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 Baltic 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.

<table>
<thead>
<tr>
<th>Name of Shale Play</th>
<th>Ţăndărei Fm.</th>
<th>Rădăuti Fm.</th>
<th>Barnett Shale</th>
<th>Marcellus Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (ft)</td>
<td>3,000 to 14,500</td>
<td>1,300 to 12,500</td>
<td>5,000 to 8,000’</td>
<td>4,000 to 9,000’</td>
</tr>
<tr>
<td>Thickness (ft)</td>
<td>30 to 400’</td>
<td>100</td>
<td>100 to 500’</td>
<td>&lt;10 to 300’</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>2 - 10</td>
<td>1 - 8….</td>
<td>1 - 9</td>
<td>2 - %</td>
</tr>
<tr>
<td>Permeability (mD)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.00009 to 0.001</td>
<td>0.00001 to 0.01</td>
</tr>
<tr>
<td>TOC (%)</td>
<td>1.0 to 1.5</td>
<td>0.6 to 2.4</td>
<td>4 to 8 type II</td>
<td>0.1 to 13 type II-III</td>
</tr>
<tr>
<td>Ro (%)</td>
<td>0.4 to 1.5</td>
<td>0.35 to 3.6</td>
<td>1.2</td>
<td>1.6 to 3.5</td>
</tr>
</tbody>
</table>

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.

**Selected References**


**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

Bogdan Popescu – Zeta Petroleum (Romania)
Serban Veliciu - Center for Green Energy Information (Switzerland)
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

East

Paleozoic: PZ
- Lopingian
- Guadalupian
- Cisuralian
- Ordovician
  - Upper
  - Middle
  - Lower

Silurian
- Pridoli
- Ludlow
- Wenlock
- Llandovery

Devonian
- Upper
- Middle
- Lower

Cambrian
- Upper
- Middle
- Lower C

Precambrian
- Neoproterozoic
- Mesoproterozoic
- Paleoproterozoic

Archean

West

36m
- Limestones, breccia-conglomerate

285m
- Dark mudstones, siltstones, sandstones, coal layers
- Detrital limestones
- Limestones, evaporites

~1230m
- Graptolite shales

~180m

>495m

>523m
- Quartzitic sandstones, siltstones

Volcano-sedimentary succession

Banded Iron formation

Microcline gneisses, pegmatites

TANDAREI Fm
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’)

[Image of a geological cross-section diagram]
### Shale Gas Reservoirs Properties of the Paleozoic Formations in Moesia

<table>
<thead>
<tr>
<th>Plays</th>
<th>Lom - Bailesti</th>
<th>Alexandria</th>
<th>Calarasi</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shale formations</td>
<td>black shales, argillites</td>
<td>black shales, argillites</td>
<td>shales, argillites</td>
</tr>
<tr>
<td>Geological age</td>
<td>Silurian - Lower&amp;Middle Devonian</td>
<td>Silurian - Lower&amp;Middle Devonian</td>
<td>Silurian - Lower&amp;Middle Devonian</td>
</tr>
<tr>
<td>Prospective Area (acres(\times)km(^2))</td>
<td>196.307(\times)794</td>
<td>2,098,981(\times)8,494</td>
<td>2,953,543(\times)11,952</td>
</tr>
<tr>
<td>Depth at the top of formations organically rich (ft.)</td>
<td>10,000 - 14,500</td>
<td>6,600 - 8,200</td>
<td>3,000 - 12,500</td>
</tr>
<tr>
<td>Average thickness of organically rich reservoirs (ft.)</td>
<td>1.132</td>
<td>2.457</td>
<td>1.217</td>
</tr>
<tr>
<td>Pressure (Mpa)</td>
<td>35</td>
<td>30</td>
<td>28</td>
</tr>
<tr>
<td>Temperature (Rankin)</td>
<td>663</td>
<td>654</td>
<td>636</td>
</tr>
<tr>
<td>TOC (wt. %)</td>
<td>0.428 - 0.966</td>
<td>0.800 - 1.500</td>
<td>0.728 - 1.457</td>
</tr>
<tr>
<td>Thermal maturity (% Ro)</td>
<td>0.74 - 1.90</td>
<td>0.85 - 1.40</td>
<td>1.00 - 1.50</td>
</tr>
<tr>
<td>Volume factor Bg</td>
<td>0.0037</td>
<td>0.0043</td>
<td>0.0049</td>
</tr>
<tr>
<td>(z) - factor</td>
<td>0.9922</td>
<td>10,000</td>
<td>11,000</td>
</tr>
</tbody>
</table>
RADAUTI PLAY
Silurian
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’)
Presenter’s notes: The Bilche-Volitsa Zone includes both the TTZ and the Rava-Ruska (Russian-Rava) Zone.
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.
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).
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.
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.
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

