The Moldova Slope and Basin Development in the Ediacaran-Early Paleozoic: A Collage with Multiple Structural Overprints*

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Abstract

This presentation describes the tectonic environment of the sedimentary cycles that build up at the boundary between the Precambrian and the Paleozoic in the Moldova Slope and in the southern, adjacent Moldova Basin. These sedimentary deposits lie over the Baltica or Eastern European Craton (EEC) and over Scythia (Scy) which is proposed as a hypothetically distinct terrain. They record the interaction of these terrains with the Western European Platform (WEP), eventually intermediated in the Paleozoic by Trans European Suture Zone (TESZ).

The Moldova Slope, as defined here, is a segment of the larger Dniester undeformed foreland basin, situated on the Ukrainian Shield in the east and limited in the west by the main lineaments of the TESZ. A part of the Moldova Slope is the Radauti-Roman Unit (Block), with a thick Early Paleozoic sedimentary succession laid down on a flexural basin slope. This unit is delineated by the Solca Fault in the west and is bound by the southern continuation of the Teisseyre-Tornquist Lineament in the east. The mobile Radauti-Roman Unit and the rigid basement essentially extend to the Murgoci Lineament in the south. The Solca Fault could merge into the major Peceneaga-Camena Fault further to the southeast. The entire Moldova Slope shows remarkable NNW-SSE Early Paleozoic facies belts over the entire Dniester Basin area.

The Moldova Basin, as re-defined here, is an approximately E-W trending elongated basin extending from the Carpathian front in the west and projecting below the Black Sea in the east. It records the deformations of Scythia's collision with Baltica during the Ediacaran-Silurian. A more complex Mid-Devonian to Cretaceous superimposed basin developed successively. The Moldova Basin has various structural overprints from the Cadomian to the Cimmerian events as well as of the Cretaceous extension associated with the opening of the Black Sea. The entire area was eventually inverted during the Latest Cretaceous-Paleogene.

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THE MOLDOVA SLOPE AND BASIN DEVELOPMENT IN THE EDIACARAN – EARLY PALEOZOIC : A COLLAGE WITH MULTIPLE STRUCTURAL OVERPRINTS

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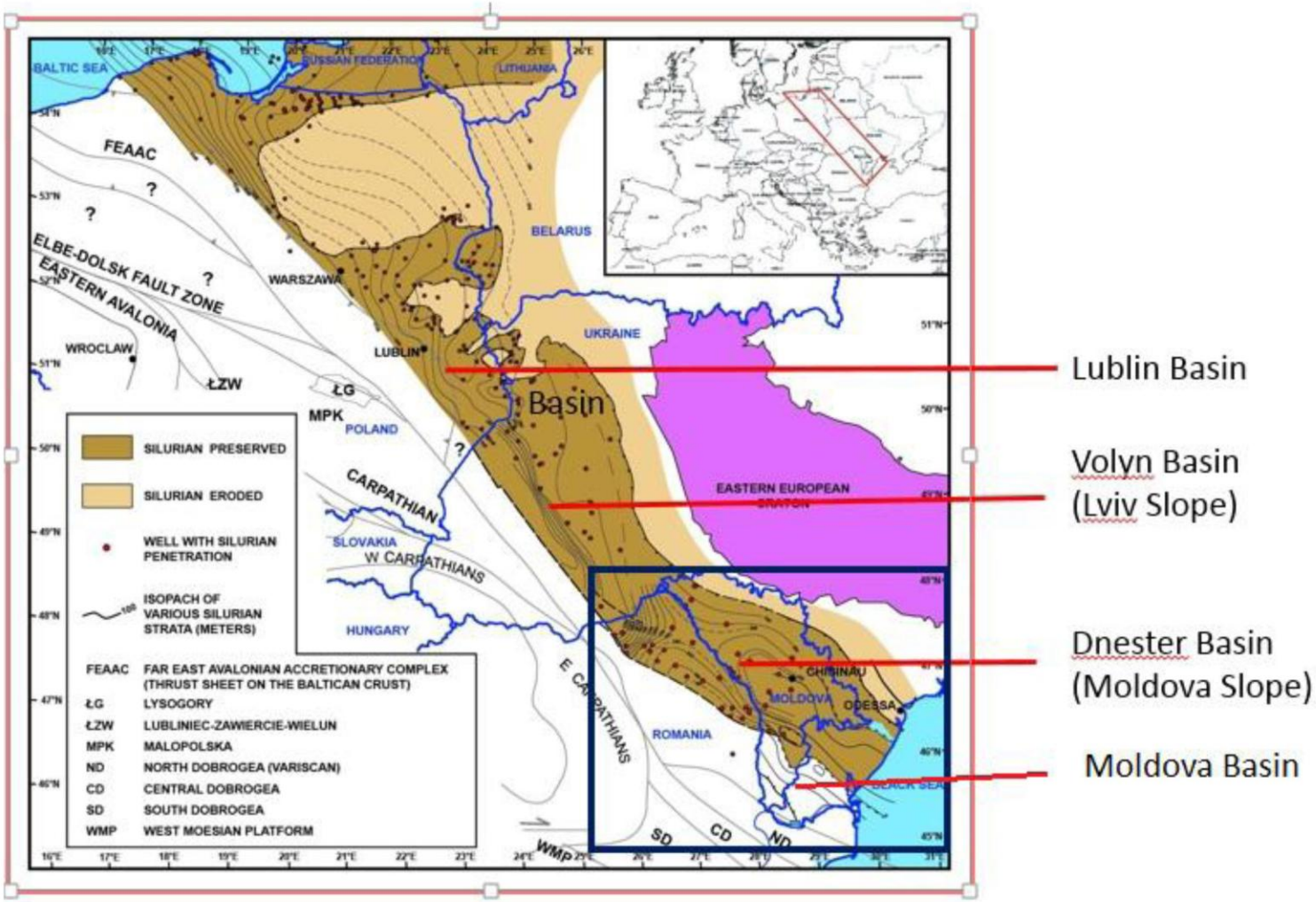
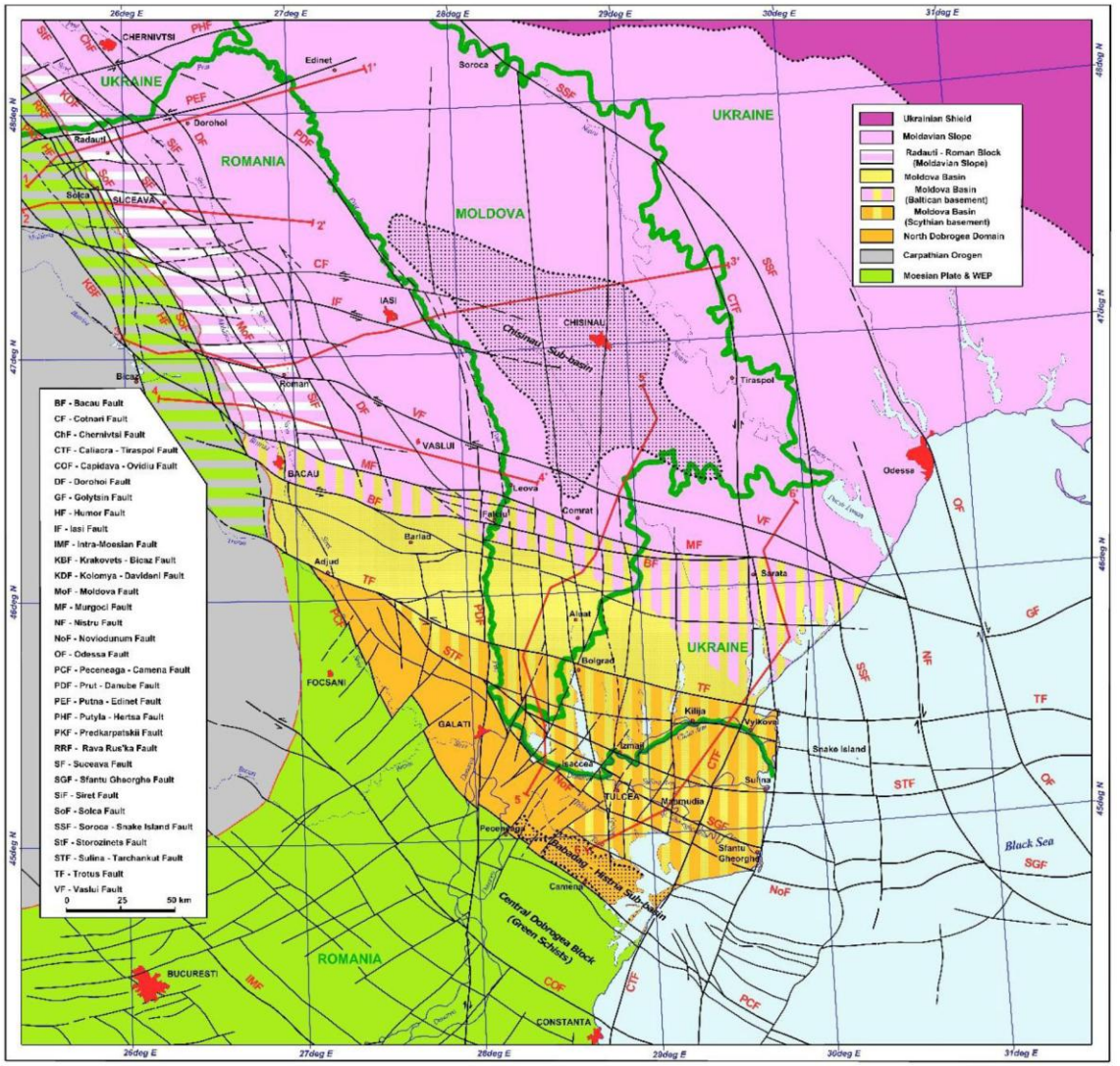
Location of the Study Area in the Early Paleozoic sedimentary basin complex of the EEC margin *(from Tari et al 2013)*



Presenter's notes: Our study area covers some 100,000 km2 in Romania, Republic of Moldova and Southwest Ukraine, above the East European Craton (EEC), Western European Platform (WEP) and Scythian Platform (Scy). This region not only contains an important segment of the Trans-European Suture Zone (TESZ) but also records, in its southern margin, the interaction of the Scythia (Scy) terrain during the Precambrian and Early Paleozoic.

