Interpretation of the Silurian Basin of Central and Eastern Europe as a Pro-foreland Flexural Basin: Implications for Shale Gas Exploration*

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Search and Discovery Article #10683 (2014)**
Posted December 15, 2014

*Adapted from oral presentation given at AAPG International Conference & Exhibition, Istanbul, Turkey, September 14-17, 2014

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Abstract

The present day collage of various Silurian Basin fragments in Central and Eastern Europe (CEE) is the result of several orogenic and rifting/drifting episodes. The proper paleogeographic reconstruction of a single, very large Silurian foredeep basin in the context of regional geology has a major impact on the ongoing unconventional shale gas exploration efforts in the region, including Poland, Ukraine, Romania, Moldova and even in Turkey. The distal segments of a large Silurian foreland basin associated with the Caledonian collisional orogene, along the perimeter of the East European Craton, can be reasonably followed along strike from northwest to southeast, from Poland all the way to the Ukrainian Black Sea coast. The foredeep basin sequence onlaps to the northeast the various pre-Silurian and crystalline basement units. The Silurian Basin of the CEE is interpreted here as a pro-foreland basin, with short-lived (less than 15 m.y.) and extremely rapid (locally more than 1,500 m per m.y.!), accelerating subsidence histories recording an important part of the orogenic history of the broader Caledonian orogeny. Besides the typical subsidence curves and the very prominent onlap of successive Silurian lithostratigraphic units onto the craton, the flexural origin is also supported by the general lack of normal faulting within the basin, contradicting some

interpretations suggesting deposition on the continental margin of the Rheic Ocean. The map-view distribution of the lithofacies within the basin, such as clastic turbidites in the southwestern perimeter of the basin, deepwater shales in the center and neritic carbonates on the northeastern foreland margin, is also consistent with the flexural basin interpretation. The location of shale gas exploration sweet spots are yet to be seen in this very large region. In the successful case, among other factors, the prediction of certain Silurian lithofacies units in different parts of this very large basin complex straddling many countries may become very important in the future.

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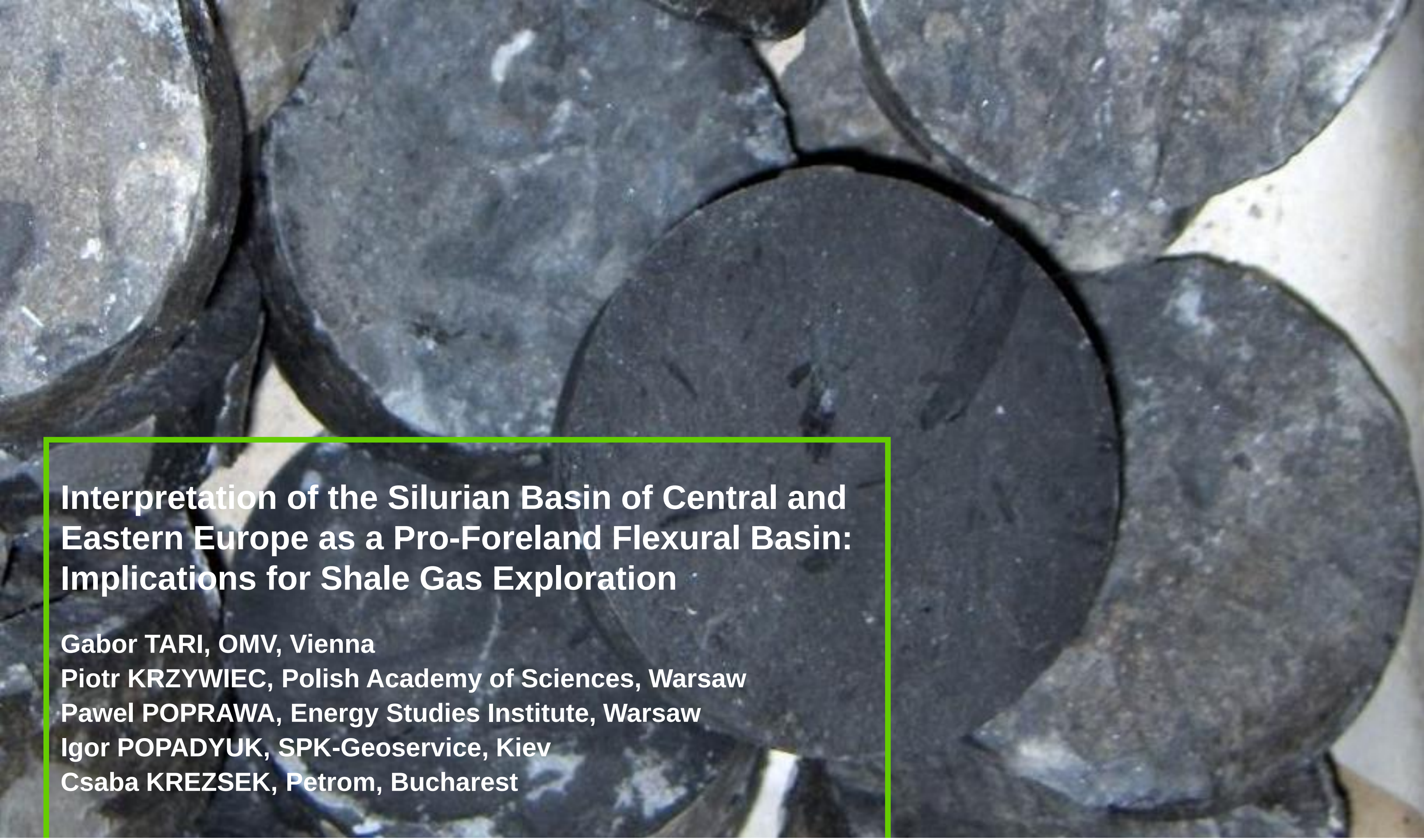

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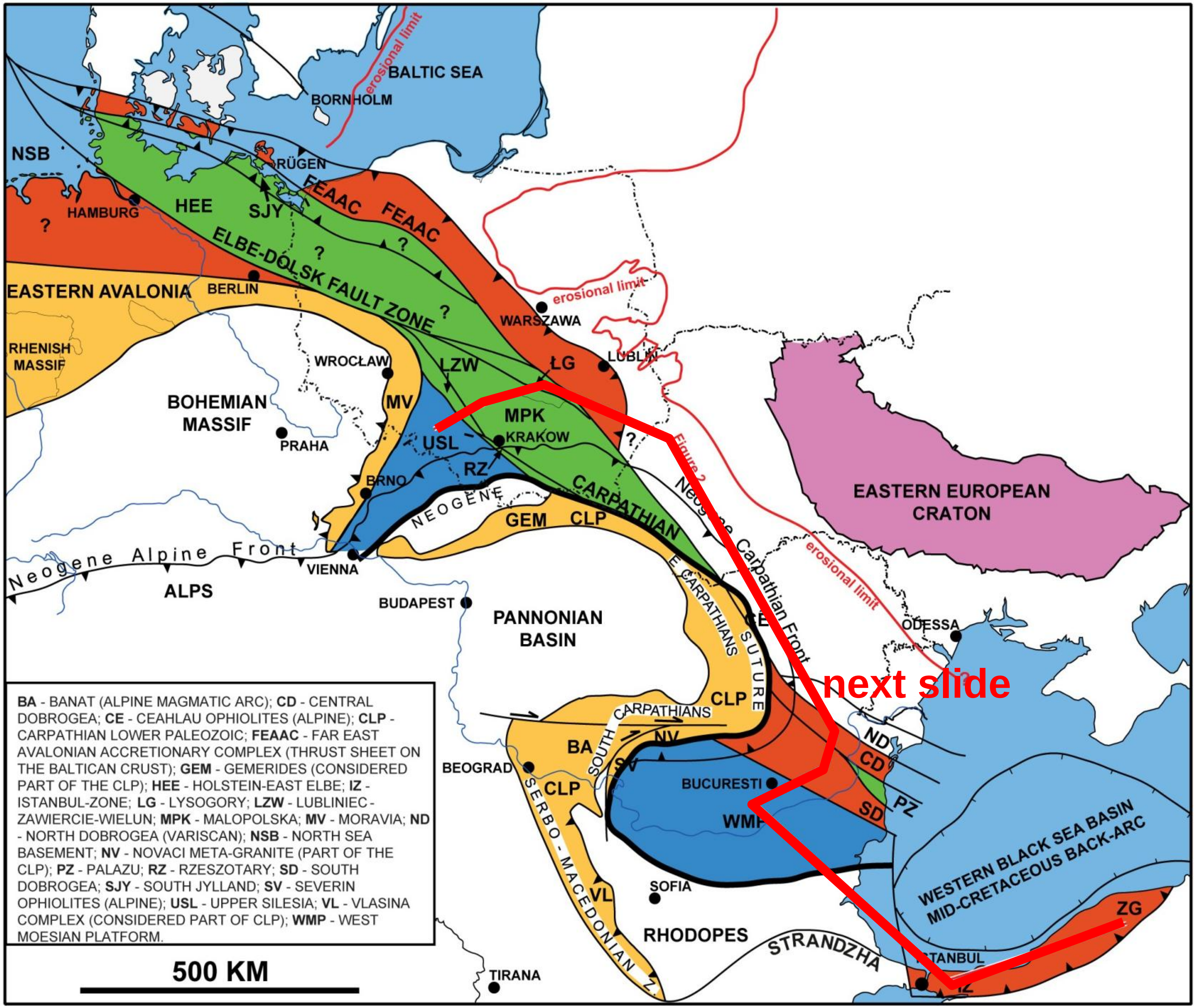
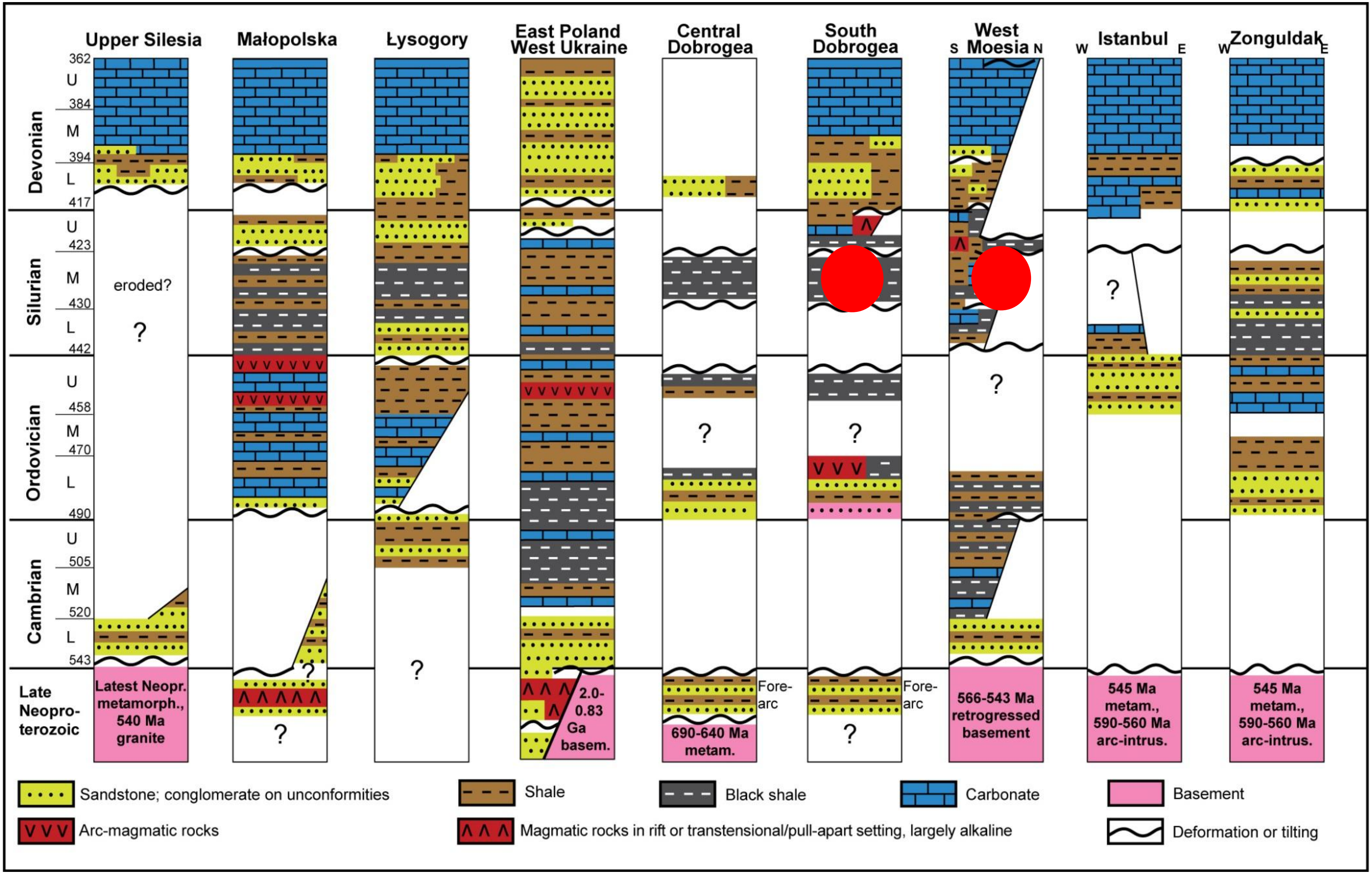
AAPG ICE, Istanbul, September 14-17, 2014

