and was inverted during the Cimmerian (Sandulescu, 1984) and Alpine (Laramian and probably Pyrenean) movements.

Paleozoic Chronostratigraphy and Facies N Dobrogea

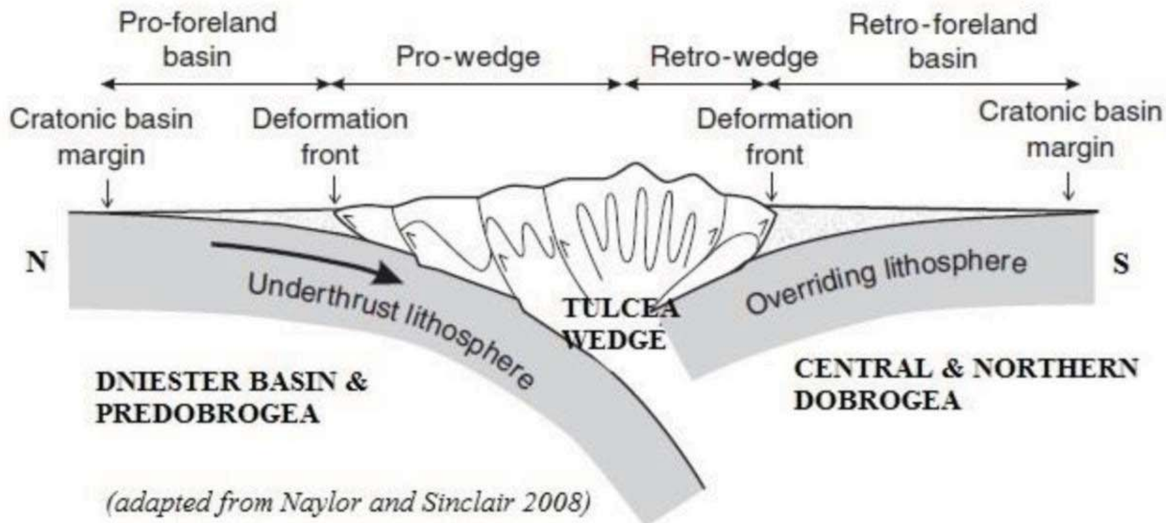
(from Seghedi 2012)



Presenter's notes: The Tulcea type Devonian (Bestepe Fm) consists of tightly folded flysch and distal turbidites (Seghedi 2012) in water depths of at least 800m. The Carboniferous is not known in the area. In the southern Macin-type (retro-foreland), the uppermost Devonian is a shallow-marine facies (the Bujoare Fm), unconformably overlain by the continental Carboniferous Carapelit facies.

Mid?- Late Devonian Plate Interaction: Baltica & Avalonia

(see Tari et al., 2012 for comparable interpretation in the northern CEE)



Presenter's notes: During the latest Caledonian Erian phases, at least the northern part of the Tulcea Unit acted as a deformational zone in front of the underthrusting Dniester pro-foreland while the Macin and Niculitel units were located behind the folding wedge and were depositional areas of Lower Paleozoic shallow-water facies of the Far Avalonia retro-foreland basins.

The TESZ, including TTZ, became a dextral slip transpressional zone in the Santonian-Maastricthian (Swidrowska et al., 2008) after a long period (ending in Mid-Cretaceous) of sinistral transtensional movements . The latest Neogene strike-slip movements, induced by the clockwise progression of the Alpine Orogeny, commonly cut the TESZ/TTZ lineaments and appear to have been, again, predominantly sinistral.

Shale Gas Reservoirs Properties of the Paleozoic formations in Moldavia

	Plays	SIRET	BARLAD
		Shales (20-80%) Limestones (10-15%) Sandstones (40%)	Shales (20-70%) Limestones (20-30%) Sandstones (30%)
	Geological age	Silurian	Devonian - Silurian
Physical extent	Prospective Area (acres**km^2**)	2,031,983**8,223**	272,267**1,102**
	Depth of top of formations organically rich (ft.)	1,350-7,500	3,000-12,500
	Average net thickness of organically rich reservoirs (ft.)	98	82
Reservoir properties	Pressure (Mpa)	35	30
	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
	Volume factor Bg	0.0048	0.0033
	z - factor	0.860	0.900

EVALUATION OF RESOURCES

1- Assessment adhering to the EIA and USGS methodology

2- Producible with current technologies, regardless of other costs

3- Based on: Veliciu S., Popescu B., 2012 - Are the Paleozoic Plays the Future of Unconventional Gas in Romania? An Attempt of Assessing the Resource