Tectonic Sketch of the Moldova Slope and Basin

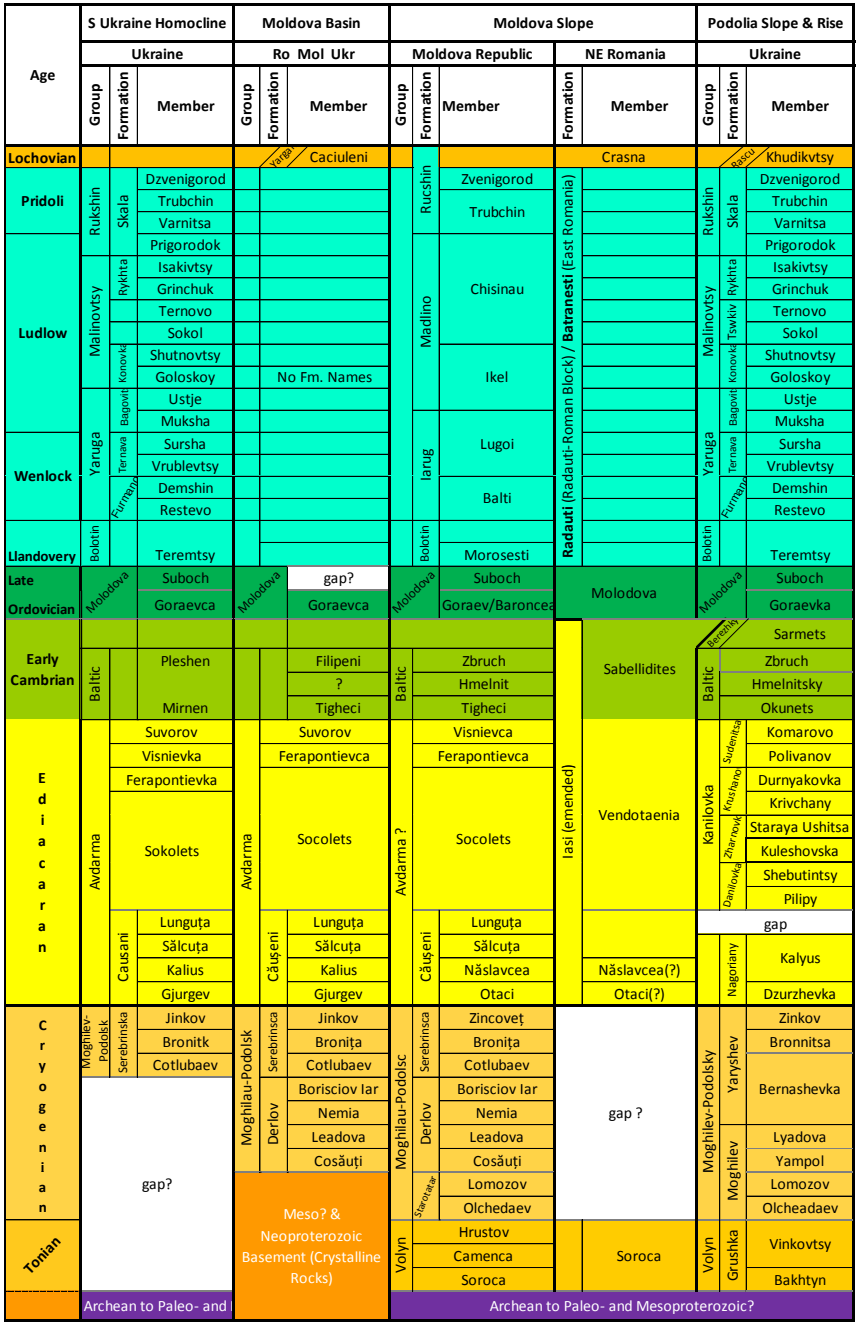


Presenter's notes: The *Moldova Slope* (magenta on the above figure), as depicted here, is a segment of the larger foreland Dniester Basin, situated on the Ukrainian Shield in the east and limited in the west by the main lineaments of the TESZ as defined in Poland and Ukraine based on deep seismic data. A part of the Moldova Slope is the Radauti-Roman Unit (stripped white and magenta), with a thick sedimentary succession laid down on the flexural basin slope (e.g. Tari et al., 2012 to 2016). The Radauti-Roman Unit is delineated (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

by the Suceava (? and Siret) faults in the east, the Solca Fault in the west and the Murgoci Lineament in the south. The Solca Fault could merge into the major Peceneaga-Camena crustal fault further to the south. As an expression of flexural basin development, the Silurian shallow facies sediments of the Moldova Slope, located over the rigid Baltican basement shows remarkable NNW-SSE facies belts (e.g. Radkovets, 2015) over the entire Dniester Basin area. The distal Radauti-Roman Unit with rapid Silurian subsidence history (Tari et al., 2016) can be recognized northwards in the Silurian foredeep.

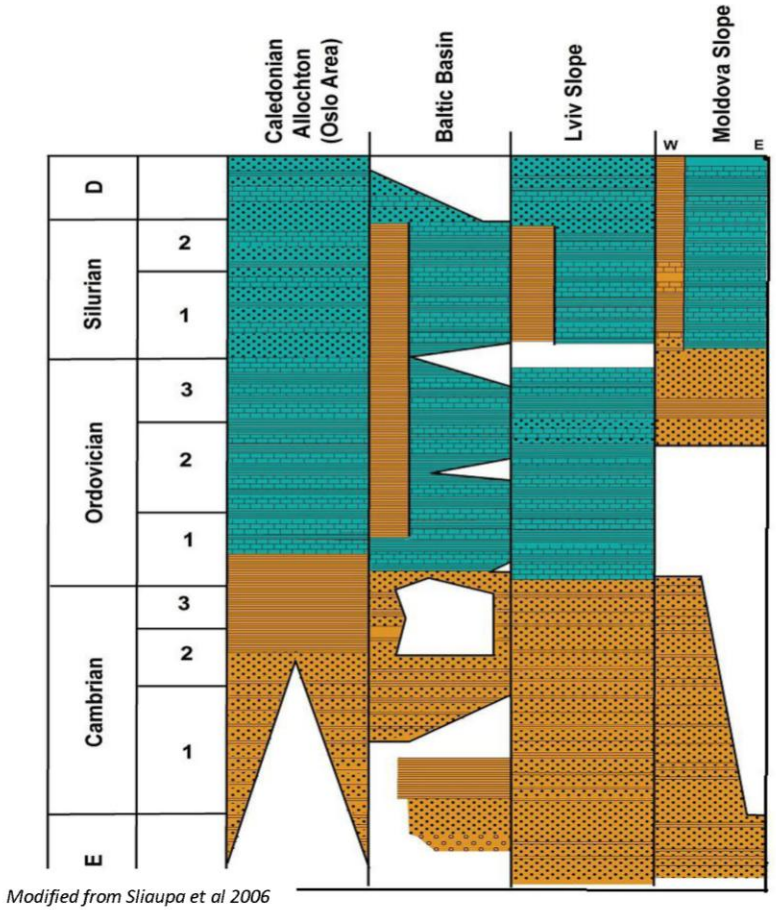
The *Moldova Basin* (yellow and orange on the above figure), as defined here, is an approximately E-W trending elongated basins extending in the region between the Murgoci Lineament and the Peceneaga-Camena Fault. It also exhibits an earlier flexural basin signature in the Ediacaran-Silurian. A more complex Mid-Devonian to Jurassic, superimposed and now concealed, basin development followed. The Moldova Basin has various structural overprints of the Cadomian, Caledonian, Variscan (?) and Cimmerian diastrophism as well as of the Early Cretaceous extension associated with the West Black Sea Basin opening. The entire area was then inverted during the Latest Cretaceous-Paleogene when the pace of sedimentation shifted eastwards. The inversion of the Moldova Basin is somewhat similar to that of the Mid-Polish Trough, during the same time interval.



Chronostratigraphic Correlation Moldova Slope and Basin

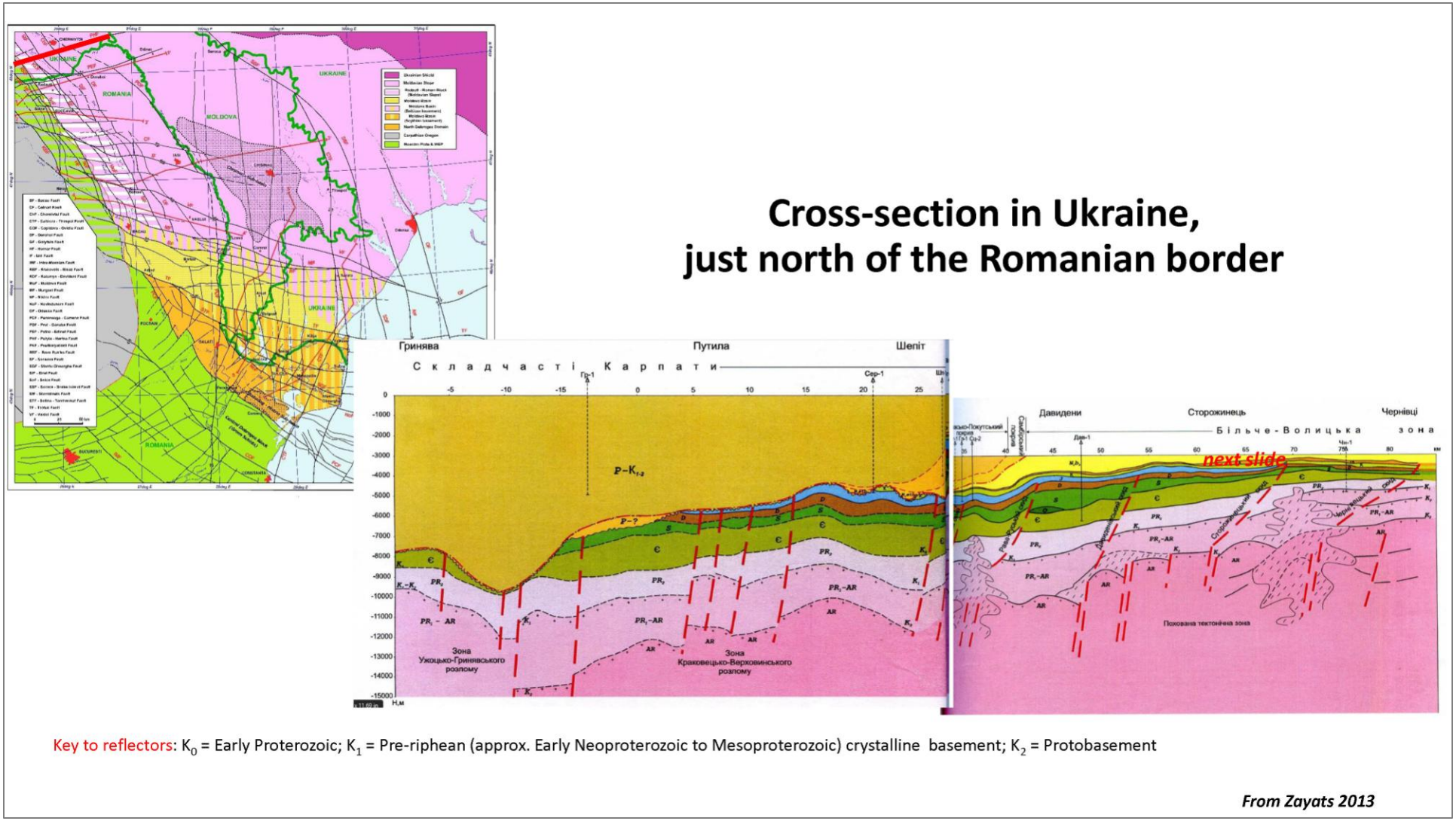
(Adapted from : Iordan 1982, Velikanov et al 1983, Bucatchuc et al 1985, Paraschiv 1985, Patrut & Danet 1985,1987, Ivantsov et al 2015)