Caledonian terranes in Central and Eastern Europe



modified from Oczlon et al. (2007)

Composite Paleozoic tectonostratigraphy, CEE



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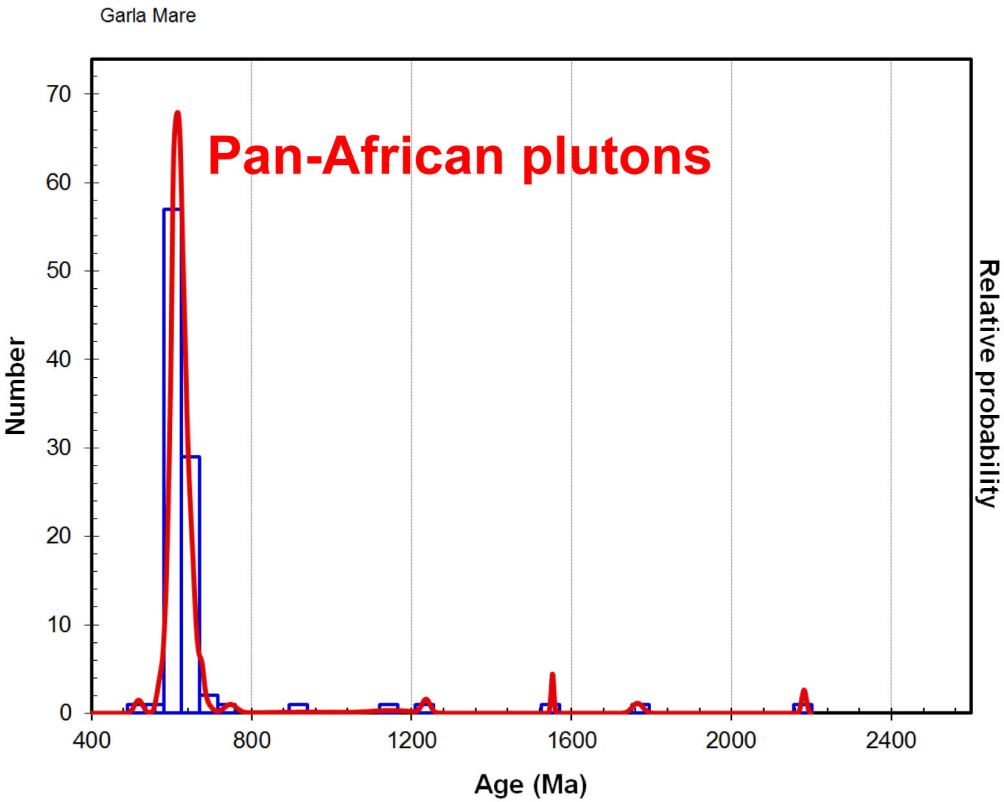
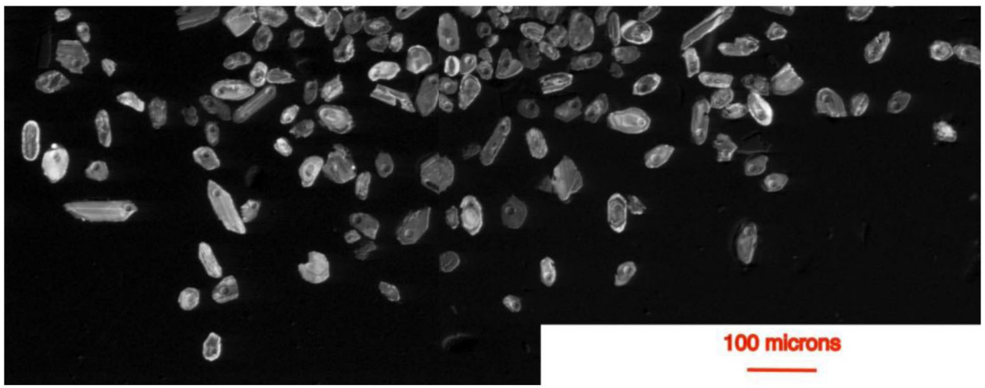
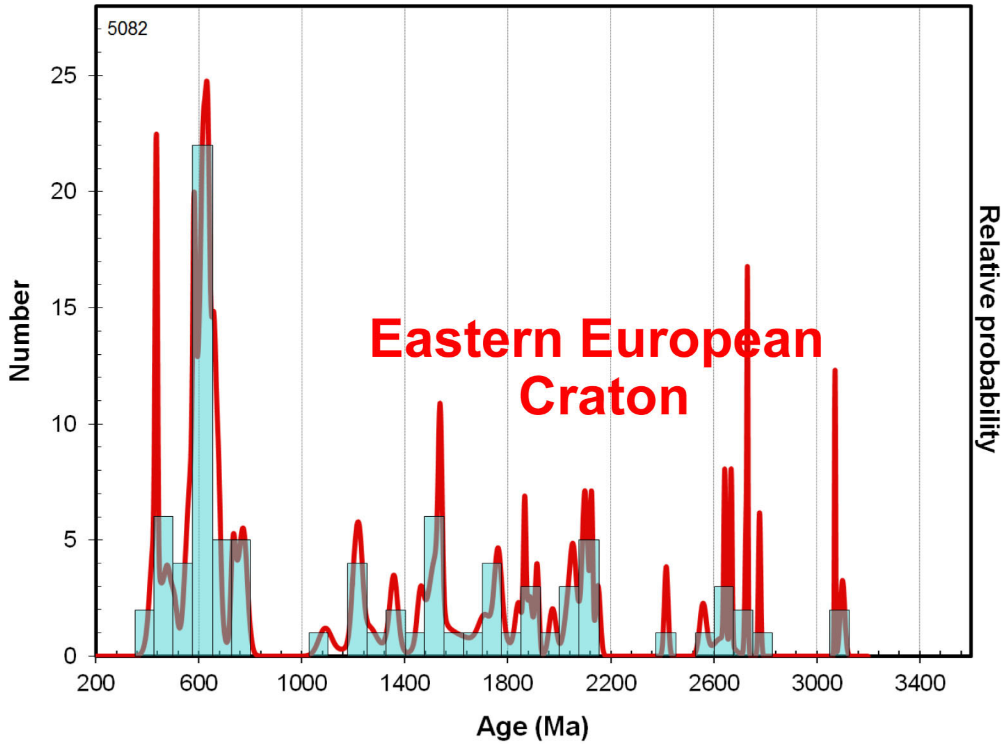
Two different Silurian basins in Central and Eastern Europe