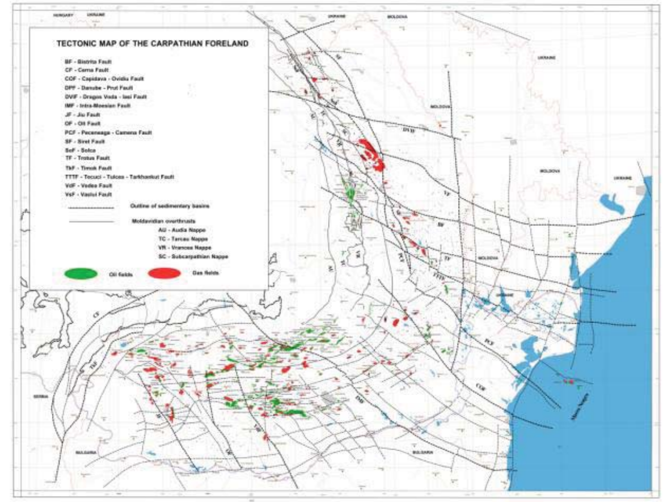
The Unconventional Production is the Result of a REVOLUTION IN RESERVOIR EVALUATION

		Conventional	Unconventional
Geological Risk		High	Lower
Trap	Frequent	Structural, lesser extent stratigraphic	Stratigraphic, pervasive at the basin extension
	Type	Buoyancy + Seal	No active drive
	2D Size	Smaller, well defined	Huge, continuous play
Reservoir	Common Lithology	Porous Sandstones and Carbonates	Mudstones, Tight Sandstones, Tight Carbonates, Tar sands, Coal
	Permeability	Millidarcies	Nanodarcies
Production	Well Design	Vertical	Horizontal
	Recovery	Initial natural flow	Stimulated
	Net Energy Factor (EROEI)	10:1 up to 100:1	1.5:1 up to 10:1 (est)
E&P Expenses		Lower	High

Adapted from : Beaumont 2013, Hall 2008

Presenter’s notes: Boundary between conventional and unconventional hydrocarbons has shifted constantly. In an ideal, predictable, economic growth world and oil prices, there should be no difference between categories. Note that EROEI in shale gas would be higher than in tight oil (1.5: up to 5).

Romania Outlook



PROS

- The major Paleozoic plays are located in rather sparsely inhabited, agricultural areas
- Relative availability of services and qualified workforce
- Availability of water and sand or other proppants
- Lower concession costs (so far!)

CONS

- Early stage of geological knowledge: primarily poor knowledge of kerogen maturation dynamics, physical rock properties, mineralogy, subtle facies changes or natural fracturing
- Unclear regulations and unending varying politics
- Public opinion insufficiently E&P educated, easy to manipulate