Lithostratigraphic correlation of the EEC Early Paleozoic Basins



Presenter's notes: Early this century, a new interest for the Late Proterozoic-Early Paleozoic formations of the EEC and Scy was again triggered by the search for unconventional plays after sizeable oil and gas production was established in similar age basins in the United States. Among others, it lead to a re-examination of terrane interaction, basin definition and respective sedimentary covers correlations (table above and chronostratigraphic chart on slide 5).

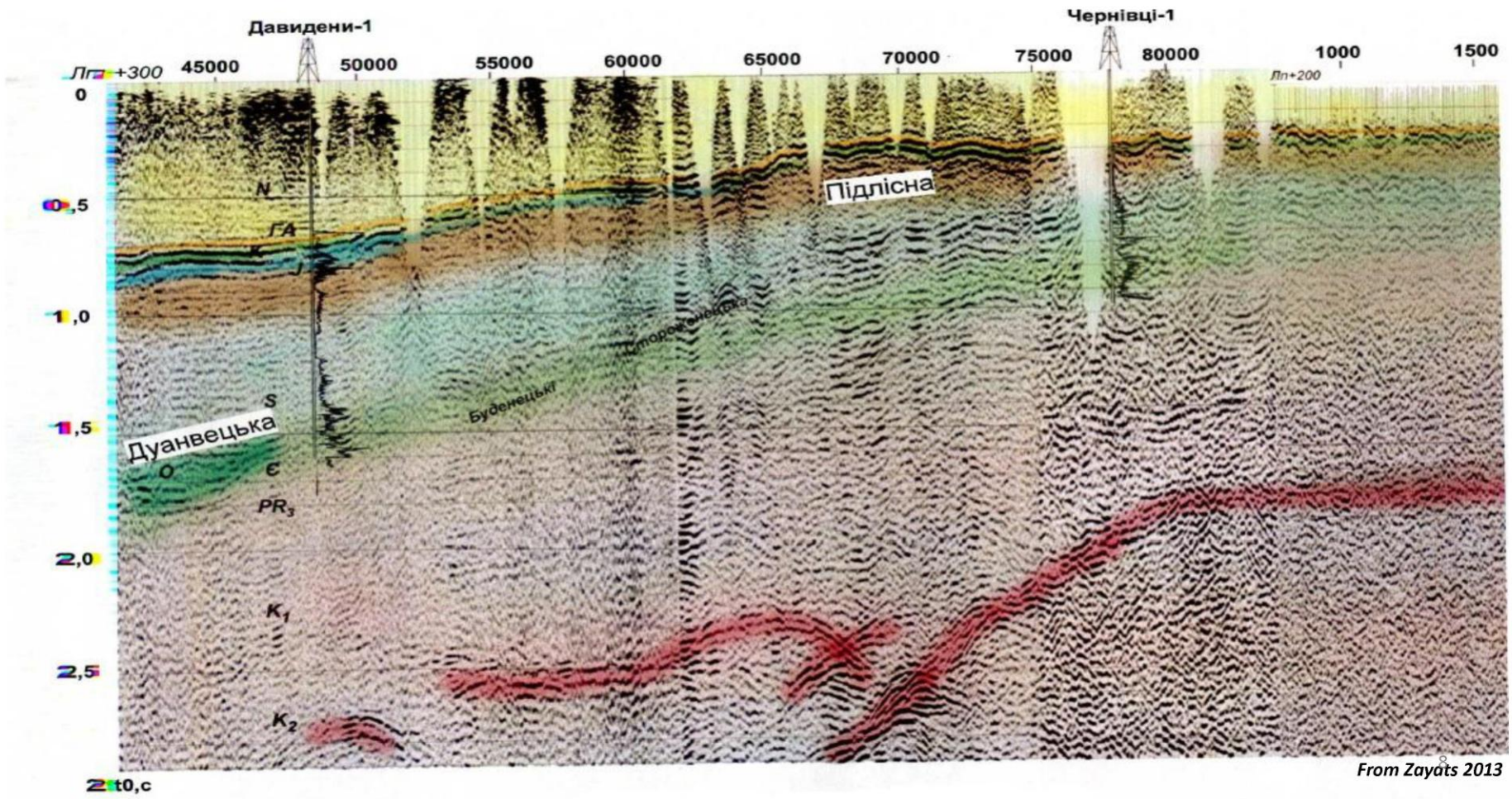
Nevertheless, in spite of local efforts, the geological information on the Late Proterozoic-Early Paleozoic sedimentary sequences of the Baltica terrane underlining our area remains incomplete and scarce being mostly dated, thus resulting in much debate and controversy.



Presenter's notes: This is Zayats (2013) interpretation of deep reflexion regional section north of the Romanian border. Of significance is that the post-Archean faults are reverse faults and show a progressive lower angle nature to the east of the Rava-Rus'ka Fault. However, they preserve a subvertical trace in the Archean 'protobasement' in this compartment.

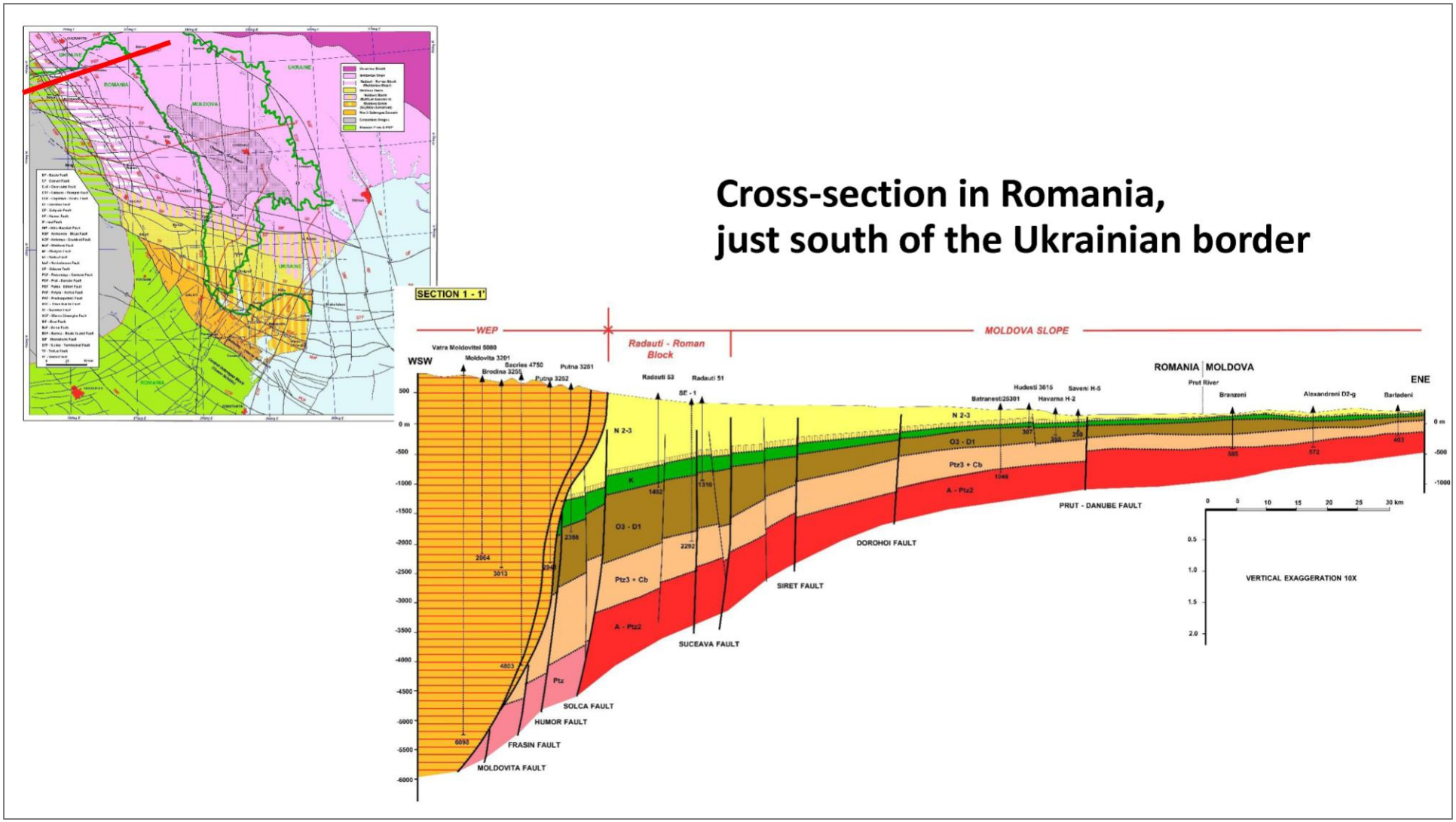
It should be noted that Zayats (2013)has extended the Archean-Early Proterozoic EEC basement on long distance west of the Rava-Rus'ka (Solca) Fault, where most authors featured WEP basement. This is similar to the recent research of Krzywiec et al. (2016) in southeastern Poland. Also author proposed a western undisturbed continuation - up to the Grinyava Lineament - of the Ediacaran to Devonian EEC-type sedimentary sequence.