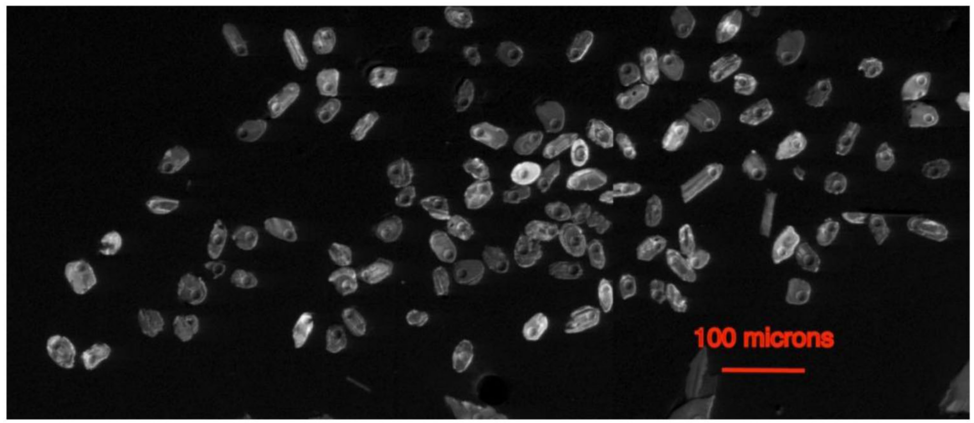
Garla Mare-1 well, West Moesia, Romania





Mangalia-5082 well, South Dobrogea, Romania

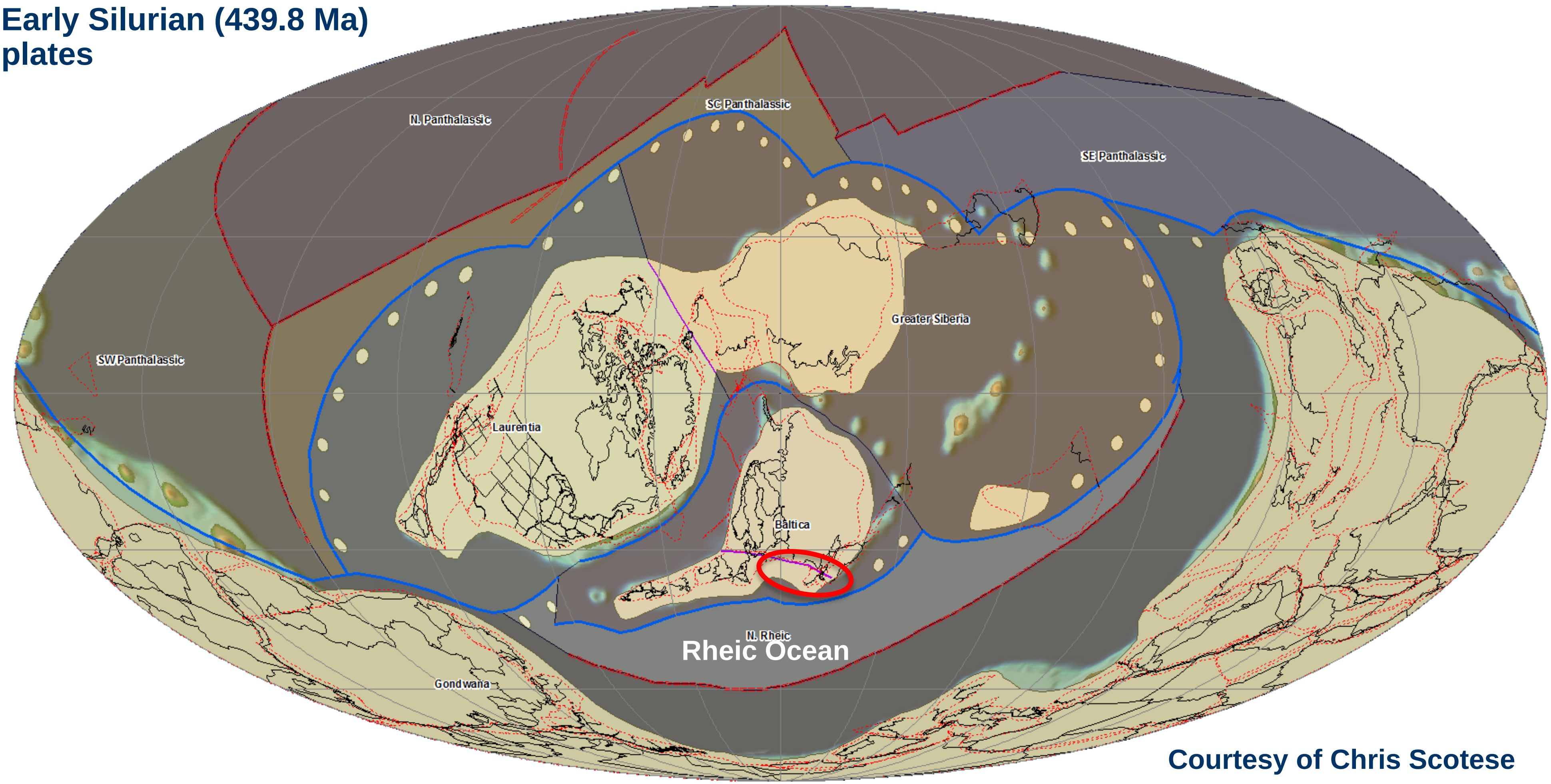




Analysis by Prof. Ducea, University of Arizona, Tucson

Silurian plate reconstruction

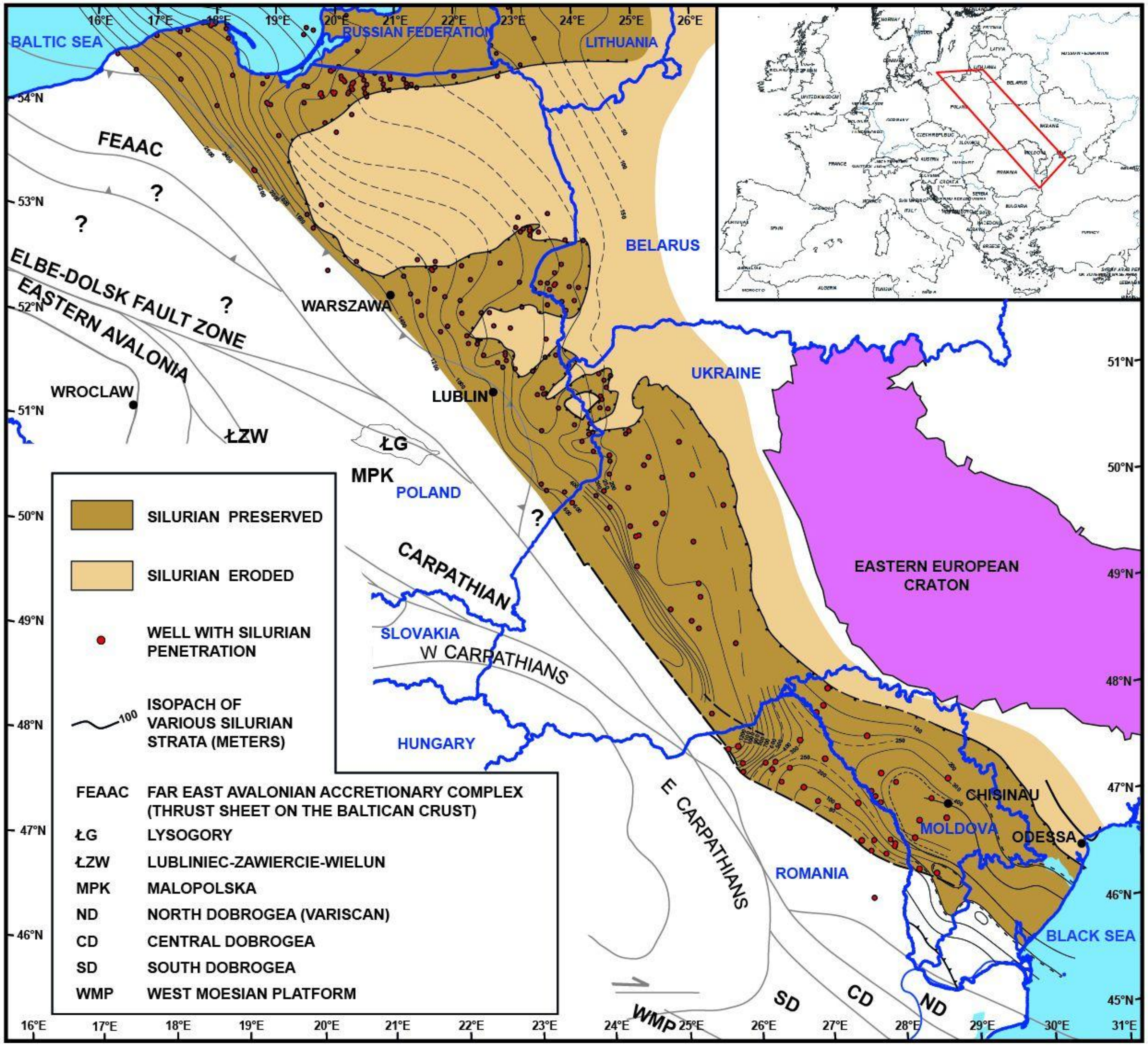
Early Silurian (439.8 Ma) plates



Courtesy of Chris Scotese

There are two major challenges to build a regionally consistent model of the very large Caledonian foredeep basin system of Central and Eastern Europe. The regional-scale understanding of the Silurian paleogeography is complicated by the fact that the remains of the once continuous basin stretch across several countries today, with highly variable levels of access to relevant geological and geophysical data and interpretation. Furthermore, a strictly technical challenge is that the present day collage of Silurian basin fragments has resulted from multiple orogenic episodes in the broader Central and Eastern Europe region, including also NW Turkey.

Regional setting and isopach of the Silurian Basin of CEE

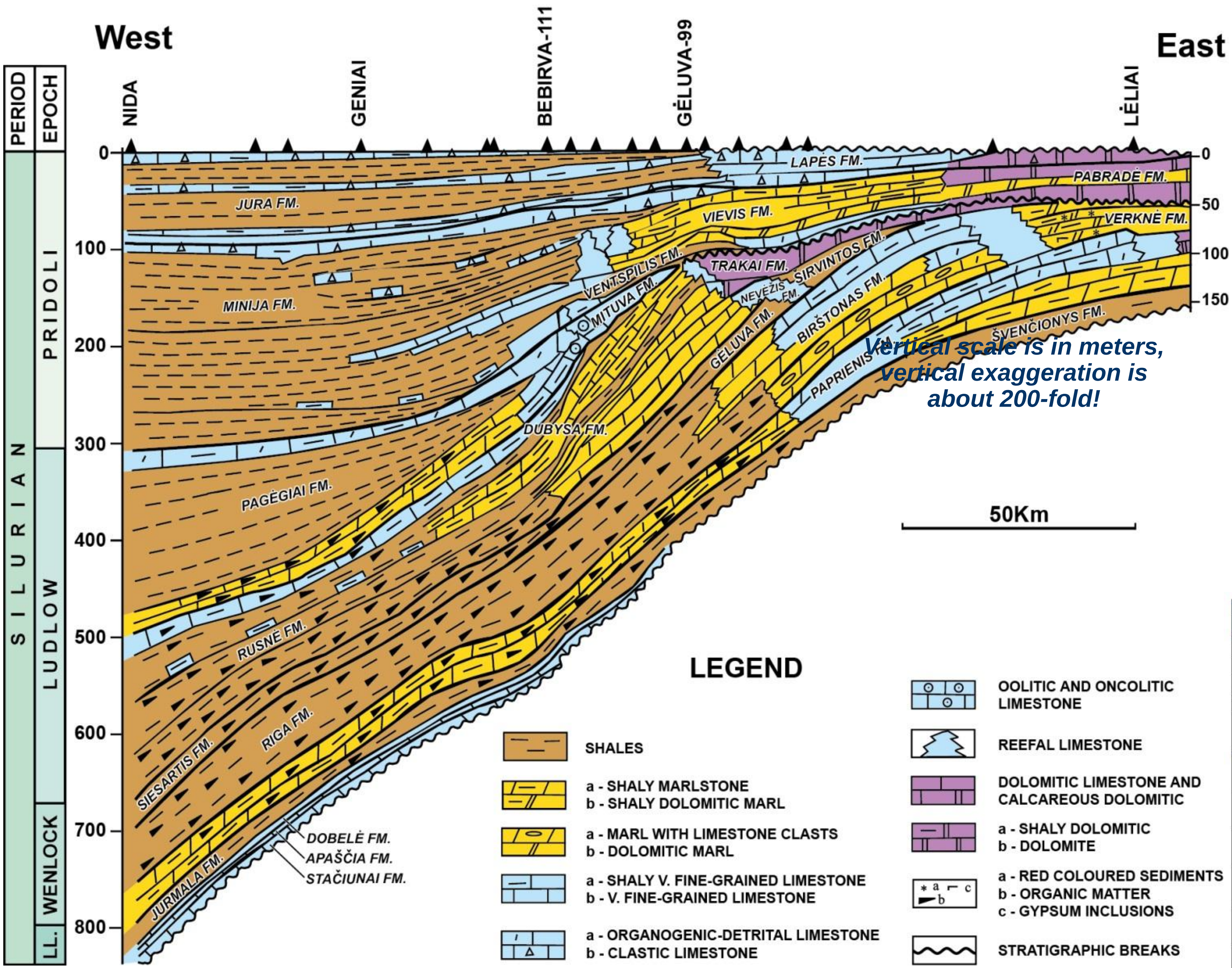


Simplified isopach map of the Silurian Basin of Central Eastern Europe, from the Baltic Sea to the Black Sea.

Note that the isopach contours of various segments do not necessarily match across country borders as the published maps may not correspond to the same Silurian sequences.

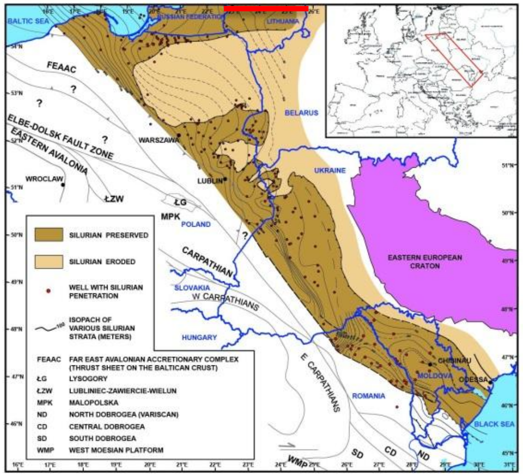
Note that isolated Silurian basin fragments, to the SW of the poorly defined Trans-European Suture Zone, are omitted here as they are interpreted to correspond to an entirely different terrane.