Assessment process used for the TANDAREI & RADAUTI gas plays

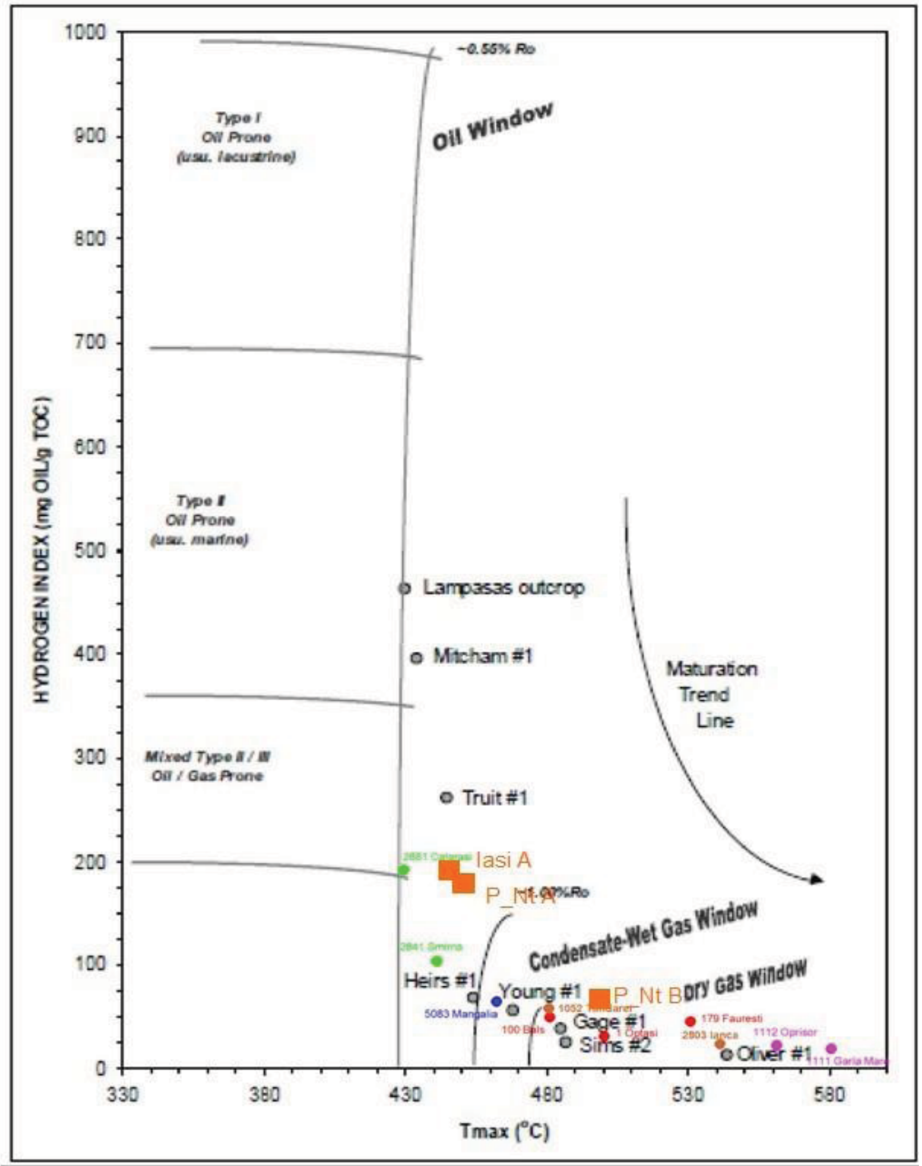
Available geological and reservoir data were assembled for each major shale formation, including the following key items:

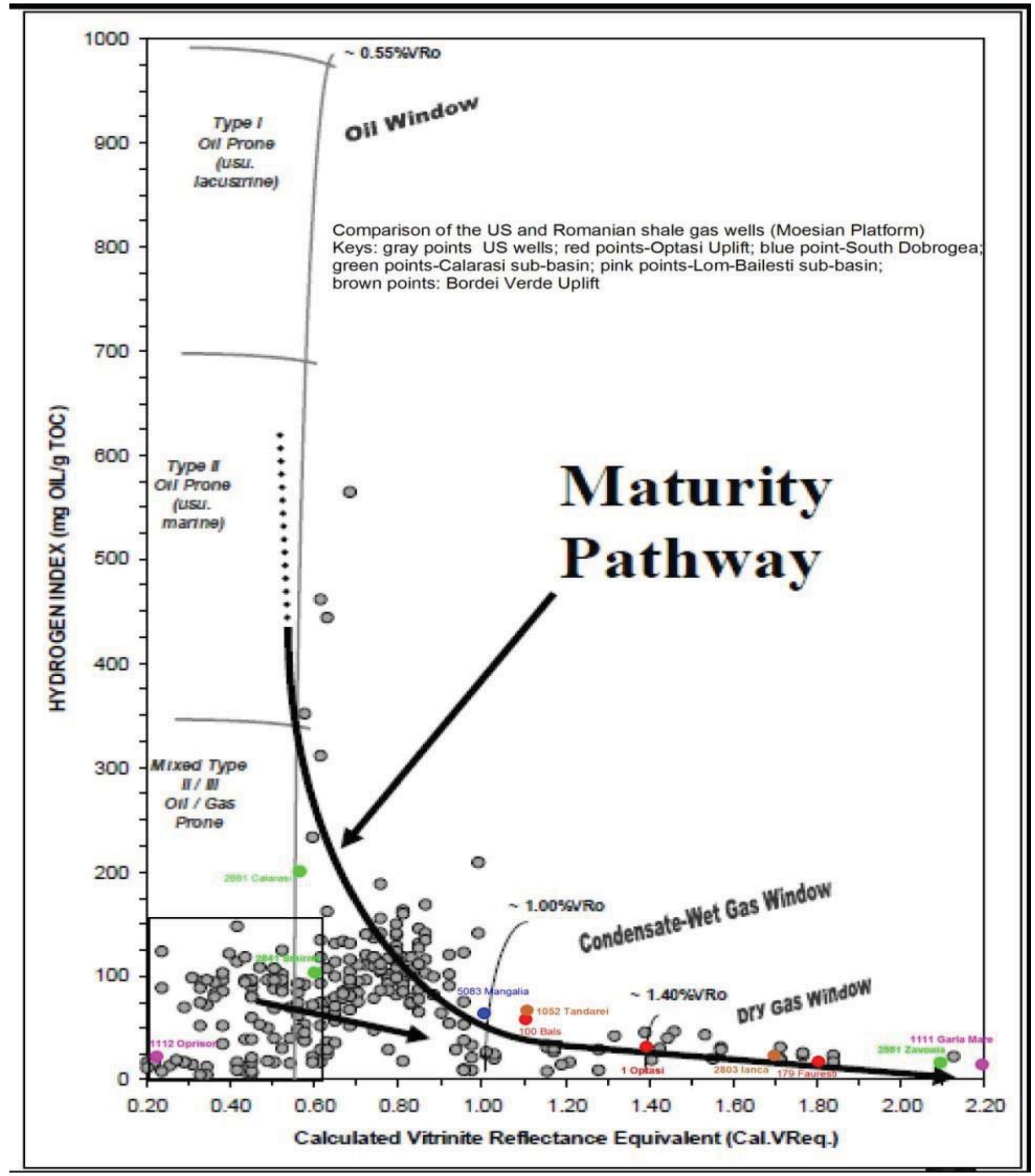
Depth of top and base of shale interval for definition of assessment unit
Structure, including major faults and relationships to terrane
Depositional environment of mudstones
Evaluation of gross shale interval and identification of depocenters
Organically rich gross- and net-shale thickness to delineate assessment units
Total organic content (TOC)
Thermal maturity (Ro)