Seismic illustration of the regional transect

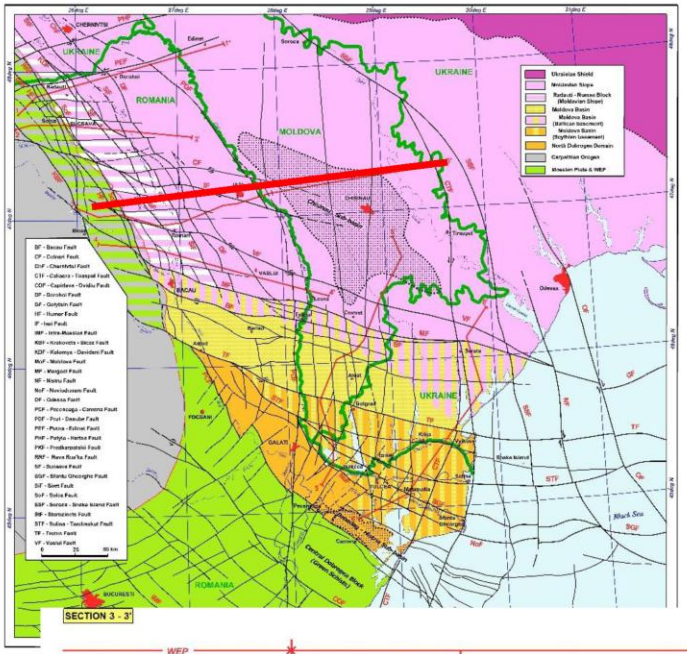


Presenter's notes: This is a close-up, between the Davideni and Chernivtsi wells, of the above section. The Kolomya-Davideni/Suceava (Radauti-Roman Unit east limit) and Storojinets (EEC firm basement western border) faults are clearly marked at the top of the Archean basement (K2) as subvertical faults and reverse above this seismic marker.

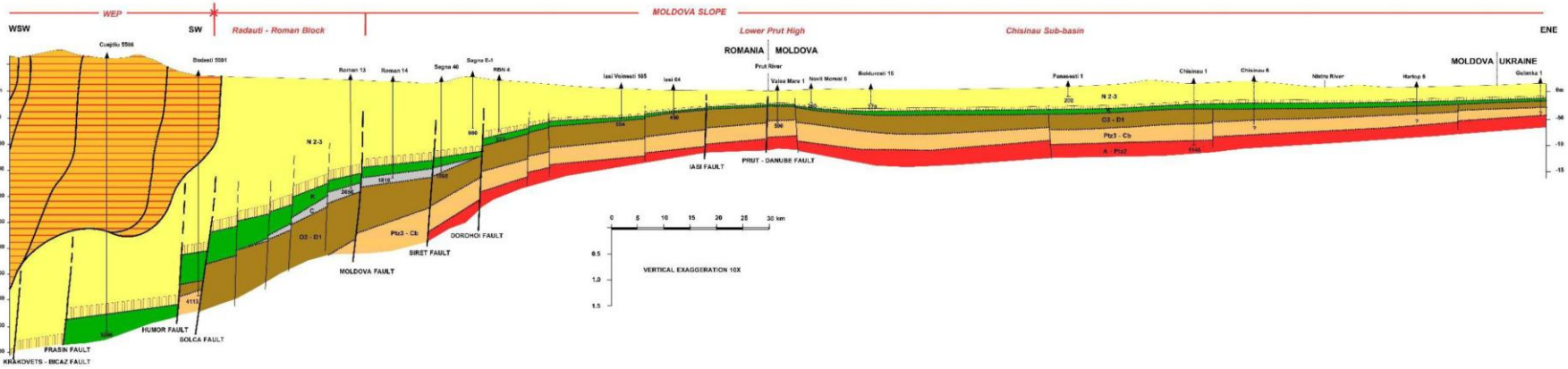
South of the Ukrainian border, similarly to Tari et al. (2012, 2016), we have interpreted the EEC Silurian – Early Devonian sequence as the expression of a foreland basin that ceased its evolution in the latest phases of the Caledonian diastrophism.



Presenter's notes: In northern Romania, due to the lack of modern deep reflection or refraction seismic regional surveys, we still interpret the faults of the Radauti-Roman Unit as subvertical and the region west of the Solca/Rava Rus'ka lineament assigned to WEP. WEP would have a basement made of Ediacaran-Early Cambrian greenschists perhaps underlined by Proterozoic higher grade metamorphics. The greenschists are comparable to occurrences in the Central Dobrogea, Lezajsk Massif and Malopolska terranes which we correlate as the tectonic unit running beneath the East Carpathians frontal area.



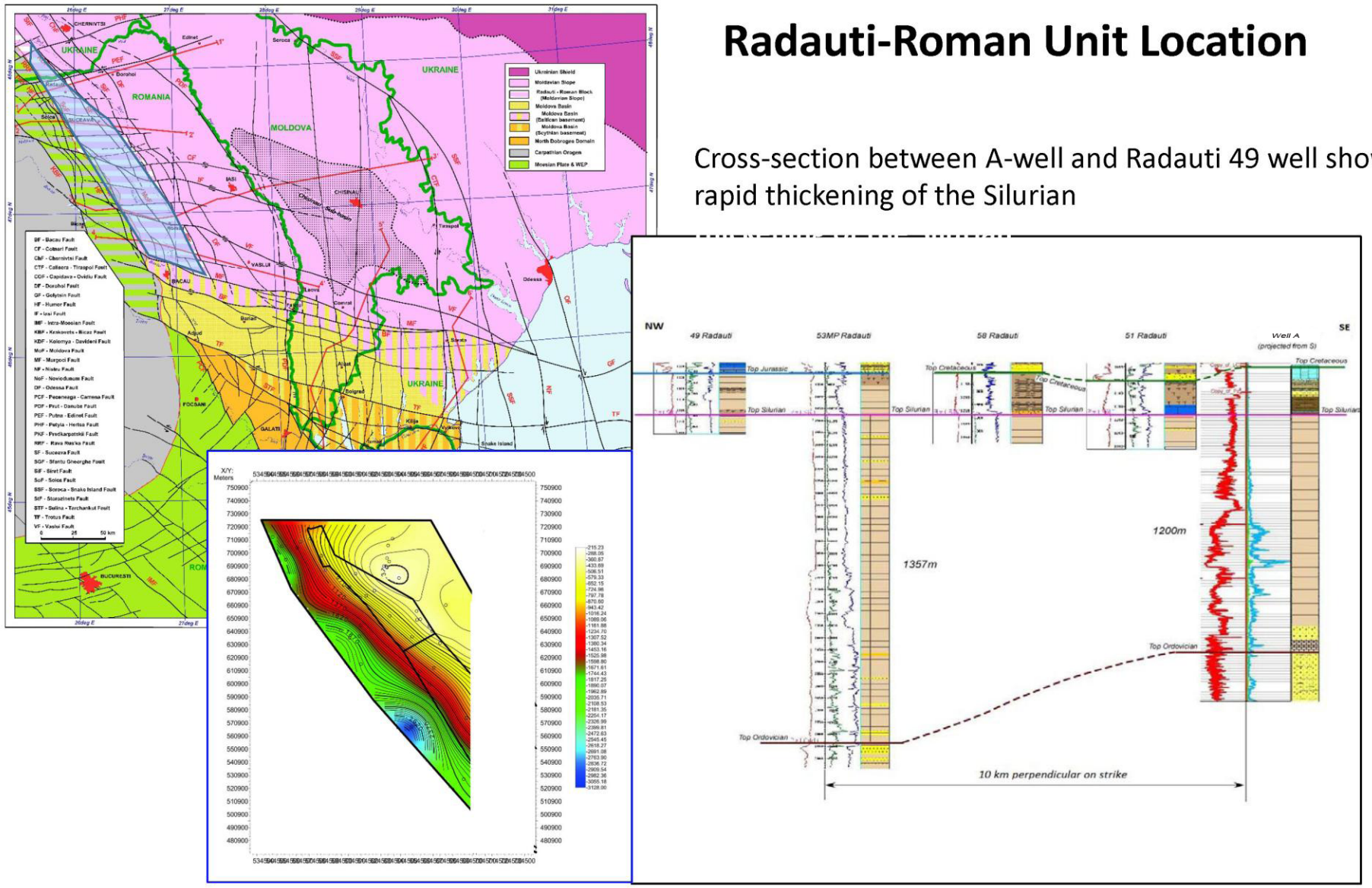
Cross-section between Cuejdiu-Roman-Iasi-Dubasari



Presenter's notes: The Lower Prut Saddle (High) reflected in the basement forebulge seems to continue northwards of the Murgoci Lineament faults. East of the forebulge develops the Silurian Chisinau Sub-basin.