Regional transect based on wells, Lithuania



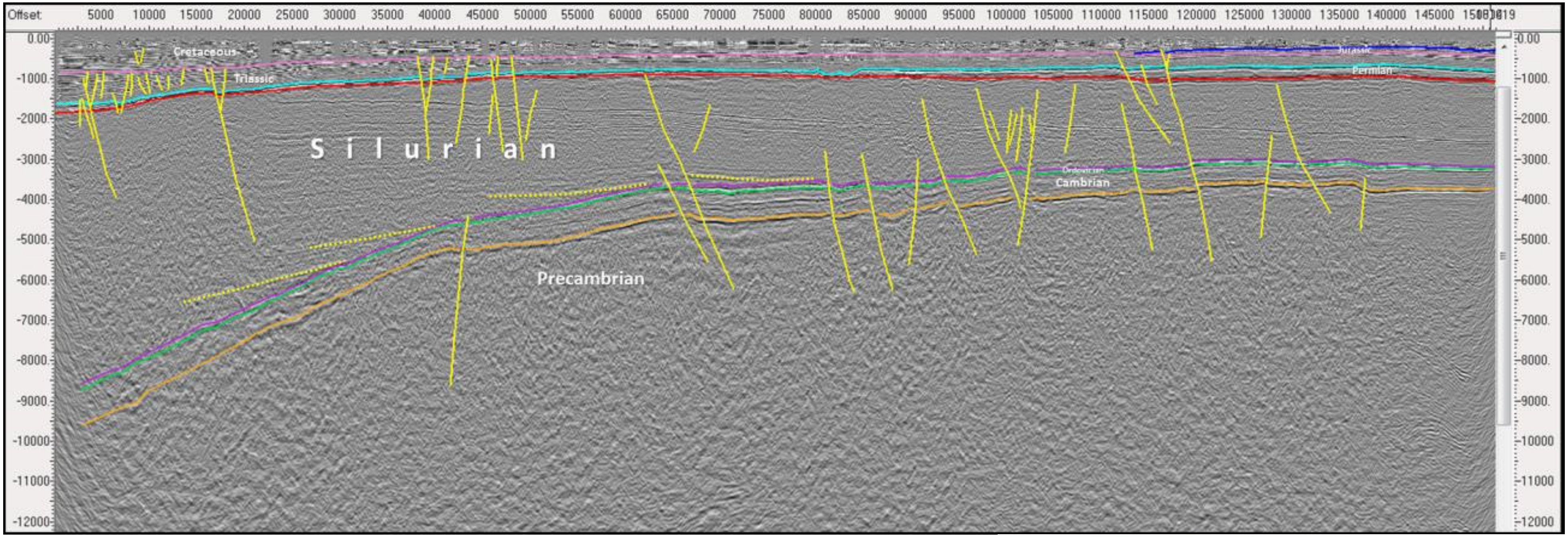
Vertical scale is in meters, vertical exaggeration is about 200-fold!

Regional transect across Lithuania showing the lithostratigraphy and local formation names of the Silurian sequence. The section has been flattened on top of the Silurian. The overall geometry of the Silurian sequence displays multiple onlap surfaces consistent with deposition at the margin of a flexural basin. Redrawn from Zdanaviciute and Lazauskiene (2007).



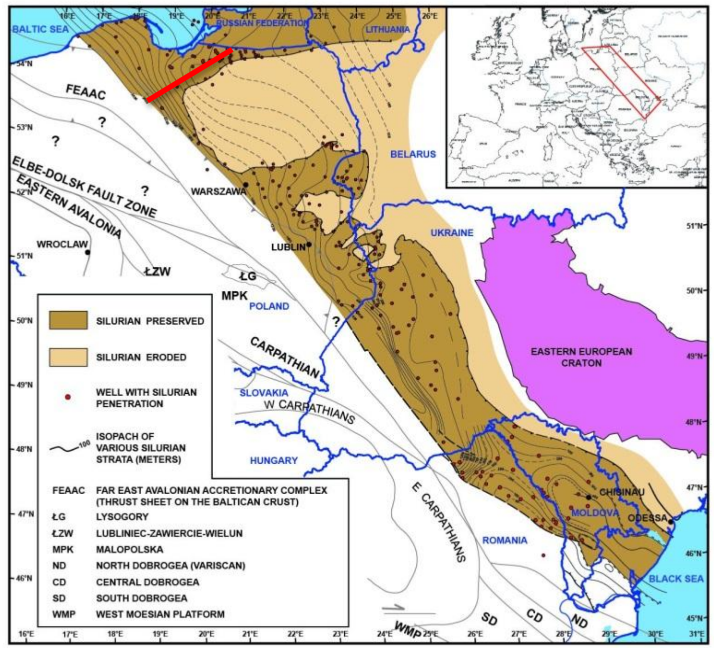
Regional PolandSPAN line, Baltic Basin, Poland

SW NE

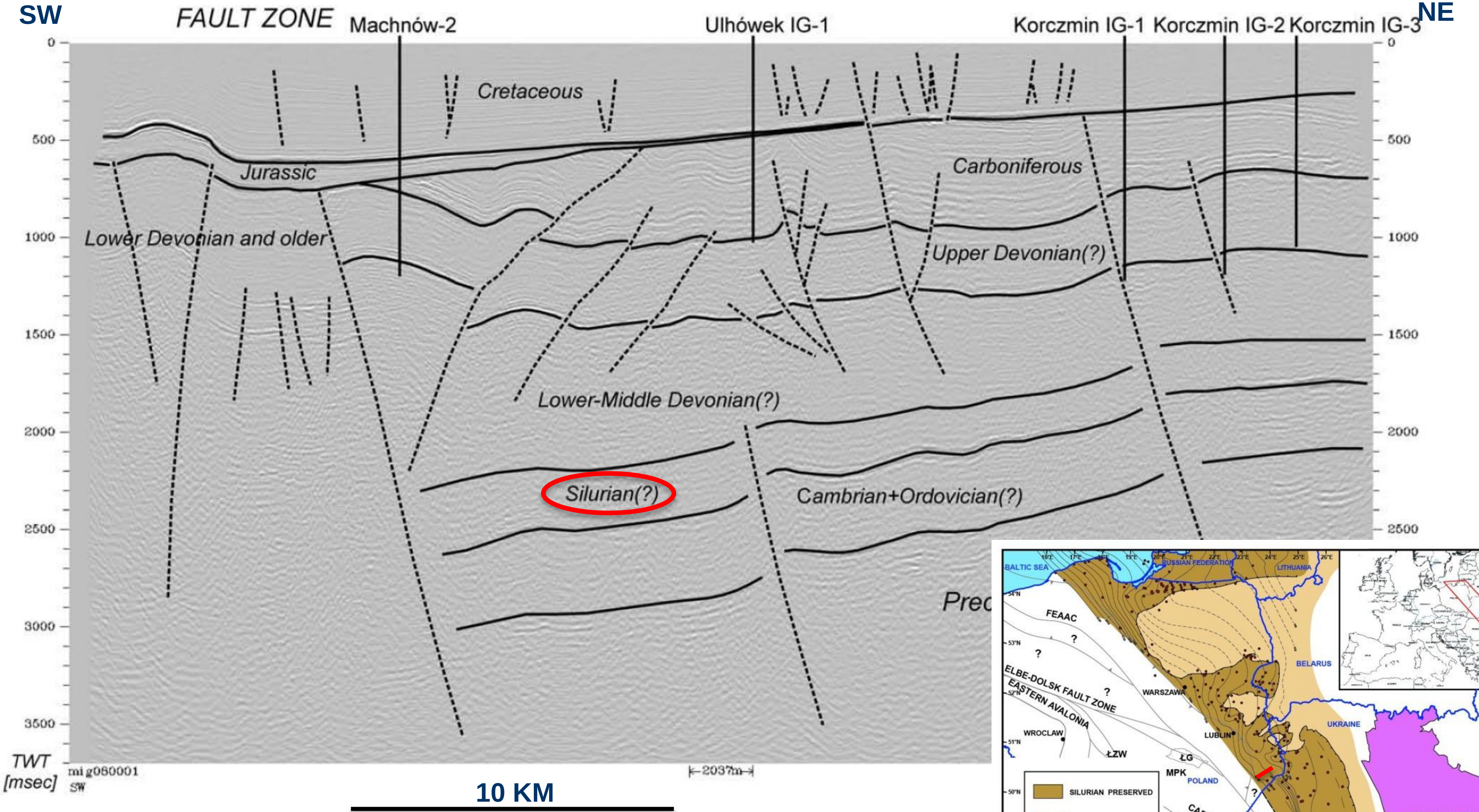


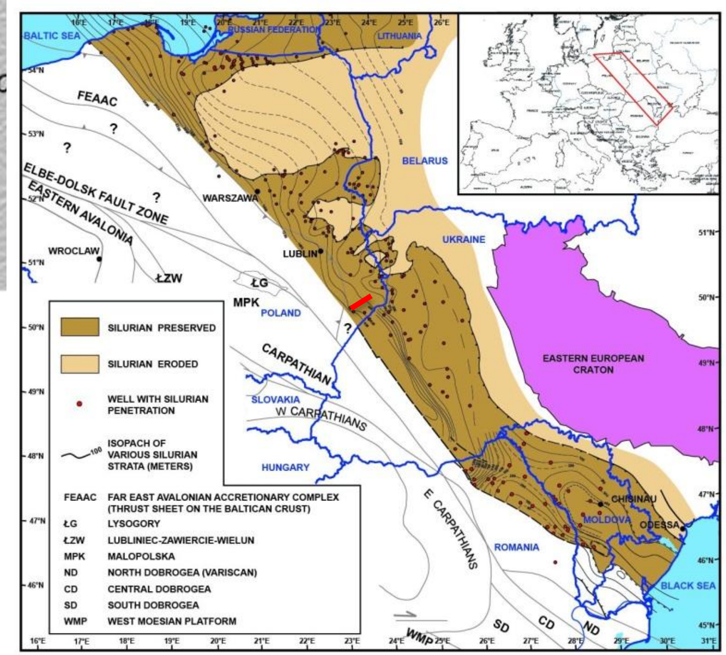
50 KM

PolandSPAN seismic line, in depth, from the Baltic Basin showing the overall geometry of the Silurian Caledonian foredeep basin. As compared to the distal Silurian basin margin of Lithuania, this seismic crosses the most proximal thickest basin center in Poland.
Note the progressive, NE-oriented onlap at the base of the Silurian sequence. Krzywiec et al. (2013).



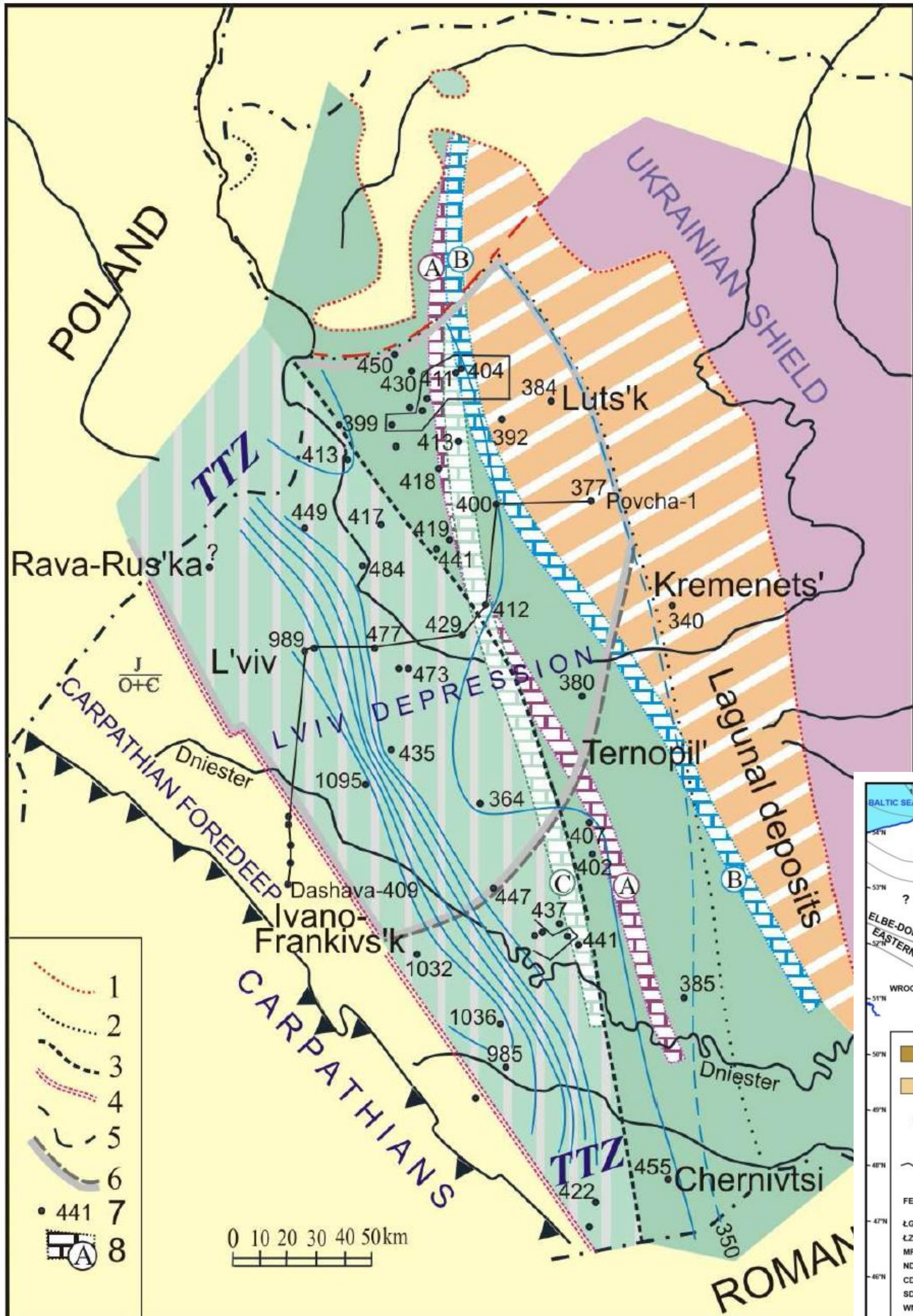
„Conventional“ seismic line, Lublin Basin, SE Poland