Romania & US - Paleozoic Shale Gas Formation Parameters

Name of Shale Play	Țăndărei Fm.	Rădăuti Fm.	Barnett Shale	Marcellus Shale
Top Depth (ft.)	3,000 to 14,500	1,300 to 12,500	5,000 to 8,000’	4,000 to 9,000’
Net Thickness (ft.)	30 to 400	100 to 300	100 to 500	<10 to 300
Porosity (%)	2 to 10	1 to 8	1 to 9	2 to 9
Permeability (mD)	n.a.	n.a.	0.00009 to 0.001	0.00001 to 0.01
TOC (%)	1,0 to 1,5	0.6 to 2.4	4 to 8 type II	0.1 to 13 type II-III
Ro (%)	0.4 to1.5	0.35 to 3.6	1.2	6 to 3.5

Comparison of the U.S. and Romanian plays





Left: Hydrogen Index vs. Tmax

Right: Calculated Vitrinite Reflectance

Moesia - Shale Gas Resources of the Tandarei Play

(from: Veliciu S., Popescu B., 2012 - Are the Paleozoic Plays the Future of Unconventional Gas in Romania? An Attempt of Assessing the Resource)

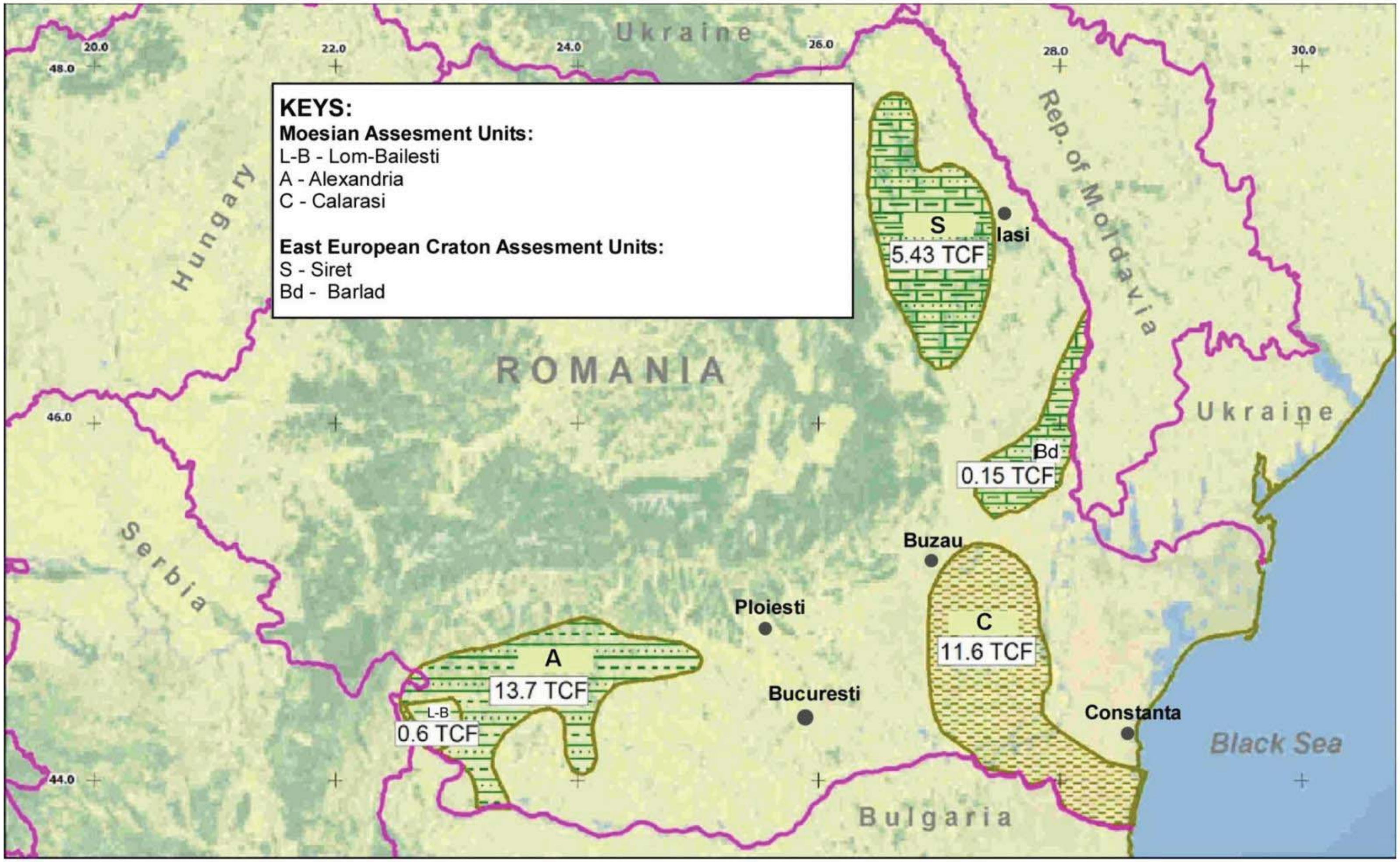
ASSESSMENT UNITS		Lom-Bailesti AU (N Slope)			Alexandria AU (N Alexandria Sb)			Calarasi - AU		
Assessment hypothesis		Pessimistic(P10)	Mean (P50)	Optimistic (P90)	Pessimistic(P10)	Mean (P50)	Optimistic (P90)	Pessimisti (P10)	Mean (P50)	Optimistic (P90)
Resources	Original gas in place OGIP (Tcf)	29			687			579		
	Technically recoverable (Tcf)		0.6			13.7			11.6	