Radauti-Roman Unit Location

Cross-section between A-well and Radauti 49 well showing rapid thickening of the Silurian



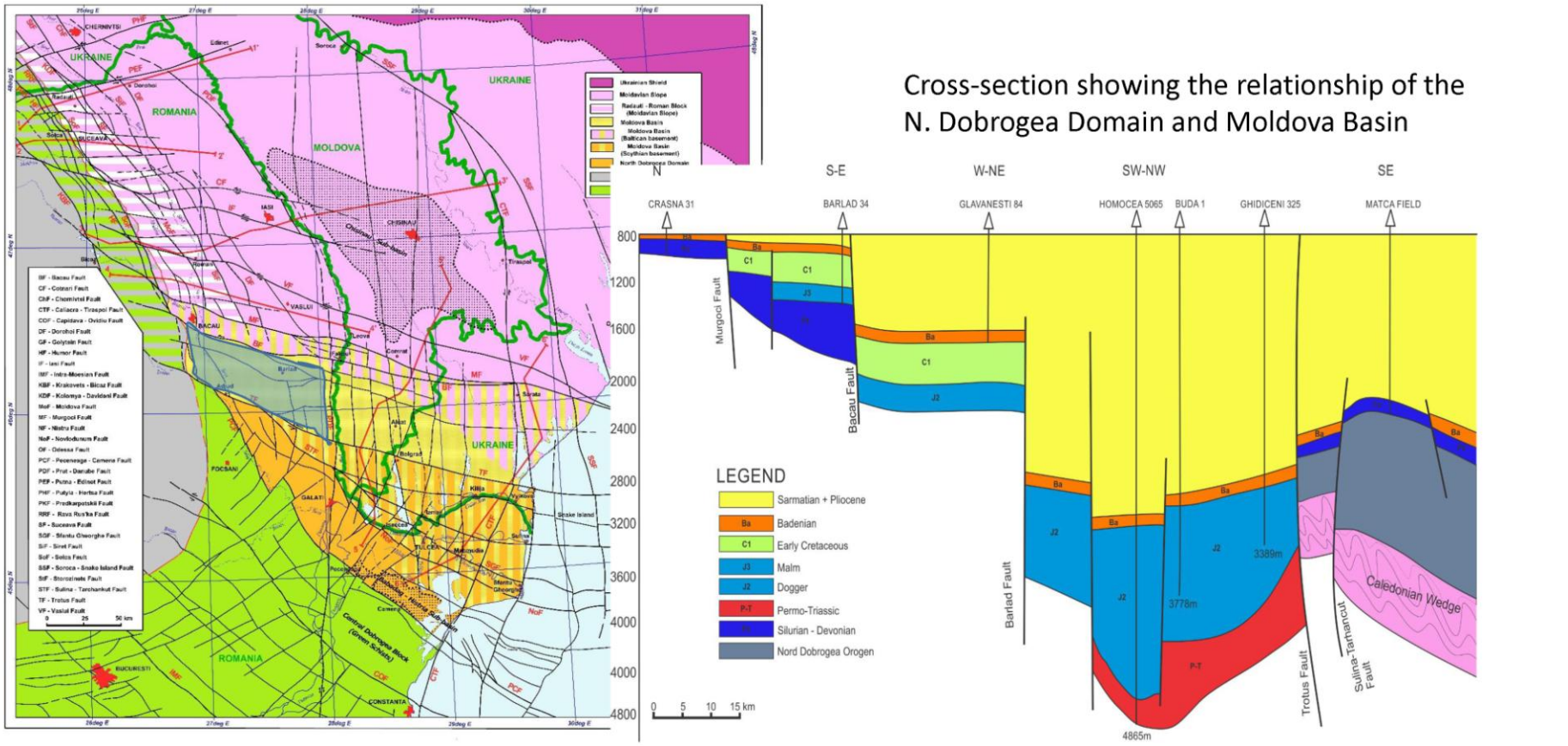
Presenter's notes: There is no direct information available yet on the basement and only partly available on the Paleozoic-Mesozoic cover of the western compartment of the Moldova Slope. Based on the industry seismic acquisitions in both Romania and NW Ukraine, we favor the existence of the Rădăuț i-Roman Unit (grey shaded and stripped on the tectonic sketch) over the extended, thinned and mobile EEC basement and its sedimentary cover. It develops from the north Putyla-Hertsa strike-slip down to the south Murgoci Lineament. (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

The similar paleontological content, general sedimentation continuity from the Moldova Slope during the Ediacaran to Early Devonian time and the NNE-SSW continuity of the Silurian sequence facies zonation (e.g. Skompsky et al., 2008; Radkovets, 2015) appear to indicate that the EEC, including the Rădăuț i-Roman Unit was not detached of EEE at least since the Late Ordovician as proved by the drilling and likely, since the Ediacaran, as results from the seismic interpretations.

We thus propose the basement and the cover developing on a strip located west of TTL is the Rădăuț i–Roman Unit, a thinned, "transition" EEC affinity block developed within the TESZ.

Barlad Sub-basin Location



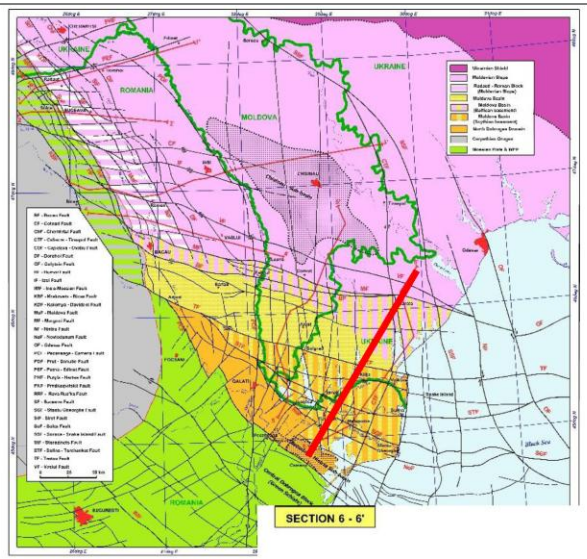
Presenter's notes: The Barlad Sub-Basin (grey on this slide) is simply the western end of the Moldova Basin, previously called the Pre-Dobrogea Depression in Moldovan and Ukrainiane literature, in spite of many early authors recognizing Murgoci's (1914) precedence. Note the presence of the interpreted collapsed Caledonian wedge beneath the internal units of North Dobrogea Domain (NDD) or Orogen of early authors.

The sub-basin (gray shaded on the tectonic sketch) develops south of the Murgoci Lineament as a half graben and appears to drops sharply between the Barlad and Trotus faults. It is bordered to the east by the Prut Saddle and the Prut-Danube Fault (PDF) and to the west, by the Peceneaga-Camena-Solca Fault, a boundary still matter of debate because it is running at high depth beneath the Focsani Basin or is concealed by the Carpathian nappes in areas with scarce drilling and deep seismic investigation. (*Presenter's notes continued from previous slide*)

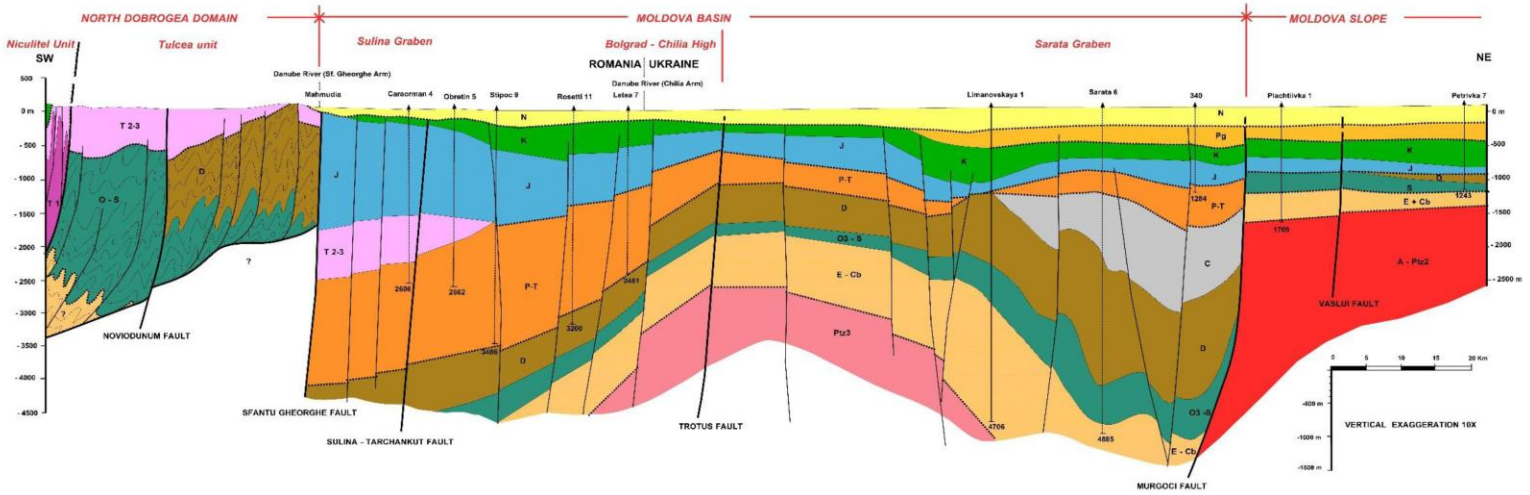
(*Presenter's notes continued on next slide*)

Sub-basin's southern limit has been revised several times by various authors with rather important consequences for the entire Moldova Basin definition. We propose the Trotus Fault as the southern boundary only of the northern string of Permo-Triassic rifts one of the components of the Moldova Basin.

Yet, in our interpretation, the Moldova Basin extends south at least up to the front of the pro-wedge marked by the Noviodunum Fault in the onshore Tulcea unit of NDD and may be, farther south, up to the Portita Fault (yellow and orange stripped area).