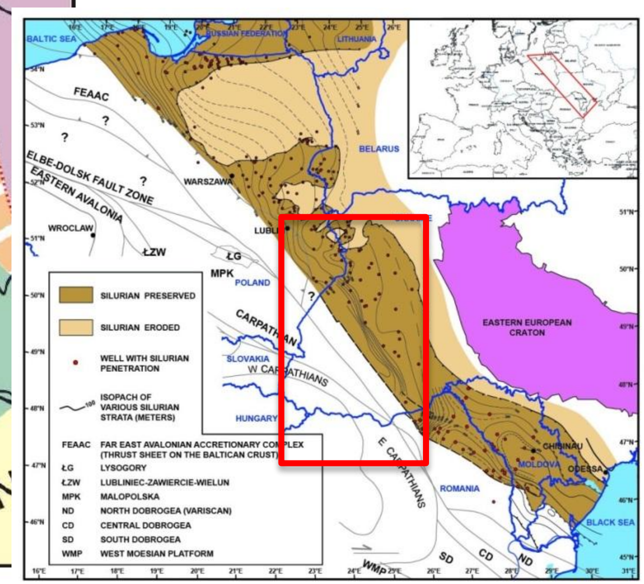


Complex system of thin- and thick-skinned reverse faults and thrusts developed during Late Carboniferous inversion of the Lublin Basin in its SE segment. This is the result of the Hercynian overprint on top of the Caledonian foredeep basin. Adopted from Krzywiec (2009).

Silurian isopach, Ukraine



Kurovets and Koltun (2012).

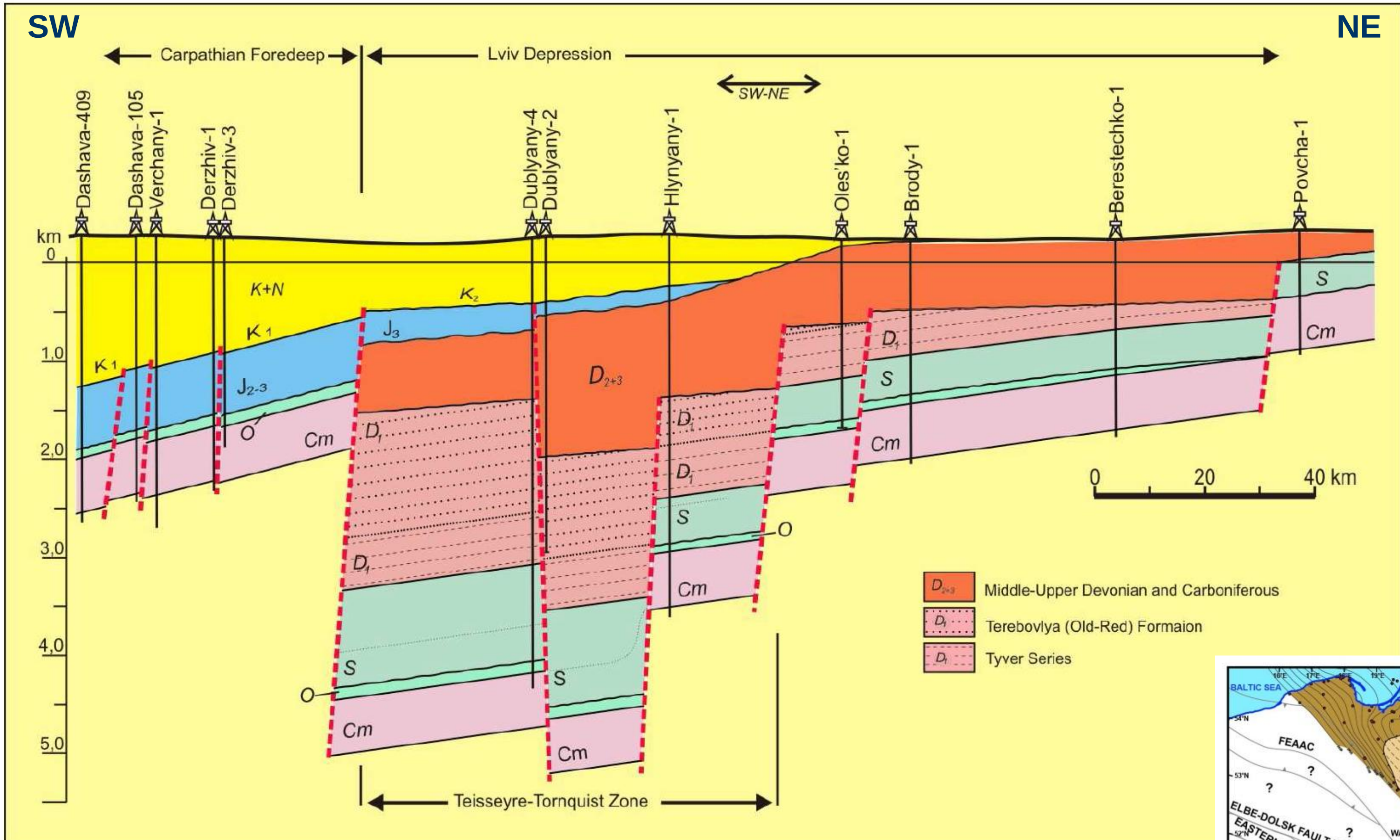


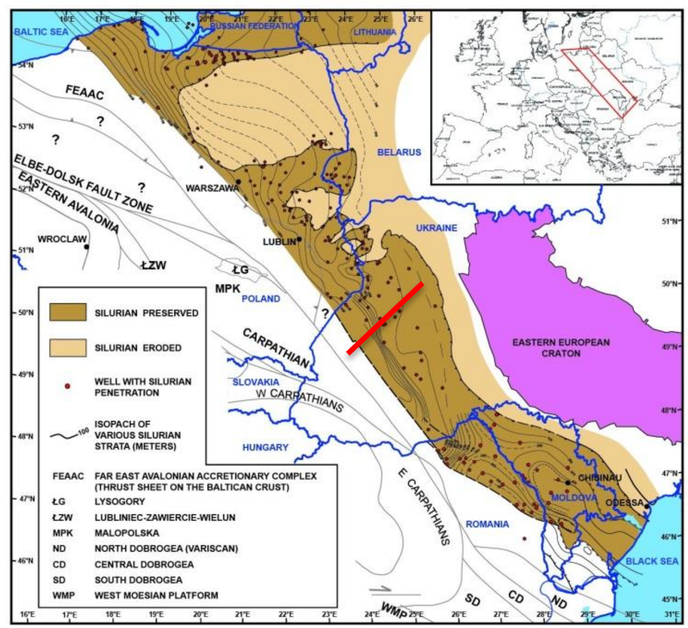
LEGEND

Blue lines: Silurian isopach based on well penetrations
TTZ :Teisseyre-Tornquist Zone

1 eastern extent of the Silurian
2-3 eastern extent of the Lower Devonian deposits
4 western extent of the Silurian and Devonian
5 fault
6 Lviv Basin boundary
7 borehole with Silurian thickness (m)
8 extent of the carbonate "biohermic" barriers: A - Bagovytsya, B - Konivka, C -Isakivtsi

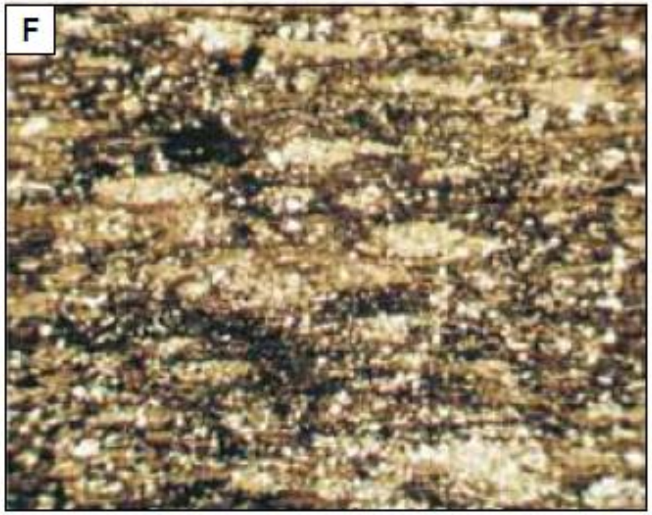
Regional transect based on wells, Ukraine





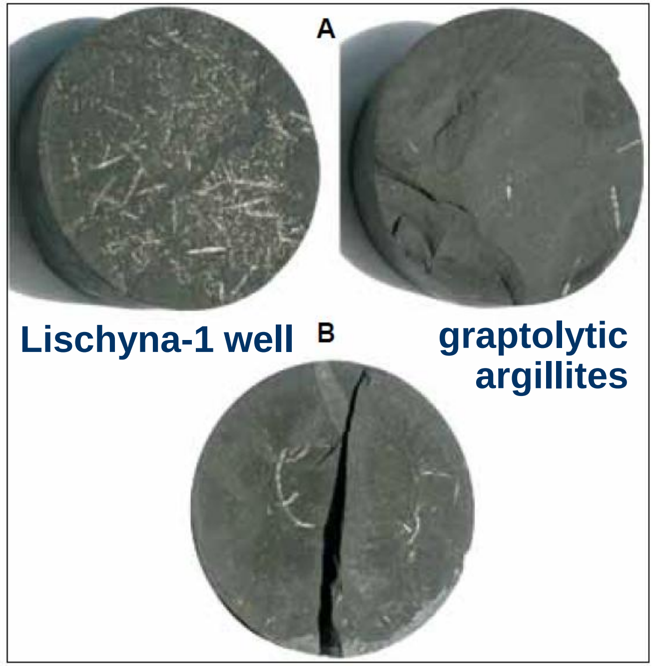
Note the thick Silurian sequence terminating abruptly to the SE, across the Trans-European Suture Zone.
Kurovets and Koltun (2012).