East Europe Craton - Shale Gas Resources of the Radauti Play

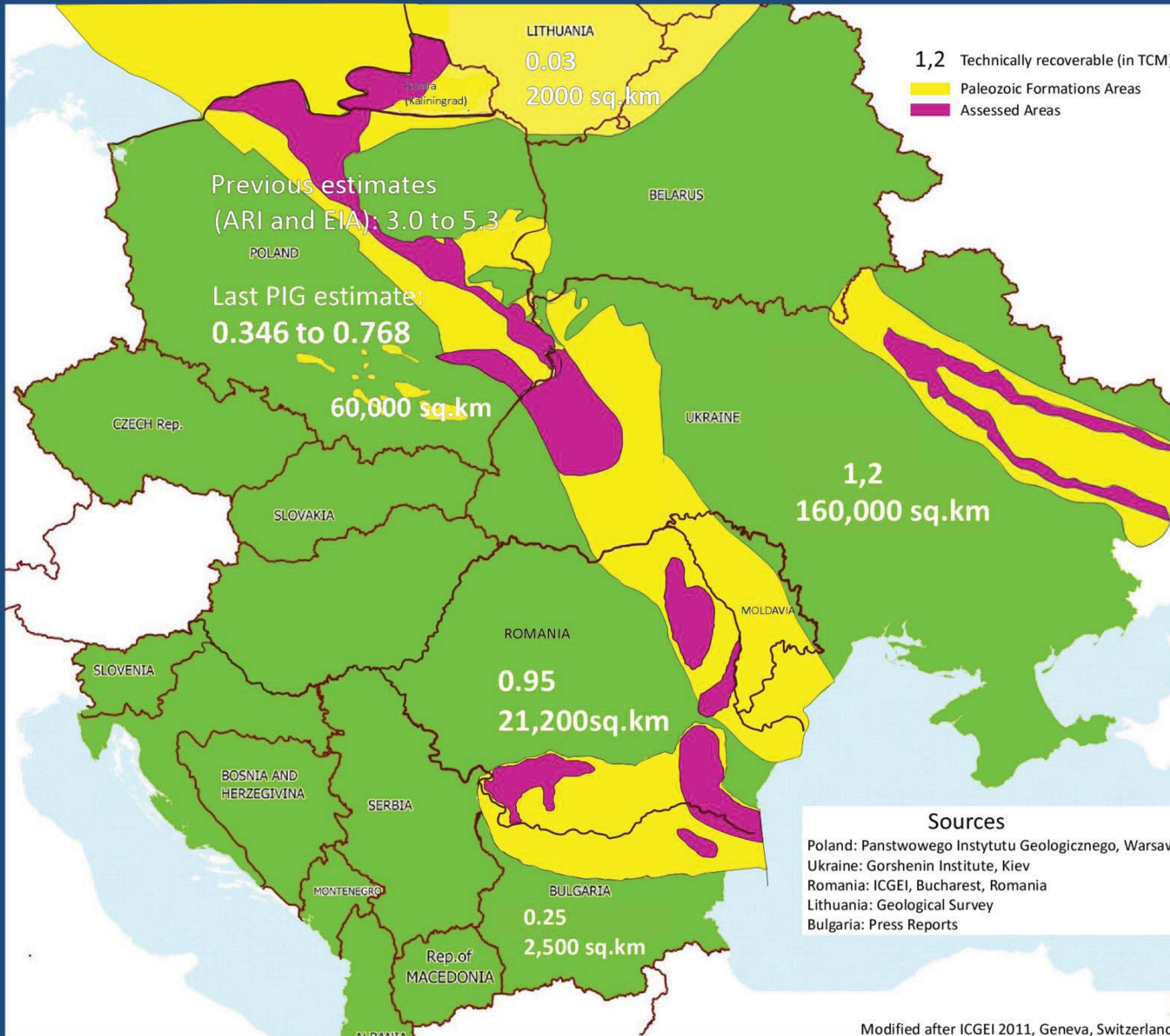
(from: Veliciu S., Popescu B., 2012 - Are the Paleozoic Plays the Future of Unconventional Gas in Romania? An Attempt of Assessing the Resource)

ASSESSMENT UNITS		Siret AU			Barlad AU		
Assessment hypothesis		Pessimistic (P10)	Mean (P50)	Optimistic (P90)	Pessimistic (P10)	Mean (P50)	Optimistic (P90)
Resources	Original gas in place OGIP (Tcf)	271.74			7.30		
	Technically recoverable (Tcf)		5.43			0.15	

Shale Gas Resources Plays & Facies of the Paleozoic Assessment Units of Romania



Presenter's notes: Total Technically Recoverable Resources from the Paleozoic mudstones reach 0.95 TCM or 60 years of production at the 2013 levels.



Central-Eastern Europe Paleozoic Shale-Gas Resource Estimations

CONCLUSIONS

BASIN AND PETROLEUM SYSTEM

Anoxia and highstand are a part of the drivers for Tandarei and Radauti black mudstone accumulation. The other driver is the tectonic regime that supplied the basin terrigenous influx from the exhumed wedge to the pro-foreland basin. The Silurian black mudstone are in the dry and wet gas generative window in the Assessment Units described herein.

However a better basin and PS evaluation faces difficulties because there is a:

•Lack of a high-quality deep seismic reflection and refraction profile across the West and East Europe platforms.

•Insufficient number of wells drilled to evaluate this possible, vast resource.

•Resulting poor knowledge of petrophysics, facies changes, natural fracturing, etc..

•Need for a coupled effort for reconsiderations of: a) various vintages of the (sparse) paleontological analysis, b) large gaps in detrital zircon data and c) controversial figures of absolute age give way to poorly constrained information;

CONCLUSIONS (CONT'D)

RESOURCE ASSESSMENT

Carried out with limited data set yet using international evaluation methods supported by US agencies

Especially lacking information on:

- physical rock properties (e.g., fracability)
- mineralogy of mudstones
- quartz diagenesis
- thermal history
- kerogen maturation dynamics
- maturation models lack pyrolysis data

Therefore, the Unconventional Resource Potential of Romania Remains to be Explored