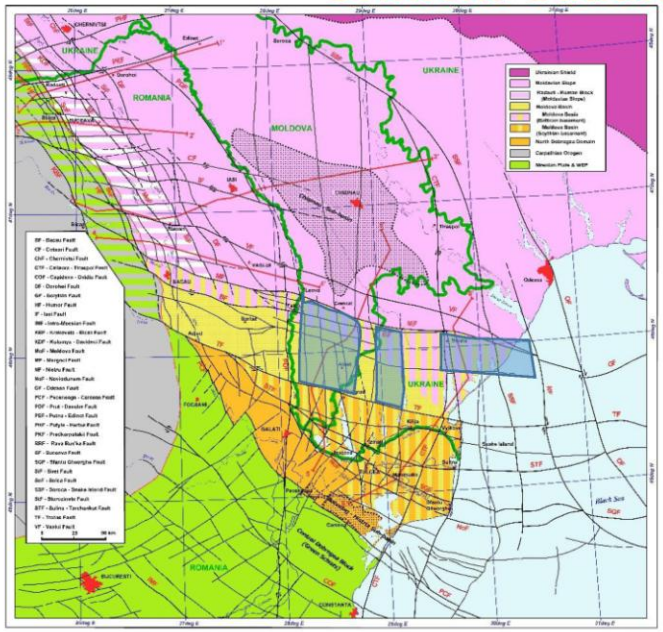


Cross–section between Babadag Mahmudia - Vilkove - Sarata - Petrivka



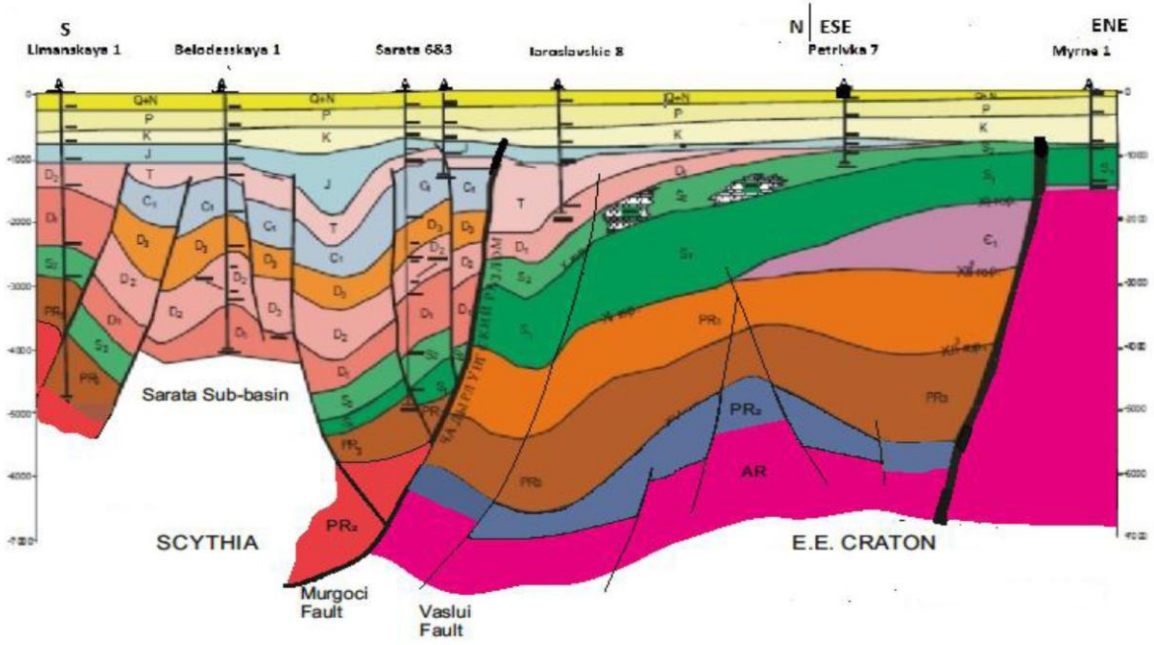
Presenter's notes: The western end of the section shows the outcrop and the deeper interpretation of the superposed Cadomian and Caledonian wedges in the northern Tulcea Unit of the NDD. They lie over a gravity low of some 5 km+ deep basement covered by lower density clastic sedimentary strata (e.g. Rosca and Atanasiu, 1993). This gravity low is adjacent to a large Paleozoic granitoid plutonic body (Seghedi (2001) assigned to the questionable Uzumbair terrane by Balintoni and Balica (2016). The pluton was not identified on the nearshore seismic (Munteanu et al., 2012). Note in eastern side the throw along the Murgoci Lineament that could reach more than 3 km.

Orihivka Saddle between Aluat & Sarata Sub-basins



An eastwards seismogeological sections through the Sarata Sub-basin showing Scythia and Baltica (EEC) tectonic imbrication. This line starts from Odessa to join our precedent slide section at Petrivka 7 well running then south, to Limanovskaya 1.

(***Adapted from Samsonov et al 2014***)



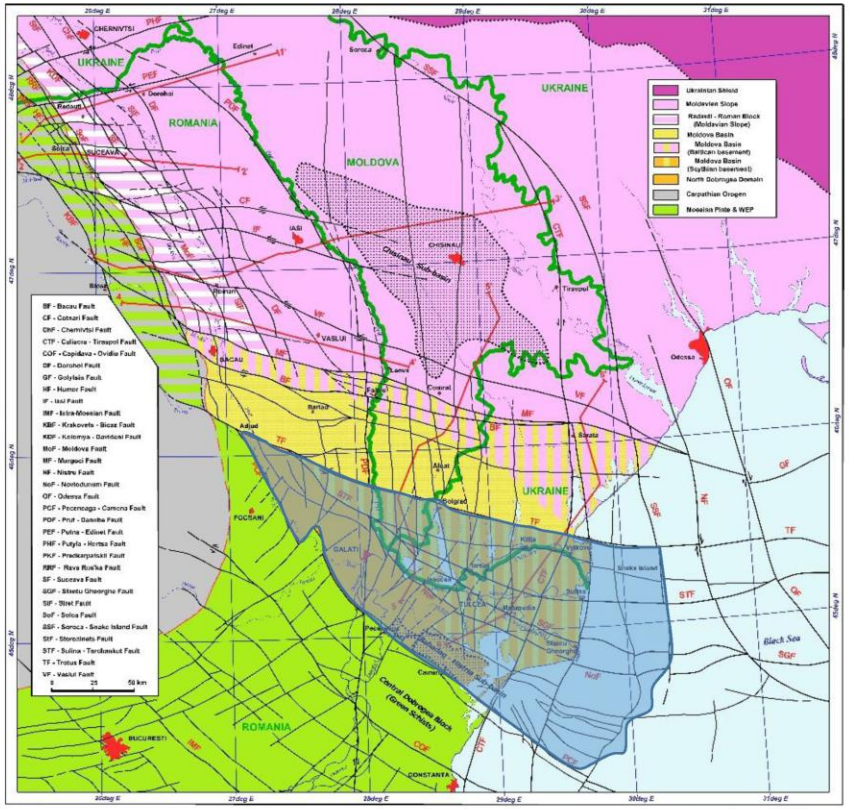
Presenter's notes: Orihivka (central grey shaded area) is one of the rare, large N-S tectonic saddle in the Moldova Basin aside the Lower Prut one, a much smaller feature. The Aluat and Sarata sub-basins (grey shaded) separated by the Orihivka Saddle consist of a number of Proterozoic-Paleozoic sedimentary sequences: (a) Ediacaran-Early Devonian, a folded molasses or flysch-like deposits ending with postectonic red sediments, (b) Mid-Devonian - Early Carboniferous evaporite-carbonate platform, (c) Carboniferous deltaic clastics and paralic coal measures, and (d) Permo-Triassic rift red-beds and volcanoclastics. (*Presenter's notes continued on next slide*)

(*Presenter's notes continued from previous slide*)

On the Orihivka Saddle, two wells bottomed in the EEC basement (Jeru 1972) below Cryogenian deposits with only 5 degree dips. These plagiogranites, or trondhjemites were dated as Cryogenian and Ediacaran. The unconformable Avdarma Group is strongly folded (Neaga, 1972) by the Cadomian advancement of Scythia.

Alternatively, these Cryogenian anatexic granitoids would represent the Scythian basement in an allochtonous position over the Baltican basement (section in the lower right).

North Dobrogea Domain



Presenter's notes: In our analysis of the region, it has been proposed the definition of the North Dobrogea Domain (NDD), as the area developing between the Peceneaga-Camena transform (Gradinaru 1984) fault in the south and the Trotus Fault in the north. It is partly covered by the Moldova Basin, in the NE, represented by the Tulcea Unit in the Trotus- Sulina-Tarchankut and Sfatu Gheorghe, en-echelon faults development area and would extend offshore over a not yet fully assessed area. The Macin and Niculitel units crop-out in the SW and were encountered in wells up to Adjud in the west. (*Presenter's notes continued on next slide*)

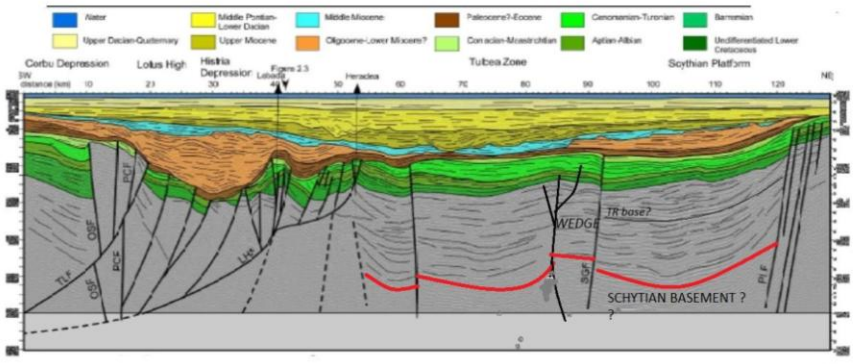
(*Presenter's notes continued from previous slide*)

The detailed lithostratigraphic description of the onshore NDD, a complex Proterozoic-Jurassic sedimentary suites with overprints of the Caledonian, Variscan, and Cimmerian diastrophic events was detailed in a recent article (Seghedi, 2012 and references therein).

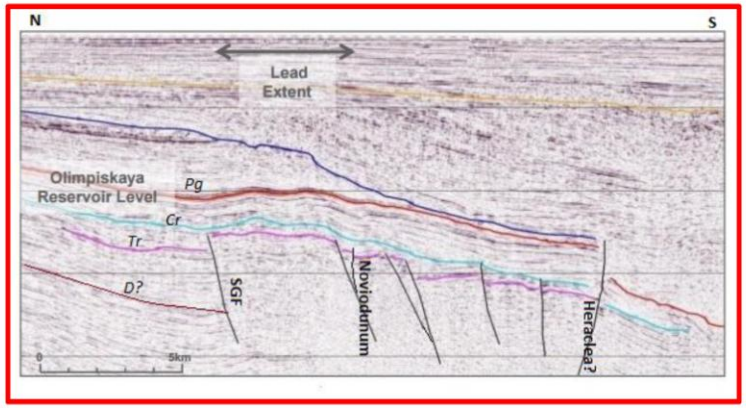
The NDD's Tulcea Unit (stripped orange and yellow area) is not yet fully assessed. It could be suggestive for the reconstruction of the Ediacaran-Early Paleozoic evolution of the Moldova Basin because it is speculated the basin extended at least up to the Noviodunum Fault - somewhat close to a portion of the trace of the new Telita Fault as re-defined by Seghedi (2012) – or probably farther south, up to the Portita Fault.