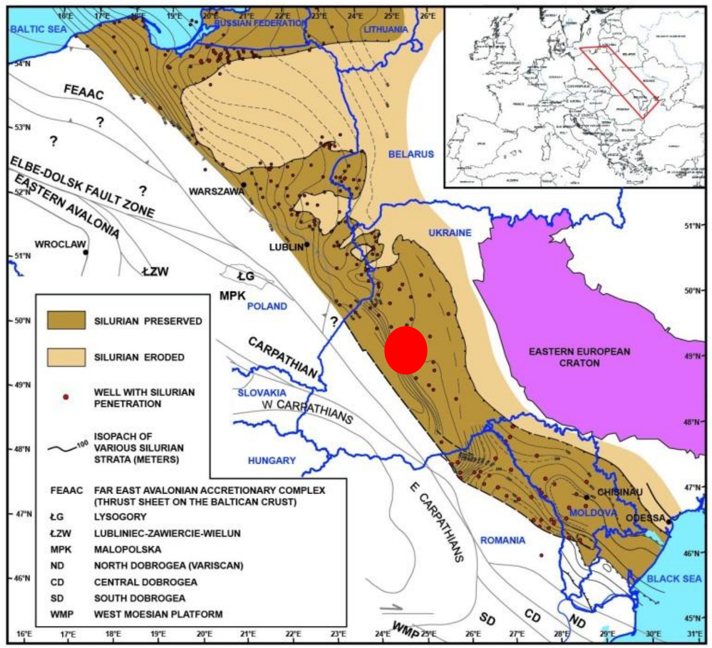
Shale gas potential in the Silurian of CEE, Ukraine



0 20 40 60 mm

0 0,5 1,0 1,5 mm

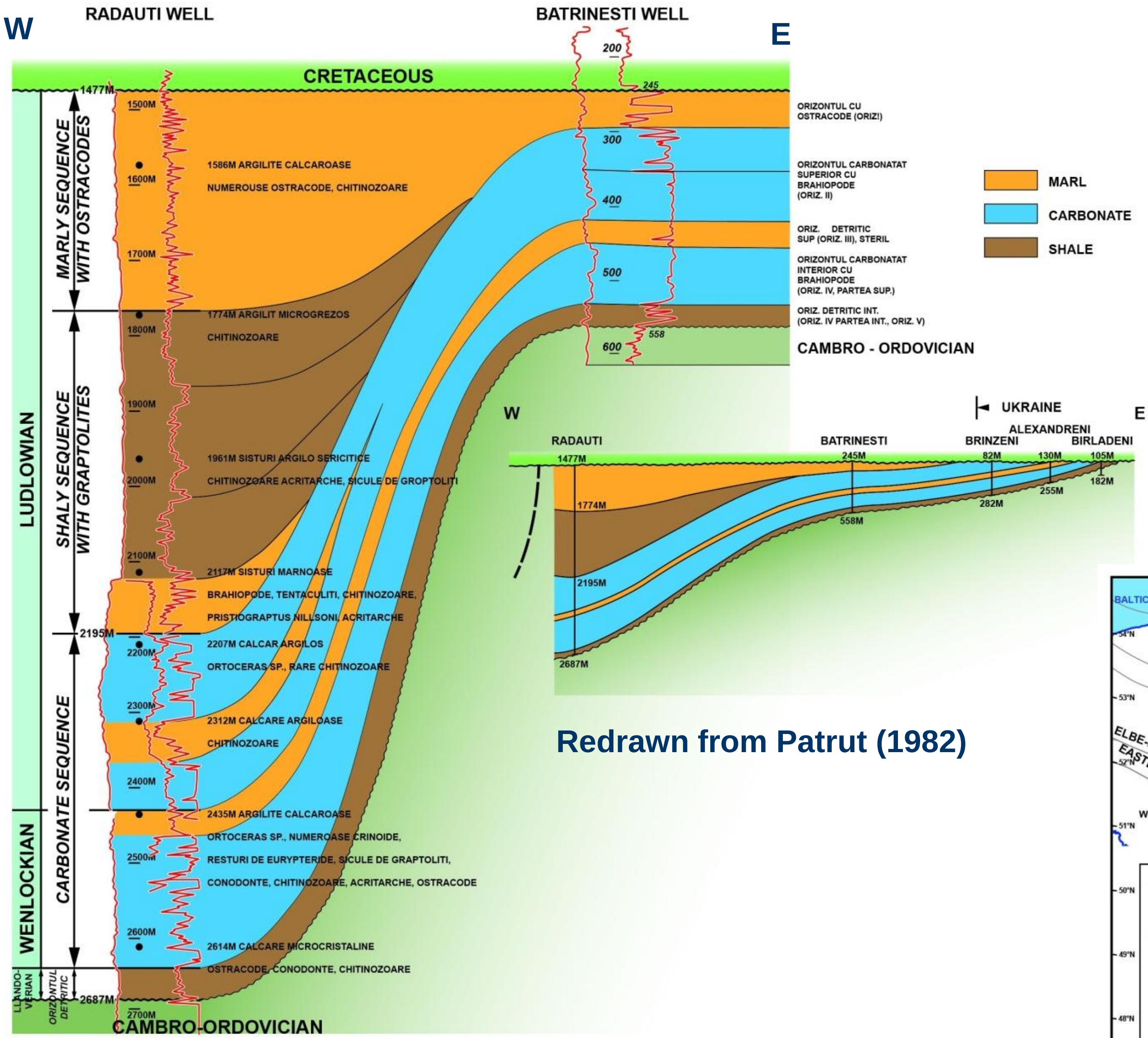




Kurovets et al., 2004

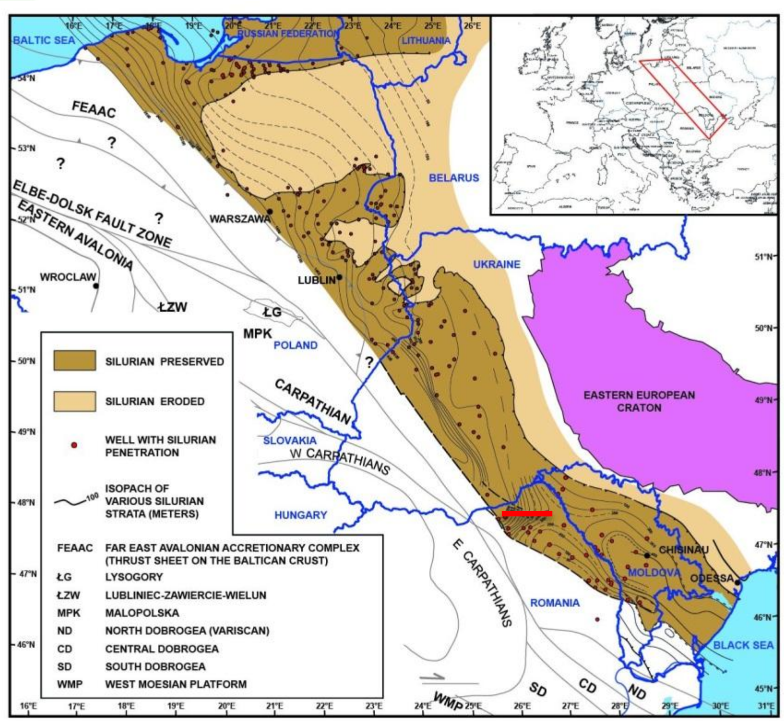
Thickness of the Silurian is more than 1000 m and methane was documented in the pore space…
but typical TOC: 0.7-2.4 %

Log-correlation of Silurian lithofacies, NE Romania

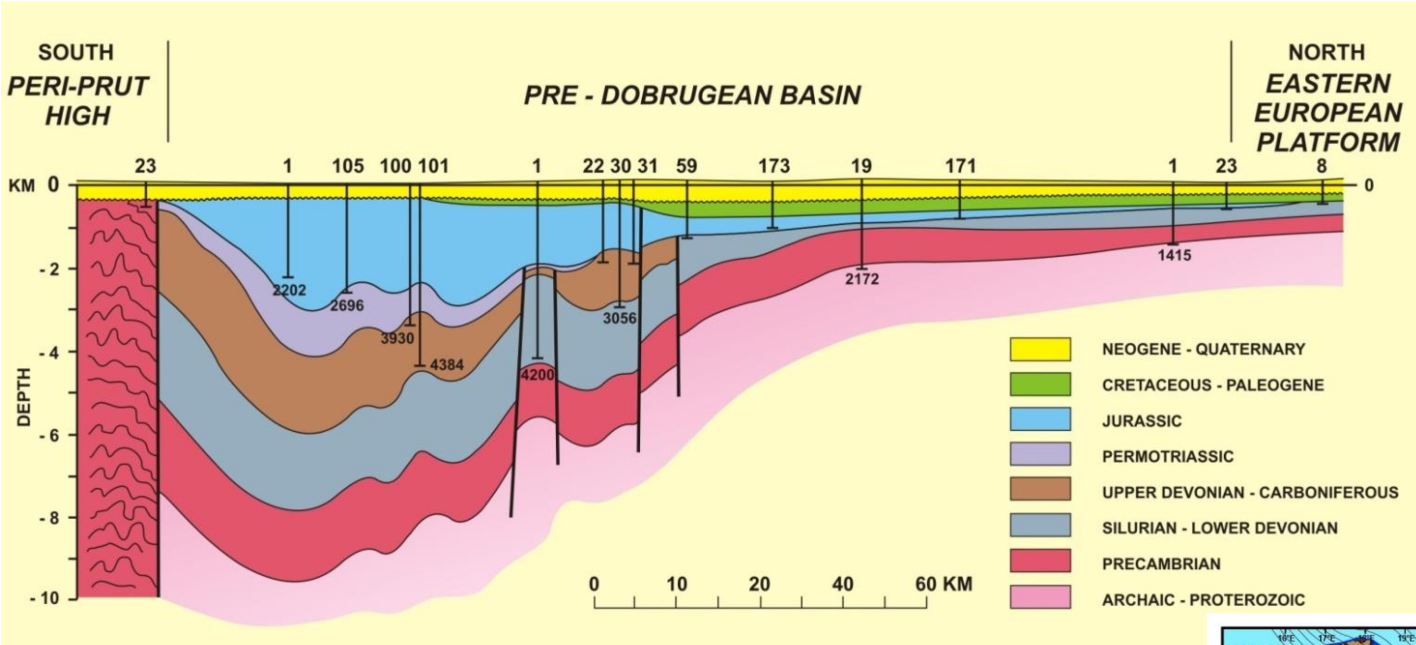


Redrawn from Patrut (1982)

The Silurian sequence could be quite thick in its proximal part in NE Romania (more than 1200 m), close to the Ukrainian border.
Note the prominent Late Ludlowian onlap of deepwater shales on top of a neritic carbonate sequence.