<table>
<thead>
<tr>
<th>Plays</th>
<th>SIRET</th>
<th>BARLAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shales (20-80%)</td>
<td>Shales (20-70%)</td>
<td>Shales (20-70%)</td>
</tr>
<tr>
<td>Limestones (10-15%)</td>
<td>Limestones (20-30%)</td>
<td>Limestones (10-15%)</td>
</tr>
<tr>
<td>Sandstones (40%)</td>
<td>Sandstones (30%)</td>
<td>Sandstones (40%)</td>
</tr>
<tr>
<td>Geological age</td>
<td>Silurian</td>
<td>Devonian - Silurian</td>
</tr>
<tr>
<td>Physical extent</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prospective Area (acres/km²)</td>
<td>2,031,983\textbf{8,223}</td>
<td>272,267\textbf{1,102}</td>
</tr>
<tr>
<td>Depth of top of formations organically rich (ft.)</td>
<td>1,350-7,500</td>
<td>3,000-12,500</td>
</tr>
<tr>
<td>Average net thickness of organically rich reservoirs (ft.)</td>
<td>98</td>
<td>82</td>
</tr>
<tr>
<td>Reservoir properties</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pressure (Mpa)</td>
<td>35</td>
<td>30</td>
</tr>
<tr>
<td>Temperature (Rankin)</td>
<td>684</td>
<td>691</td>
</tr>
<tr>
<td>TOC (wt %)</td>
<td>1.1-1.6</td>
<td>1.0-2.4</td>
</tr>
<tr>
<td>Thermal maturity (% Ro)</td>
<td>0.35-1.6</td>
<td>0.58-3.6</td>
</tr>
<tr>
<td>Volume factor Bg</td>
<td>0.0048</td>
<td>0.0033</td>
</tr>
<tr>
<td>z - factor</td>
<td>0.860</td>
<td>0.900</td>
</tr>
</tbody>
</table>
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

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

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).
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)
<table>
<thead>
<tr>
<th>Name of Shale Play</th>
<th>Țăndărei Fm.</th>
<th>Rădăuti Fm.</th>
<th>Barnett Shale</th>
<th>Marcellus Shale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Depth (ft.)</td>
<td>3,000 to 14,500</td>
<td>1,300 to 12,500</td>
<td>5,000 to 8,000’</td>
<td>4,000 to 9,000’</td>
</tr>
<tr>
<td>Net Thickness (ft.)</td>
<td>30 to 400</td>
<td>100 to 300</td>
<td>100 to 500</td>
<td>&lt;10 to 300</td>
</tr>
<tr>
<td>Porosity (%)</td>
<td>2 to 10</td>
<td>1 to 8</td>
<td>1 to 9</td>
<td>2 to 9</td>
</tr>
<tr>
<td>Permeability (mD)</td>
<td>n.a.</td>
<td>n.a.</td>
<td>0.00009 to 0.001</td>
<td>0.00001 to 0.01</td>
</tr>
<tr>
<td>TOC (%)</td>
<td>1.0 to 1.5</td>
<td>0.6 to 2.4</td>
<td>4 to 8 type II</td>
<td>0.1 to 13 type II-III</td>
</tr>
<tr>
<td>Ro (%)</td>
<td>0.4 to 1.5</td>
<td>0.35 to 3.6</td>
<td>1.2</td>
<td>6 to 3.5</td>
</tr>
</tbody>
</table>
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


<table>
<thead>
<tr>
<th>Assessment hypothesis</th>
<th>Lom-Bailesti AU (N Slope)</th>
<th>Alexandria AU (N Alexandria Sb)</th>
<th>Calarasi - AU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pessimistic (P10)</td>
<td>Mean (P50)</td>
<td>Optimistic (P90)</td>
<td>Pessimistic (P10)</td>
</tr>
<tr>
<td>Original gas in place OGIP (Tcf)</td>
<td>29</td>
<td>687</td>
<td>579</td>
</tr>
<tr>
<td>Resources</td>
<td>Technically recoverable (Tcf)</td>
<td>0.6</td>
<td>13.7</td>
</tr>
</tbody>
</table>
### 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)

<table>
<thead>
<tr>
<th>ASSESSMENT UNITS</th>
<th>Siret AU</th>
<th>Barlad AU</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Assessment hypothesis</strong></td>
<td>Pessimistic (P10)</td>
<td>Mean (P50)</td>
</tr>
<tr>
<td><strong>Resources</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original gas in place OGIP (Tcf)</td>
<td>271.74</td>
<td>7.30</td>
</tr>
<tr>
<td>Technically recoverable (Tcf)</td>
<td>5.43</td>
<td>0.15</td>
</tr>
</tbody>
</table>
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

Previous estimates (ARI and EIA): 3.0 to 5.3

Last PIG estimate: 0.346 to 0.768

60,000 sq.km

1,2

160,000 sq.km

0.95

21,200 sq.km

0.25

2,500 sq.km

Sources

Poland: Panstwowego Instytutu Geologicznego, Warsaw
Ukraine: Gorshenin Institute, Kiev
Romania: ICGEI, Bucharest, Romania
Lithuania: Geological Survey
Bulgaria: Press Reports

Modified after ICGEI 2011, Geneva, Switzerland
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