The Early Paleozoic develops in a turbidite facies accumulated on a flexural plate (Seghedi 2012) and is presently exposed in an accreted (?) terrane (Seghedi, 2001) located in the Tulcea Unit. Instead we interpret them as the remnant of the Caledonian Wedge of the Moldova pro-foreland basin (Popescu and Veliciu, 2014) as well as the site of an earlier Cadomian Wedge, a testimony of the Scythia/Baltica collision.

Cross-sections in the Western Black Sea nearshore and Muridava Block area showing the Tulcea Unit individual structure. The Codomian, Caledonian and Variscan wedges run E-W parallel and south of to the Noviodunum Fault



Modified from Munteanu et al 2011



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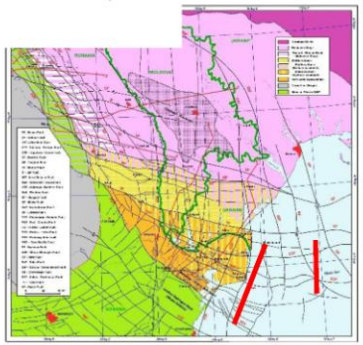
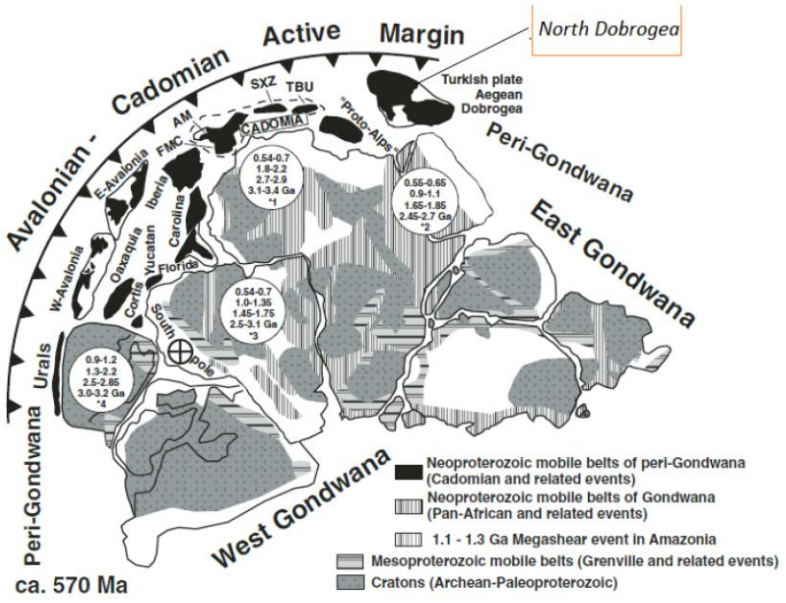
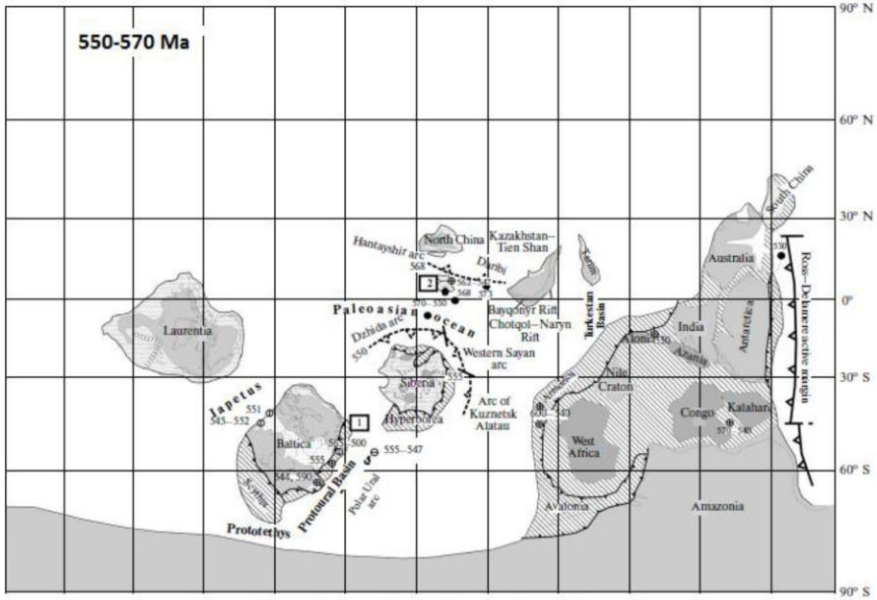


Presenter's notes: Examples of seismic lines showing the offshore extension of the Tulcea Unit between Sfantu Gheorghe Fault (SGF) and Heracleea/Portita faults. Pre-Triassic sedimentary sequences seem less disturbed compared to onshore mapped ones.

Position of North Dobrogea (Scythia) in the Late Ediacaran



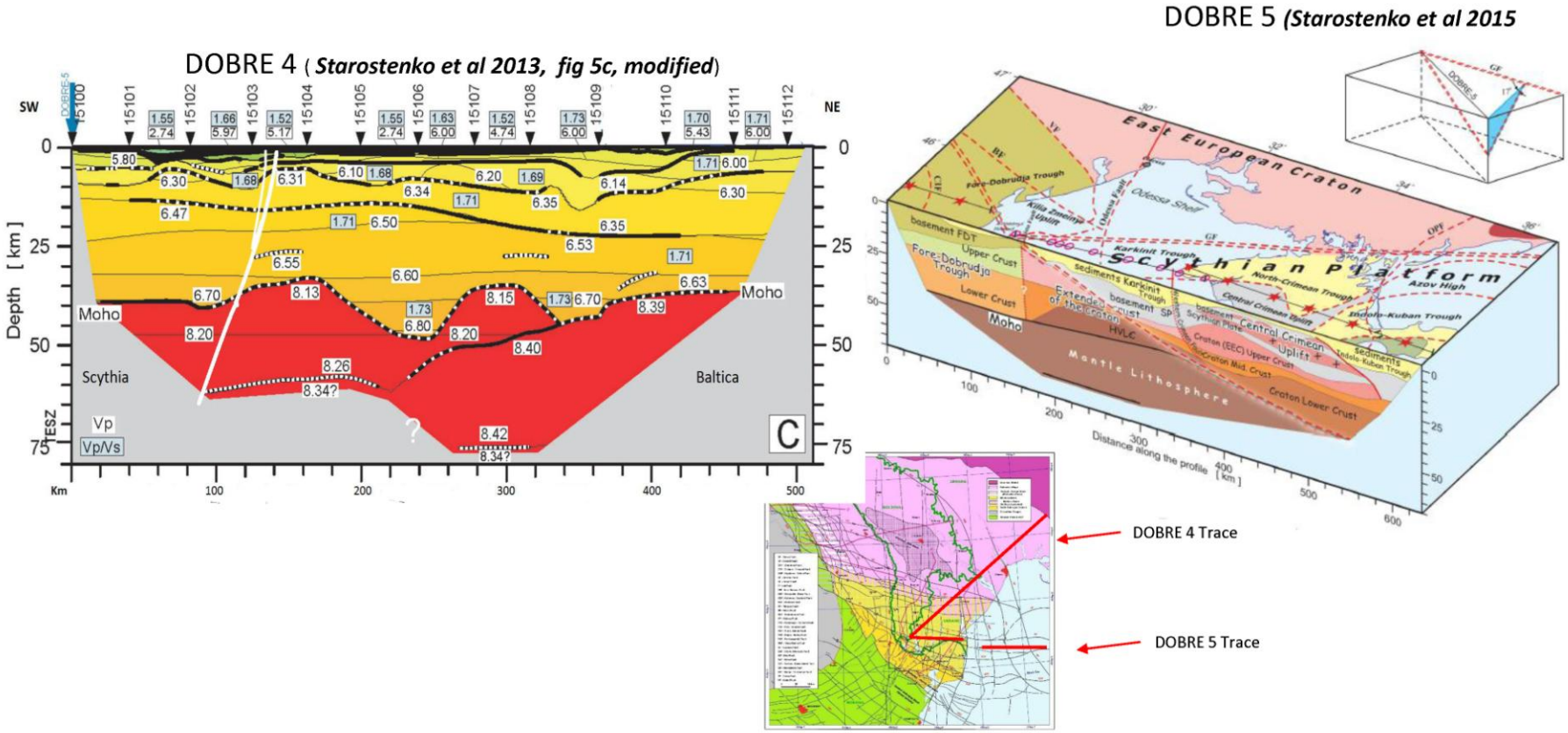
From Linnemann et al 2007



From Kheraskova et al 2015

Presenter's notes: Two paleomagnetic terrane reconstructions before or during the collision of Scythia to southern Baltica, both at some 550-570 Ma. The local geological information suggests collision with southern Baltica actually took place in post Early Cambrian, some 520 Ma.

Present day relationship between the Southern EEC and the Scythian Platform



Presenter's notes: Starostenko et al. (2013) are the first to show, on the SW-NE Dobre 4 section the Moho buckling and the upper crust folding. This can be an indirect confirmation of the deep seated effects of the Scythia intermittent northern push since the Late Ediacaran to Cretaceous.

Starostenko et al. (2015) draw the approximate northern extension of Scythian basement up to the Vaslui Fault, actually one of the faults of the Murgoci Lineament, in agreement with our interpretation. On the Dobre 5 section, it is also acknowledged that in the Moldova Basin area there are two superposed types of basements: a thin Scythian (i.e. Fore Dobrogea Through) thrusted (?) over the thick, two-layer Baltican one. (See also precedent slide for the initial terrane opposition). (*Presenter's notes continued on next slide*)

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This Scythian basement could partly correspond to metamorphics which have their top at below 5 km deep (e.g. Botezatu et al., 1961; Rosca and Atanasiu, 1993) south of the Dobre 4 end, in the Tulcea Unit where it is covered by folded clastics that crop out north of the Noviodunum Fault.

Serpent Island is important because it would mark the limit of the western compartment of the Proterozoic Soroca-Serpent Island Fault (Starostenko's Nistru Fault, fide Morosanu, 2007). This fault separates two sharply distinct compartments.