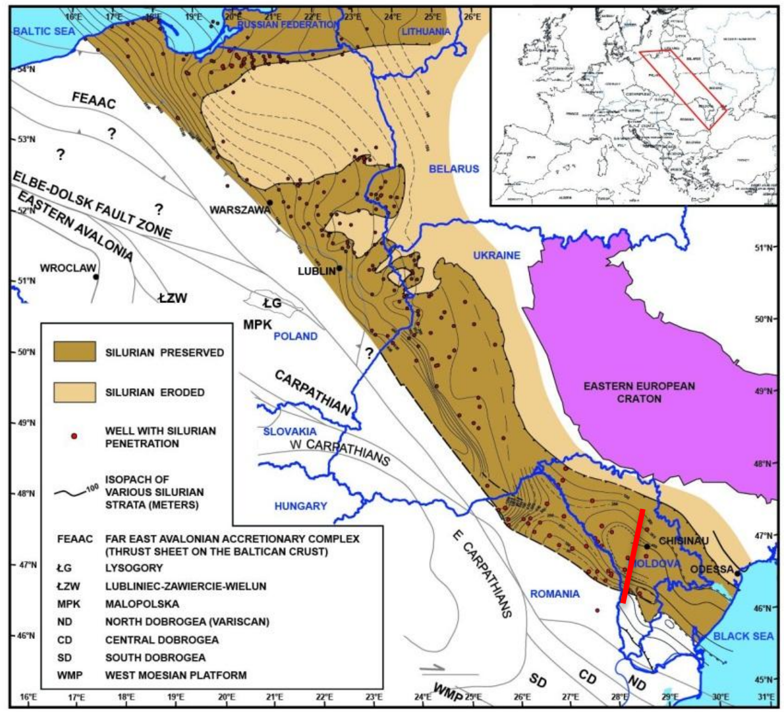


Regional transect based on wells, Romania and Moldavia

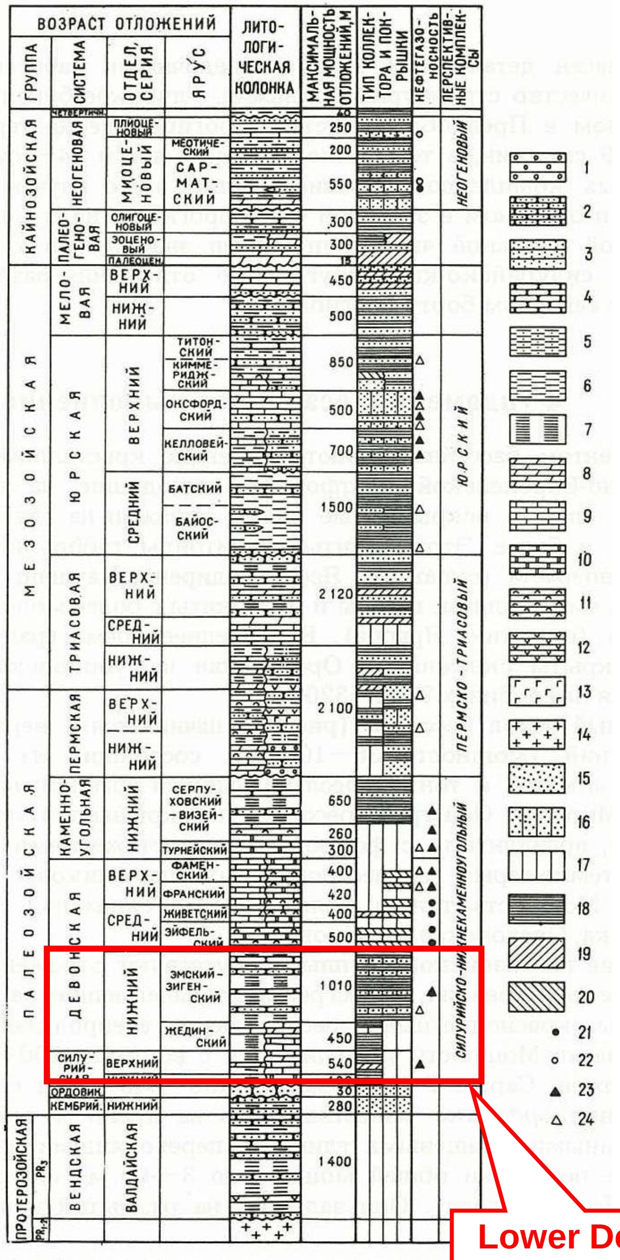


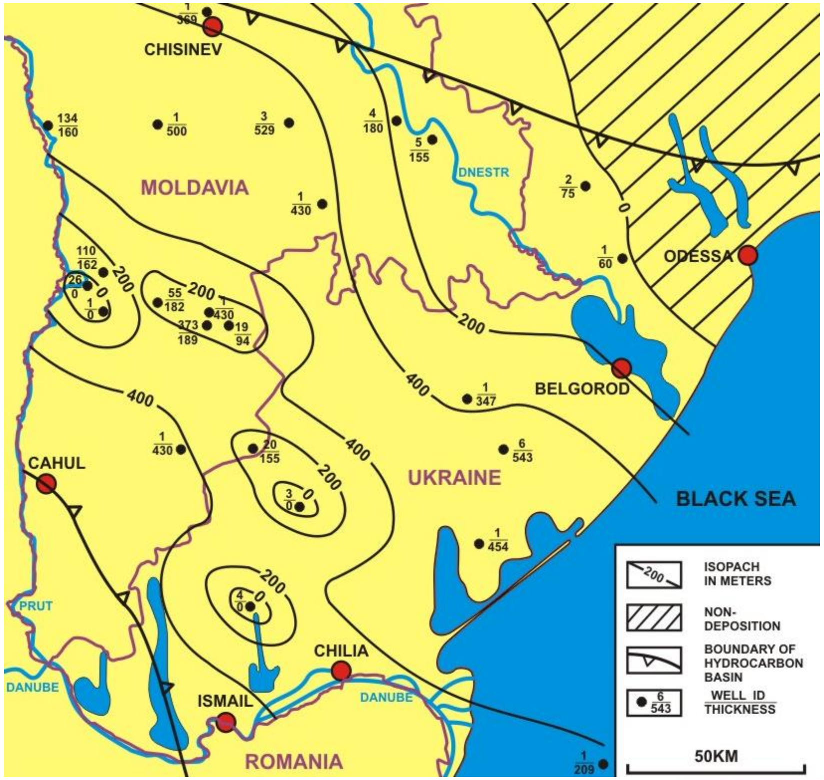
Note the thick Silurian to Lower Devonian sequence terminating abruptly to the SE, against the Trans-European Suture Zone.

Semenovich and Namestnikova (1981)

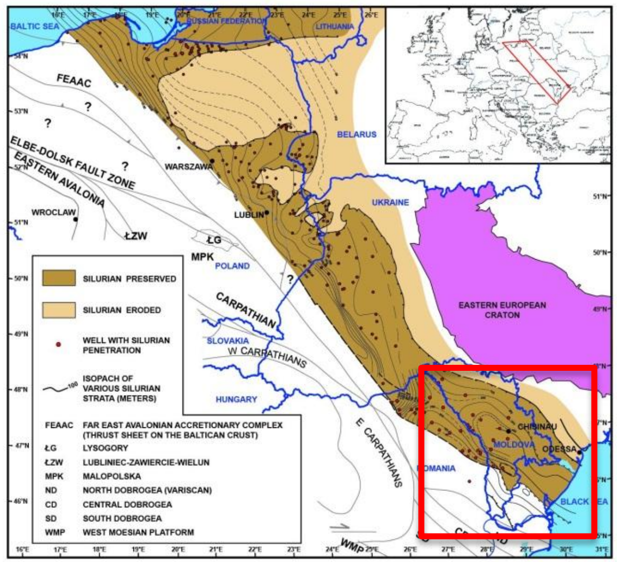


Silurian isopach, Moldavia



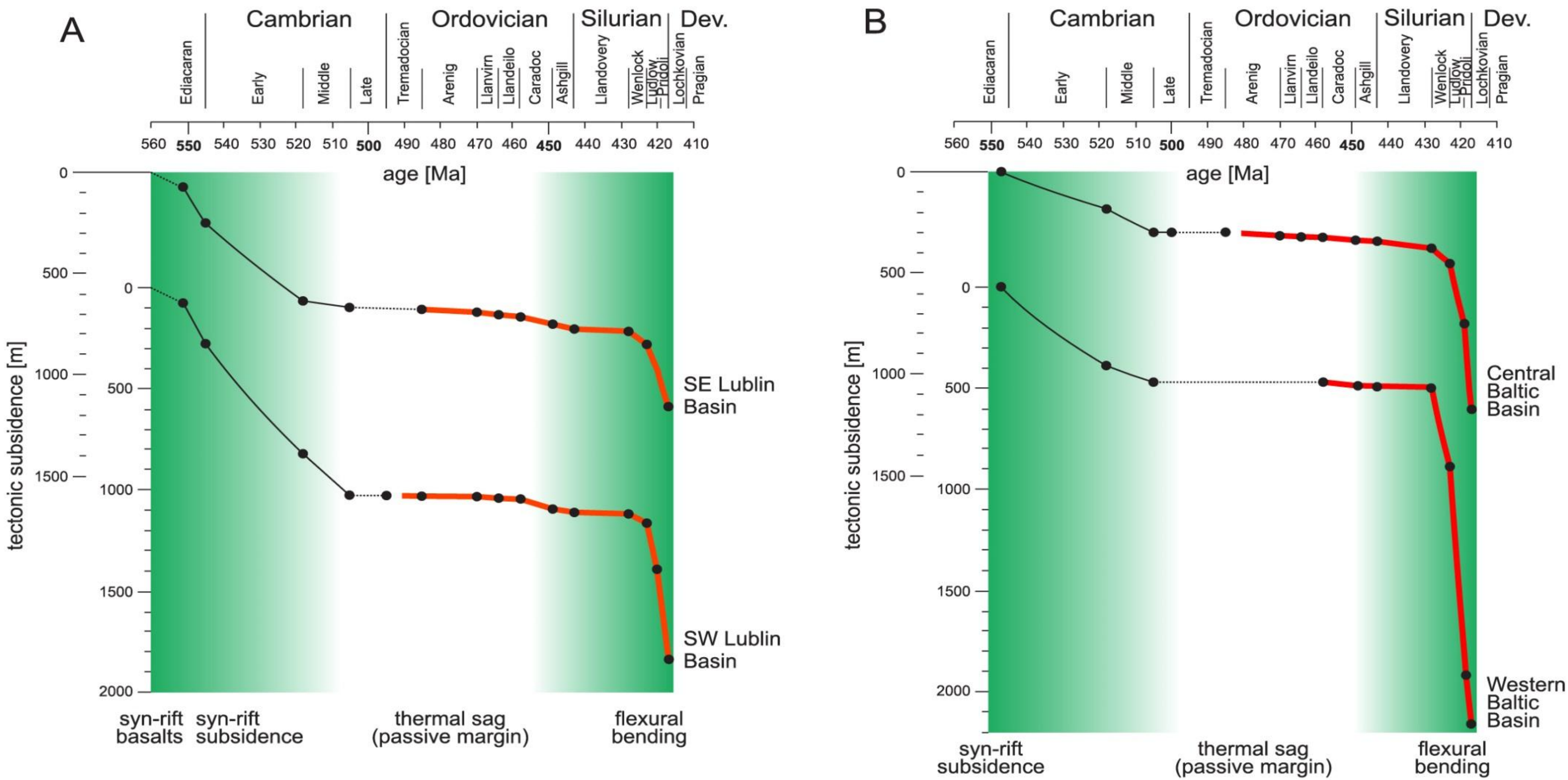


Semenovich and Namestnikova (1981)



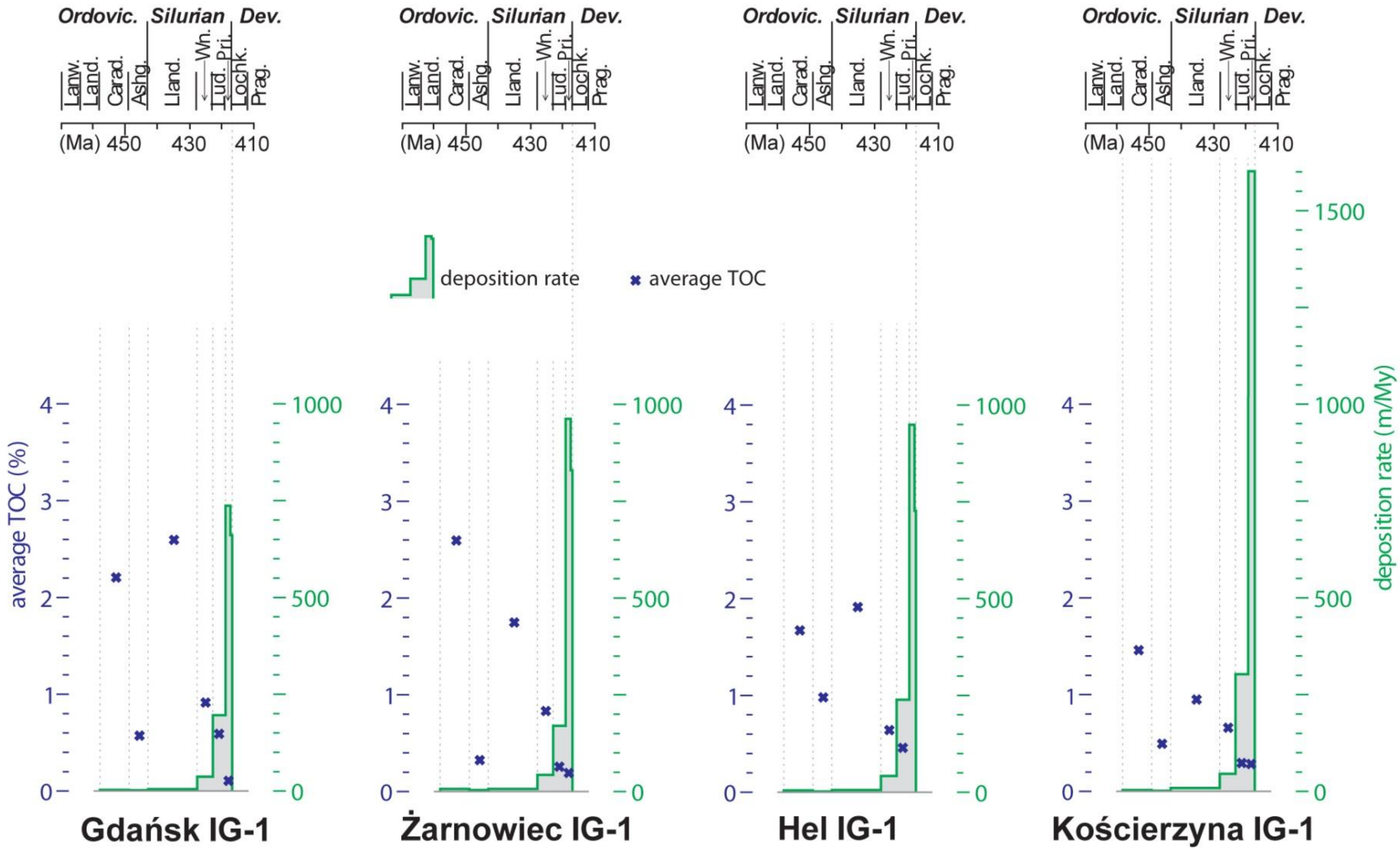
Lower Devonian
Silurian

Subsidence curves in the Polish segment of the Silurian Basin



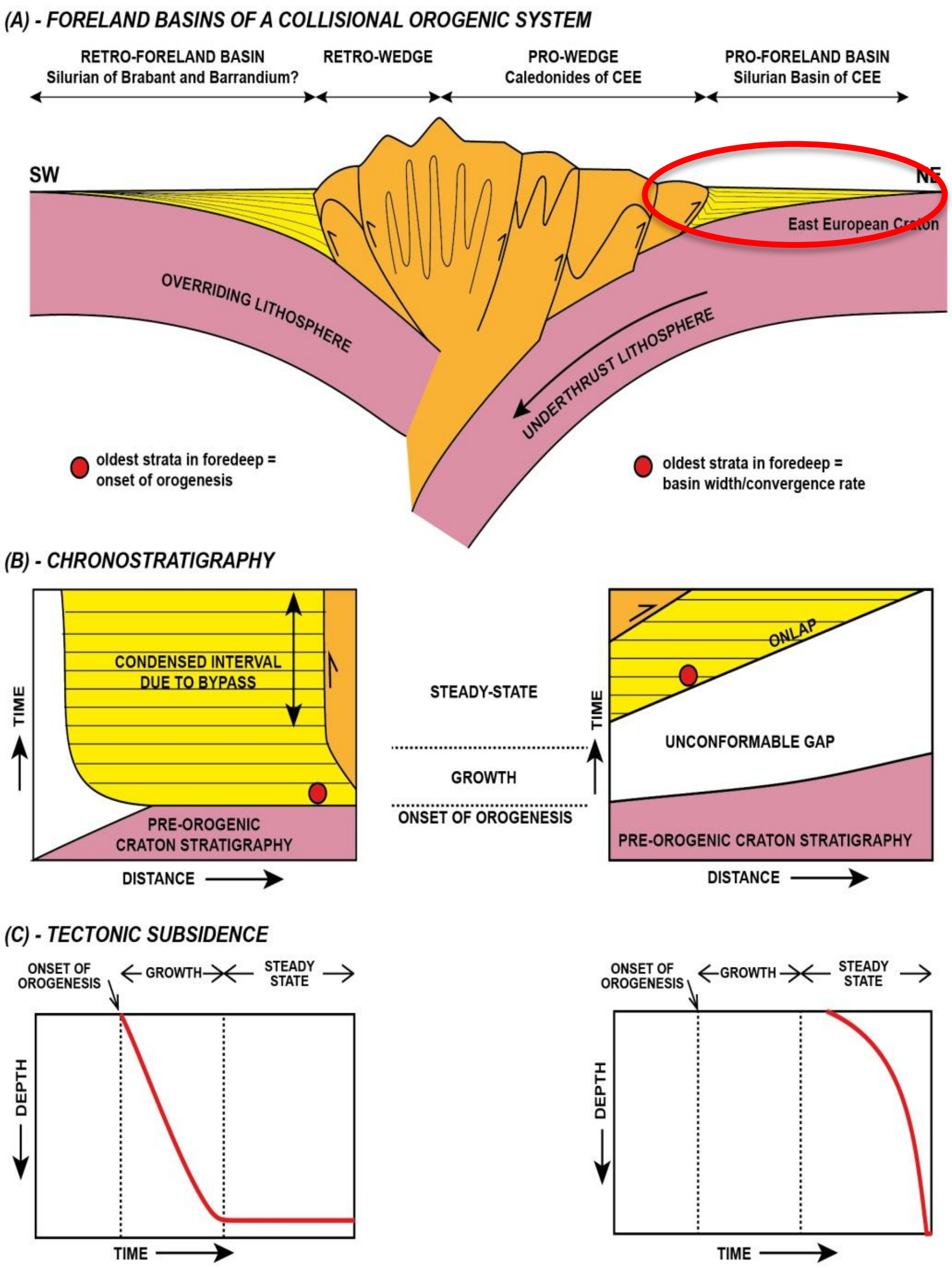
Tectonic subsidence curves for representative wells from the (A) Lublin-Podlasie and (B) Baltic basins of the Polish segment of the Silurian Basin, modified from Poprawa et al. (1999) and Nawrocki and Poprawa (2006).

TOC versus depositional rates in some Polish wells



Relationship between sediment deposition rate for the Upper Ordovician and Silurian and average organic matter content (TOC) in a few representative wells in Poland (modified from Poprawa, 2006; 2010). The generally inverse relationship between these factors has implications for shale gas exploration. Shale gas targets with high TOC are expected at the lowermost part of the flexural basin sequence.

The new tectonic interpretation of the Silurian Basin of CEE

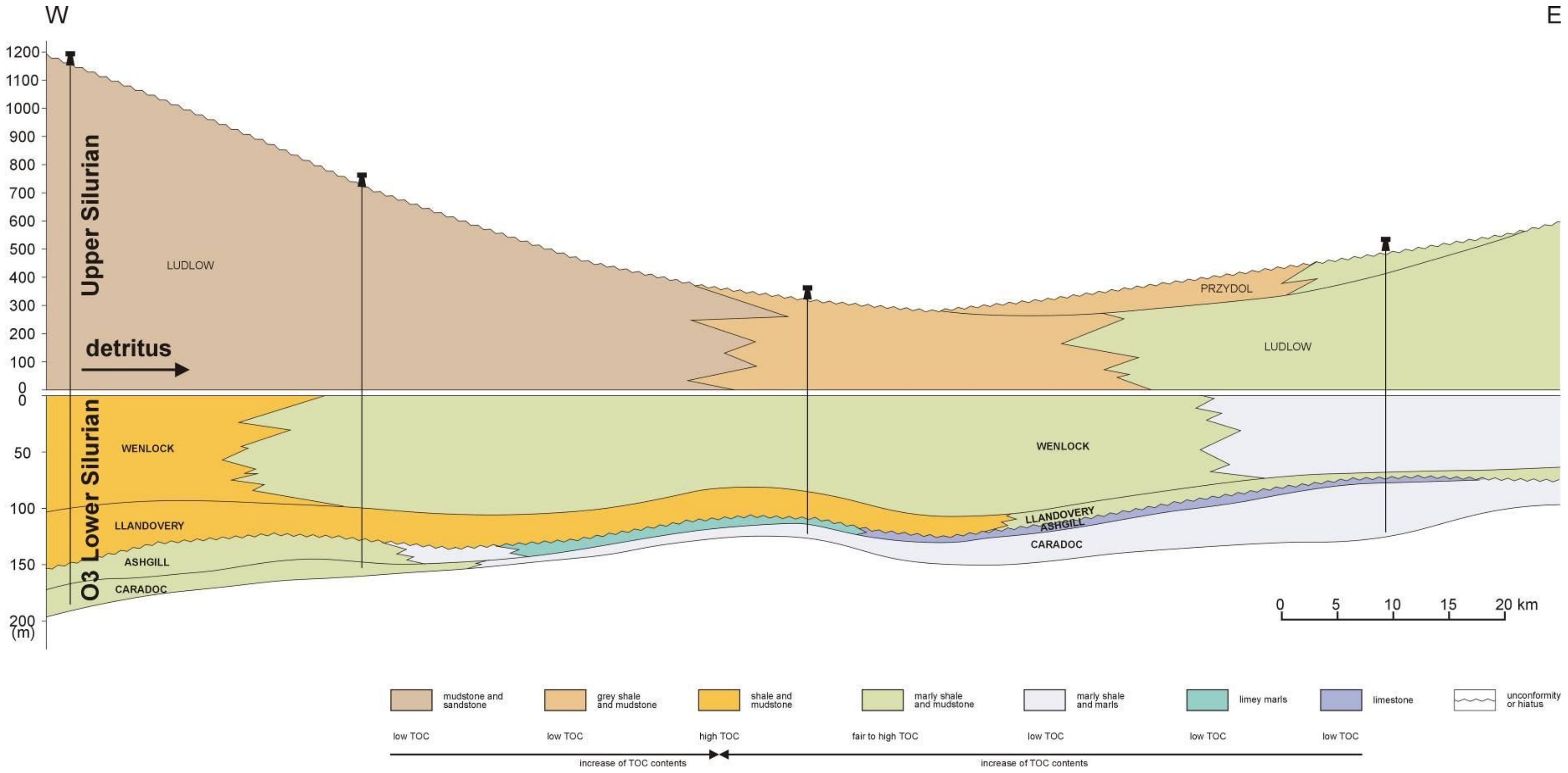


Summary figure contrasting the basin characteristics of pro-foreland versus retro-foreland foreland basins (adapted from Naylor and Sinclair, 2008).

The pro-foreland foreland basin exhibits dramatic basin onlap of the cratonic margin, at a rate greater or equal to the plate convergence rate dependent upon whether the thrust wedge is in a growth or steady- state phase, respectively; in contrast the retro-foreland basin records little onlap except in the early stage of growth.

We interpret the Silurian Basin of CEE as a pro-foreland basin based on the prominent and progressive stratigraphic onlap onto the craton and the subsidence curves.

So, where are the unconventional sweet spots…?



Lithofacies changes across the Podlasie Basin of Poland within the Upper Ordovician and Silurian. Section flattened on top of the Lower Silurian

Note the dramatic transgression and shift of shale sedimentation towards the east onto the East European Craton during the Llandovery (Early Silurian) due to a) foredeep subsidence and b) partially due to post-glaciation eustatic sea level rise.
Also note the supply of clastic detritus from the West from the Caledonian collision zone during the Late Silurian.

Conclusions

- Whereas Lower Paleozoic shales with shale gas exploration potential are fairly well studied and understood in Poland, considerably less is known about the extension of the same basin system towards the Black Sea region in the SE, i.e. in Ukraine, Romania, Moldavia, Bulgaria and Turkey.

- Despite the widespread erosion and marked tectonic overprint in many places, the distal segments of a large Silurian foredeep basin, trending NW-SE across Central and Eastern Europe can be reasonably followed along strike from Poland to Ukraine and Moldavia, all the way to the Black Sea coast.

- These basin segments are interpreted as parts of the same pro-foreland flexural basin which formed as the result of the Caledonian collisional orogeny during the Silurian.

- This new interpretation may have some predictive power as to the temporal and spatial distribution of sweet spots for unconventional exploration targeting Silurian black shales in the broader Central and Eastern Europe region.