Discussion: Baltican basement vs. Avalomian (West European) and Peri-Gondwana (Scythia) terranes

Our research points out there were two significant events that controlled the western and southern margin of Baltica during the period under review.

The Moldova Slope interacted with the West European Platform during the Caledonian and Variscan diastrophisms. While the first one is still challenged by some researchers, the second one seems to reach a consensus. We adopt the idea of the development of a flexural basin during the Late Proterozoic to Early Devonian on the eastern mobile zone of the Moldova Slope as it was demonstrated along the strike in Ukraine and Poland.

The Moldova Basin - initially developed starting Late Cryogenian on the southern thinned Baltican margin – revealed a polyphase history. It underwent beginning the Latest Ediacaran two major contractions at the contact with the Peri-Gondwana, Scythian terrane during the:

1 - Cadomian Orogeny – Ediacaran/Cambrian

2 – Late Caledonian Orogeny - Early Devonian

Both compressional stages generated wedges in the North Dobrogea highly mobile zone of the Moldova Basin. They had northern vergences whereby the younger one partly cannibalized the older one. This architecture was further altered by the Variscan deformation front that induced high deformational structures with various grades of metamorphism, anatexic granitoids intrusions, earlier wedge truncation and reworking, etc. The Cimmerian events created additional high-angle compressional faulting and thrusting which almost finalized the Dobrogea Highlands tectonic configuration as we know it today.

Due to the coupled Moesia/Scythia and push to the north in both contractional phases, the Ediacaran package (?and its basement) was folded and faulted in the whole Moldova Basin up to the deep seated Murgoci Lineament separating the basin of the firm Baltican basement. This lineament, with up to 3 km throws continues eastwards into the Golytsin Fault zone.

The transform Peceneaga-Camena Fault was probably active since the Ediacaran, separating the basins and wedges of Scythian from the southern Central Dobrogea, Moesia terrane. The fault was reactivated several times notably in the Variscan and Cimmerian contactions and strike-slip events as well as in the Early cretaceous West Black Sea Basin opening. It goes NW from the Black Sea up to the Focsani deep Neogene trough then NNW and separates EEC and WEP up to the Moho level.

Presenter's notes: Numerous authors discussed the relationships between North Dobrogea Domain and Moldova Basin on one hand and between the Moldova Basin and Baltica on the other hand: Atanasiu et al. (2005), Balintoni et al. (2010, 2013), Balintoni and Balica (2016), Besutiu et al. (2005), Bocin et al. (2013), Bucatchuc et al. (1988), Bush (2014), Dinu et al. (2005), Cosma et al. (1983), Gradinaru (1984), Hippolyte (1996, 2002), Kalvorda et al. (2003), Kheraskova et al. (2015), Khriachtchevskaya et al. (2010), Kozlenko and Kozlenko (2014), Morosanu (2007), Moroz et al. (1997), Munteanu et al. (2011), Mutihac and Mutihac (2010), Nikishin et al. (1998), Paraschiv and Paraschiv (1978), Patrut et al. (1995), Pharaoh et al. (2006), Sandulescu (1984), Seghedi and Oaie (1995), Seghedi (2001, 2012, 2016), Slyusar (1984), Starostenko et al. (2013, 2015), Yegorova et al. (2010), Yudin (2012), etc., to quote some researchers that were intrigued by this relationship and interpreted it in various ways.

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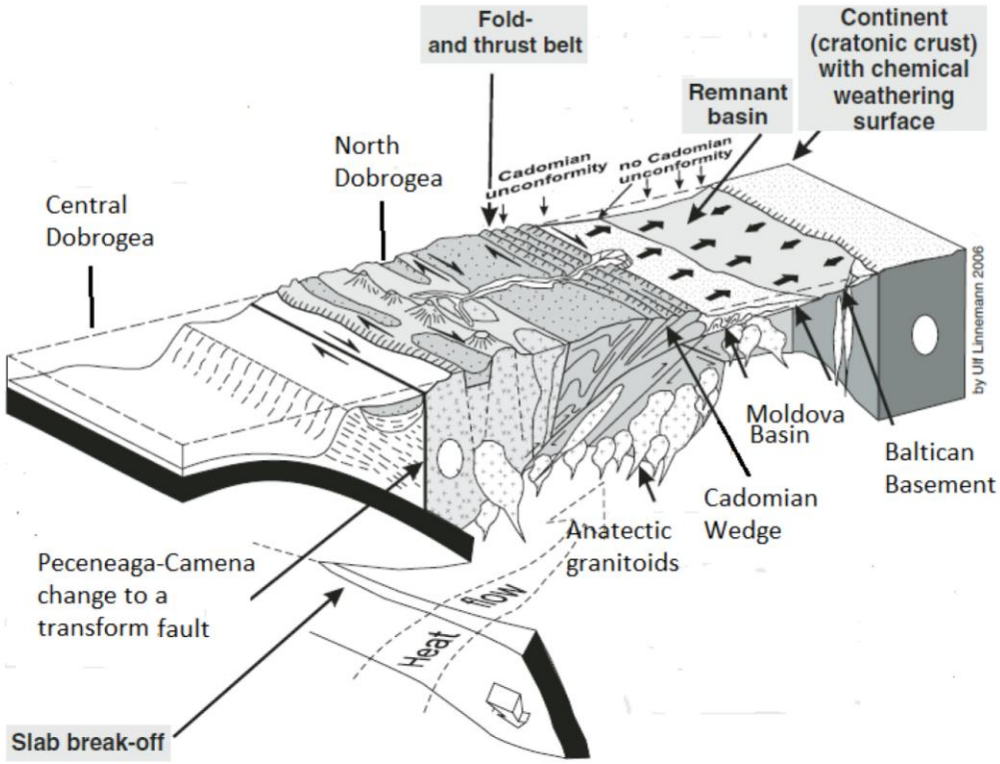
Our research tried, among others, to unravel the broad Scythia and Baltica interaction during a period spanning over 250 Ma, between the Ediacaran and the Devonian. While Baltica is a rather a well constrained terrane during the period under review, the western Scythia terrane is not yet fully constrained, especially along its southern border, alongside the Peceneaga-Camena major crustal fault. Along this fault, there develops in the NW end of NDD, the Boclugea, Megina and Orliga terranes (Balintoni et al., 2010) which would represent a transtensional belt (Gradinaru, 1984). These splinters' arrangement is related to the cumulative offsets cutting various Gondwanan micro-terranes from the Ediacaran onwards by the mainly dextral oblique Peceneaga-Camena Transform Fault movements.

Conceptual Model of the Cadomian Collision of Peri-Gondwanan Terranes to South Baltica Limb

(adapted from Linneman et al 2007)



Presenter's notes: This model, adapted from Linnemann et al. (2007), shows tentative relationships between North Dobrogea (southern Scythia) and Baltica intermediated by the nascent Moldova Basin. It has a noteworthy similarity whereby the couple Central Dobrogea and North Dobrogea (i.e. North Dobrogea Domain/NDD) is impacting the Moldova Basin and Slope. We interpret it as a possible evolution of our region, some 550-520 Ma ago. The Peceneaga-Camena crustal fault could had been there since the Ediacaran. The Cadomian orogeny acted in its late phases of the collision, some 520 Ma ago, post Early Cambrian.

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The ideas emerging in the Caspian (Kheraskova et al., 2015) and between the Caspian and Azov Sea (Bush, 2014) propose that a Scythian plate started moving onto the EEC in the Vendian. This model seems to replicate in its westernmost segment, i.e. Moldova Basin area, as shown in the previous slide.

The mobile Moldova Basin, including its NND area, was again subject to the Caledonian compression, around 410-400 Ma, in the Early Devonian. It was followed by the Variscan orogeny NDD, then by the Permian rifting, widespread in the Moldova Basin which would mark the collapse of the Variscan orogen (Seghedi and Neaga, 2016) and by the Triassic rifting (Vlad, 1978).

After the Early Devonian contraction, on the Gondwanan-Cadomian Retro-foreland will continue to some extent individual basin(s) evolution including the sedimentary record of the southwestern exotic terranes of NDD, whose individual development is contrasting with that of the Moldova Basin (Seghedi, 2001).

Conclusions

- Moldova Slope (EEC) and Moldova Basin (EEC + Scythia) basements and their sedimentary covers, roughly separated by the deep crustal Murgoci Lineament are a collage with multiple structural overprints: Cadomian, Caledonian, Variscan, Cimmerian and Latest Cretaceous-Paleogene.

- The Radauti-Roman Unit represents the TESZ in Romania and intermediated the Moldova Slope rigid basement collision to WEP. The eastern TESZ's Tornquist-Teisseyre Lineament running parallel to this block will not continue eastwards according to our proposed interpretation.

- The Scythian terrane (Scy), embodied in the present Dobrogea Highlands (i.e. NDD), initially collided the Baltica in the Late Cadomian orogeny resulting in the folding of the Ediacaran-Earliest Paleozoic sedimentary sequence up to the Murgoci Lineament. The further Caledonian underthrusting induced minor folding and reverse faulting of the entire Moldova Basin sediments and resulted in an accretionary wedge south of the Danube. Finally the Variscan and Cimmerian events proceeded to reverse faulting, especially in the onshore southern basin area (e.g. Tulcea Unit) and in the whole adjacent NDD terrain.

- The southern Laurussia accreted territory, reformed by the Scythia collision and subsequent compressional and extensional events was eventually inverted in the Latest Cretaceous-Paleogene including the North Dobrogea Domain and the West Black Sea (WBS) Basin up to the Peceneaga-Camena deep crustal fault.

- We interpret the present-day collage of various faults as the superposition of a WNW-ESW trending Cenozoic (mostly Neogene) fault set on significantly older NNW-SSE sub-longitudinal fault sets. The group of old faults were active longer on the westernmost flank of the rigid EEC, as part of the broader Teisseyre-Tornquist Lineament. The continuation of this fault set seems to stop at the Murgoci Lineament although a number of authors prefer to see the latter as the continuation of the same fault lineament. The group of younger faults with Neogene senestral strike-slip character, also affecting the frontal part of the Carpathian thrust-fold belt, is interpreted to offset the traces of the older transpressive or transtensive faults sets. In particular, the en-échelon faults south of the Trotus Fault could had been active below the Carpathian nappe stack and caused the prominent half-window in the East Carpathians.